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**In-sequence tectonic evolution of Ediacaran nappes in the southeastern branch of the Brasília Orogen (SE Brazil): Constraints from metamorphic iterative thermodynamic modeling and monazite petrochronology**

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# LITHOS

## In-sequence tectonic evolution of Ediacaran nappes in the southeastern branch of the Brasília Orogen (SE Brazil): constraints from metamorphic iterative thermodynamic modeling and monazite petrochronology

--Manuscript Draft--

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<b>Abstract:</b>	<p>The metamorphic and kinematic evolution of medium-high grade rocks of the Andrelândia Nappe System (ANS), the orogenic wedge of the Southern Brasília Orogen (SBO), was investigated in this work. Field and microstructural observations were combined with metamorphic petrology (i.e., iterative thermodynamic modeling) and monazite petrochronology to reconstruct the tectono-metamorphic history of the ANS rocks. The Liberdade Nappe experienced prograde metamorphism at ca. 610 Ma, achieving peak metamorphic conditions of ca. 650°C and 9.5-10 kbar. This stage was followed by isothermal decompression linked to tectonic transport toward SE, at ca. 570 Ma. On the contrary, the Andrelândia Nappe experienced prograde metamorphism later, at ca. 580 Ma, reaching peak metamorphic conditions of ca. 680°C and 11-12 kbar. The obtained results indicate that each nappe of the Andrelândia System records a single metamorphic cycle of burial and decompression, although it took place at different ages over a period of ca. 60 myr, from 630 to 570 Ma. The nappes experienced prograde and retrograde metamorphism whose ages progressively decreased toward the bottom of the nappe stack. We attribute this pattern to propagation of older buried material from the orogenic wedge (i.e., Liberdade Nappe), via thrust-and-fold, upon recently accreted rocks (i.e., Andrelândia Nappe), conducting a younger metamorphism event on the footwall of the ductile thrust nappes. This mechanism is consistent with the ANS in-sequence fold-and-thrust architecture.</p>
<b>Suggested Reviewers:</b>	<p>Alice Westin, PhD University of São Paulo alice.teixeira@usp.br Dr. Westin has worked in the Southern Brasília Belt, with several papers published in the area.</p> <p>Gregory Dumond, PhD Dumond, PhD gdumond@uark.edu Dr. Dumond research is focused on collisional belt evolution, applying as methodology macro- and microstructural studies, thermodynamic modeling, and monazite geochronology.</p> <p>Regiane Fumes, PhD regiane.fumes@unesp.br Dra. Fumes has developed her work using monazite petrochronology and metamorphic modeling techniques in the Southern Brasília Belt.</p>

	<p>Glaucia Queiroga, PhD glauciaqueiroga@ufop.edu.br Dra. Queiroga has an expertise in metamorphic petrology and monazite petrochronology. She has developed her research in the Neoproterozoic fold-thrust belts from Brazil.</p>
<b>Opposed Reviewers:</b>	

**In-sequence tectonic evolution of Ediacaran nappes in the southeastern branch of  
the Brasília Orogen (SE Brazil): constraints from metamorphic iterative  
thermodynamic modeling and monazite petrochronology**

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August 18<sup>th</sup>, 2023

Dear Editor,

I am pleased to submit an original research manuscript entitled “Tectonic evolution of Ediacaran nappes in the southeastern branch of the Brasília Orogen (SE Brazil): constraints from metamorphic iterative thermodynamic modeling and monazite petrochronology” written by Benetti, B., Campos Neto, M.C., Carosi, R., Luvizotto, G., Iaccarino, S., and Montomoli C. to be examined for publication on LITHOS.

The paper presents new data and interpretations about the tectonic, metamorphic, and time evolution of the Andrelândia Nappe System, the orogenic wedge hinterland of the Southern Brasília Orogen. The manuscript contains field and microstructural observations combined with the leading-edge techniques in metamorphic petrology (i.e., thermodynamic iterative modeling) and geochronology (i.e., monazite petrochronology). The obtained data carry precious information and implications concerning the tectono-metamorphic events experienced by the Andrelândia Nappe System rocks. The combination of our new data with literature information suggest that the Andrelândia Nappe System spread of ages is related to different periods when the different nappes of the system experienced prograde and retrograde metamorphism during the Southern Brasília Belt protracted and progressive continental collision development.

I confirm that the manuscript has not been published and is not under consideration for publication elsewhere, and look forward to hearing from you in due course.

Yours sincerely,  
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Dear Editor,

We sincerely appreciated the reviewers comments and editorial work aimed to improve our manuscript. We have considered the comments and suggestions of the two reviewers, improving the manuscript accordingly.

We have attached a revised version of the manuscript where new parts are highlighted with red text and the deleted ones are strikethrough. In addition, we also provide updated figures. In the following parts, we reply to the reviewers comments specifying in detail how we have addressed the raised points. Original comments are in black text, whereas our replies are in blue text. We indicate with “Line” the corresponding lines, in the revised version of the manuscript with changes marked. In the cases, where we do not share the same point of view of the reviewers, we explain our reasons.

In addition, taking into account reviewers comments to emphasize the subject of the present work we decided to modify the title to “In-sequence tectonic evolution of Ediacaran nappes in the southeastern branch of the Brasília Orogen (SE Brazil): constraints from metamorphic iterative thermodynamic modeling and monazite petrochronology”.

Reviewer #1: Relevance of the manuscript to the Lithos audience: This manuscript by Benetti et al. represents a multi-disciplinary attempt to constrain the Neoproterozoic tectono-metamorphic evolution of two nappes within the Brasília orogen in southeast Brazil. The most intriguing result of this study is documentation of differences in age and timing of deep crustal metamorphism that are consistent with thrust loading and subsequent decompression in an evolving orogenic wedge. This manuscript is well aligned with the journal's aim and scope and would be an excellent contribution.

General Comments to the Authors and Editor: I think this manuscript makes an important contribution to our understanding of the metamorphism and tectonism recorded in the Brasília orogen, and it is very well written. It is certainly suitable for Lithos, and I have only modest comments and suggestions mentioned below. It is an excellent integration of petrology and monazite geochronology. As I am not an expert on the geology of the Brasília orogen, I have reserved my comments to general ones throughout the text.

We thank the reviewer#1 for his detailed review of our manuscript and your positive comments. We have addressed the raised points, as detailed explained below.

Comments and Suggestions by line for the Authors:

Lines 30-35 I would clarify these sentences by re-writing them as: "The nappes experienced prograde and retrograde metamorphism that progressively decreased toward the bottom of the nappe stack. We attribute this to propagation of older material from inner parts of the orogenic wedge during thrusting of nappes over recently accreted rocks, leading to younger metamorphism in the external parts of the wedge. This mechanism is consistent with the in-sequence fold-and-thrust belt architecture to the ANS."

Done (see Line 31-40).

However, it is not clear to me what you mean by "external parts of the wedge". In the paper, you seem to conclude that the deepest levels of the wedge experienced the youngest metamorphism. Wouldn't it be better to say "deeper" instead of "external"? I may not understand this correctly, but please word it differently so that your audience does understand. You use some of this same text in Lines 606-606. Be sure to clarify this in those lines, too.

When we refer to external parts, we mean the “footwall of the ductile thrust”. The text was modified in both suggested parts to make it clear (see Line 38 and 652).

Lines 54-55 I would re-write as "... changes during the development of an orogen as recorded

by its kinematic history and internal structure."

[Done \(see Line 65-66\)](#)

Line 59 "... hinterland of an orogenic wedge."

[Done \(see Line 73\).](#)

Line 60 "... intense debate during the past several decades."

[Done \(see Line 74\).](#)

Lines 61-62 "... that the ANS evolution was due to polymetamorphism related to two separate tectonic events during different orogenic cycles. The first event was..."

[Done \(see Line 75-78\).](#)

Lines 67-68 "... isograds during NW-SE contraction at 600-560 Ma. The tectonic event is attributed to the..."

[Done \(see Line 83-85\).](#)

Lines 69-70 "The second model proposes that the ANS evolution was due to a single orogenic cycle."

[Done \(see Line 87-88\).](#)

Line 70 You cite the authors who prefer the second model at the end of this sentence. It's not necessary to say "According to them..."

[Done \(see Line 88-89\)](#)

Line 78 What you have done is much more than "elementary". I would replace this word with "fundamental".

[Done \(see Line 97\)](#)

Line 79 "internal" should be "internally".

[Done \(see Line 99\).](#)

Line 80 These techniques can be used to make "pseudosections", but more generally, we refer to this as "... databases to create phase equilibria models that can be used to constrain..."

[Done \(see Line 99-100\).](#)

Line 82 Change "to set up" to "to link"

[We prefer not to repeat the word "link" in a phrase.](#)

Line 85 "... or titanite can provide ages for specific metamorphic reactions and deformation events..."

[Done \(see Line 104-105\).](#)

Lines 86-88 "This approach is one of the most effective ways to understand the complex frameworks of collisional belts."

[Done \(see Line 107-108\).](#)

Lines 89-92 These two sentences can simply and more effectively occur at the end of the previous paragraph. There's no need to have them as a separate paragraph.

[Done \(see Line 96-114\).](#)

Line 318 H20 should be H2O.

[Done \(see Line 345\).](#)

Line 416 What do you mean by "punctual"? Perhaps you could say "... 84 EMPA spot analyses were..." You could also use this phrase for the beginning of Line 436.

[Done \(see Line 443 and 463\).](#)

Line 446 Th is rarely a trace element in monazite. It often occurs at the wt.% level.

[Done \(472\).](#)

Line 455 It is important to clarify that monazite's microstructural position and its internal chemical zonation both help provide this information.

[Done \(see Line 481-482\).](#)

Line 462-463 I would rephrase this as "If monazite grows at these conditions prior to growth of garnet, the monazite will display..."

[Done \(see Line 489-490\).](#)

Line 464 If garnet is growing and incorporating Y, it is doing so as the product of a reaction

and not as a reactant. I would re-write this as "When monazite grows in equilibrium with garnet, the monazite tends to be depleted in Y since this element partitions strongly in garnet."

Done (see [Line 492-493](#)).

Line 484 "The monazite grains..."

Done (see [Line 515](#)).

Lines 496-497 "...presented here help elucidate the complex..."

Done (see [Line 529](#)).

Lines 516-520 This is what is called a run-on sentence. It would be clearer if you break this long sentence up into two or more sentences.

Done (see [Line 552-556](#)).

Line 527 In this line and in Line 83, you use the term "blastesis-deformation" relationships and refer to Passchier and Trouw (2005). "Blastesis" does not occur anywhere in this book. The more common phrase (and also used by these authors) is "porphyroblast-matrix" relationships. [The reference of Passchier and Trouw \(2005\) used for referring to the "blastesis-deformation" relationships was deleted \(see Line 103\).](#)

Line 549 Change "time constraints" to "timing constraints".

Done (see [Line 590](#)).

Line 593 It is not usually appropriate to cite a reference unless it is either accepted or in press. You should ask the editor if this is okay or not for (Westin et al., submitted).

[This reference was deleted \(see Line 627 and -639\).](#)

Lines 603-606 See my first comment for Lines 30-35.

Done (see [Line 652](#)).

Well done!

[Thanks again to Rev#1 for the very constructive comments to improve this manuscript.](#)

Gregory Dumond  
University of Arkansas

Reviewer #2: B. Benetti and co-authors investigate the tectono-metamorphic evolution of the Andrelândia Nappe System (ANS) in Southern Brasilia Orogen (SBO) using thermodynamic iterative modeling and monazite petrochronology. The main results were determining the maximum P-T conditions and the ages of prograde metamorphism, and part of the retrograde metamorphism, of the Liberdade and the Andrelândia nappes. These results are interpreted in the context of the SBO evolution and collision between the Paranapanema and São Francisco cratons. This work presents a lot of new geochemical and geochronologic data that certainly contribute to the understanding of the regional geology, however, it lacks a clear problematic, and the work is missing a discussion regarding the implications of your work for Tectonic/Petrologic studies worldwide, and/or the evolution of Neoproterozoic fold-and-thrust belts, to deserve publications in a journal like LITHOS. Also the interpretations regarding thrust stacking, decompression and exhumation of the studied complexes are conceptually poor. Authors must go deeper in the bibliography of the formation of FTBs and the tectonics problems behinds it, specially regarding new studies. I have regards in the way you present your geochronological data, once your ages have decrease progressively, using the mean age is meaningless and your must use the ranges of the maximum and minimum age of your samples, it changes your main conclusions. I also suggest estimating depths for the metamorphic events you constrain your P-T-t, using a geothermal gradient for collisional orogens. The beginning of your study is confusing, whereas part of the discussion is clearer, and so you may rebuild part of your introduction and discussion before publication.

We would like to thank Rev#2 for the very detailed and constructive review done. We made significant changes in the abstract and introduction following his suggestion to leave the work problem clear and improve the bibliography. Regarding the geochronological data the EMPA monazite dating, different from other isotopic methodologies, requires that few punctual data be accumulated until achieve an acceptable level of precision (see Williams et al., 2006, Chemical Geology, vol. 225). We explained better this topic below. Finally, the estimative of depths and geothermal gradients were added in the text and new Figs. 14 and 15.

#### Point-by-point Reviews:

Abstract. 16-20: useless first and second sentences, I suggest saying directly that you found medium-high P-T rocks in the Andrelandia Nappe System and that you aim to decipher the metamorphic and kinematic evolution of this fold-and-thrust belt. Also, just saying it's a topic of debate is not enough. What is the debate about?

Done (see Line 16-21). Regarding the "topic of debate", how this phrase was deleted, the nature of this discussion is explained after in the introduction (see Line 72-95).

l. 23. Prograde metamorphism is a process, so the Nappe does not "attain" it, change by "experienced", and "attained" for your measured P-T.

Done (see Line 24).

l. 27 be consistent when using ~ or ca. for temperature.

Done (see Line 25).

l. 29-30. myr instead of Ma if you are referring to an interval of time.

Done (see Line 31).

l. 30-31. "prograde and retrograde metamorphism".

Done (see Line 32).

Decrease of what? Depth, T, P ?

The phrase was modified to make clear that the decrease cited is related to the ages (see Line 31-33).

l. 32-35. Here it becomes confusing. The thrusting occur during tectonic burial? What is the older material? The Liberdade Nappe units? Above which younger material? The Andrelandia Nappe units?

The phrase was modified to make it clear that the thrust took place after tectonic burial and the older and younger accreted material cited is correlated to, respectively, the Liberdade and Andrelandia Nappe (see Line 34-38).

If you are interpreting both prograde and retrograde metamorphism occurring during thrust stacking, what changes in your tectonic evolution to trigger retrograde metamorphism?

Several mechanisms could trigger the onset of the thrust stacking, and consequently the retrograde metamorphism in the hanging-wall and prograde in the footwall, such as a change in the critical wedge angle or an insertion of a stiff material under the wedge. However, this is not discussed in this manuscript, being beyond the topic. We mostly focused on the diachronic equilibration (both of prograde and retrograde metamorphisms) within the nappe stack, in the discussion and consequently in the abstract.

First you say that your ages and P-T-t paths record "a single metamorphic cycle of burial and decompression" and after you say that folding and thrusting conduct "a younger metamorphism event on external parts of the wedge". Thus, it's one or multiple metamorphic events? I seems that you still didn't decide if your retrograde metamorphism occur during tectonic burial or exhumation. Same observations for the highlights, please decide if you interpret one single of multiple metamorphic events.

What we were trying to say is that each one of the nappes of the Andrelandia System records only one metamorphic loop (prograde followed for decompression and retrograde metamorphism). This achievement is especially important because, as explained in the

introduction, some research considers that the ANS underwent two metamorphic loops, one of high-pressure and another of high temperature. If so, all the nappes of the system would record two metamorphic loops, which is not the case. Then, we modified the text and emphasized that each one of the nappes underwent one tectonic cycle of burial and decompression in different ages, not the system as a whole as previously written (see Line 28-31).

40-42. Crustal accretion occurs by tectonic processes as well, such as by thrust stacking and this is a process you are focusing on your study, so it's crucial to cite it here.

Done (see Line 46).

Consider reading and citing the works of Davis and Dahlen that explain the growth of fold-and-thrust belts and accretionary wedges, as well as Ruddiman et al., 1997, Willett, 1999, Beaumont et al., 2001; Egholm et al., 2009; Whipple, 2009 for the tectonic vs. erosion role on mountain building.

We added the following references Beaumont et al., 2001, Davies et al., 1983, Whipple, 2009 and, Willett, 1999 (see Line 48-49).

"Tectonic and post-orogenic thinning" by tectonic erosion? Extension? Delamination? Please be more precise.

The phrase was modified to be more precise about the mechanism of crust removal during orogenesis as suggested by rev#2 (see Line 47).

42-45. External and internal "factors" are very broad, and "structure" means nothing in this context, you mean tectonic. I suggest excluding this phrase to avoid mistakes, it's the same as the first one, and does not connect with the next one. Also, surface processes are not discussed on your paper, so I don't see the point on using the first lines of your manuscript to talk about surface-deep Earth interactions.

Done (49-51).

47-49. "the balance of the orogen active forces leads to exhumation" this is a very vague phrase to talk about exhumation. Exhumation actually occurs due to erosion or extension, but it can be forced by tectonic shortening or any geodynamic process forcing rock uplift if your erosion rate is strong enough to indeed "exhume" rocks. Please revise bibliography... (England and Molnar, 1990 and Molnar and England, 1990; works of T. Ehler, B. Carrapa, S. Willett...).

We modified this sentence to highlight the mechanism of exhumation (e.g., erosion, normal faulting, and ductile flow; see Line 54-56). In addition, the references of England & Molnar, 1990; Ring et al., 1999 were added (see Line 56-57).

49-50. How? Thrust stacking increases the geothermal gradient?

Link this quite random phrases to the processes you are studying.

To link the introduction with one of our main conclusions, that is the metamorphism as a consequence of loading of an overlying nappe, a phrase explaining the hot iron model was added. This model admits that the overthrust of hot rocks over colder ones can serve as a heat source for the footwall rocks metamorphism (see Line 62-64). The references of England & Molnar, 1993, and Le Fort, 1975 were added (see line 63-64).

52-57. It's true but quite obvious, any rock record a P-T. Change the goal saying that the P-T recorded in deeply buried rocks is valuable to understand the deep-Earth dynamics of accretionary wedges. Cite also what is still not fully understood amongst the processes that form fold-and-thrust belts (and why P-T-t studies are useful).

Done (see Line 64-68).

60. Exclude "Indeed", it's for when you are arguing about something previously said.

Deleted (see Line 74).

65. Reference, especially when you use ages.

The following references were added Coelho et al., 2017, Li et al., 2021, Reno et al., 2012 and, Trouw et al., 2013 (see Line 81-82).

68. Reference, please.

The following references were added Coelho et al., 2017, Fontainha et al., 2020, Heilbron et al., 2017, Trouw et al., 2013 and, Zuquim et al., 2011 (see Line 84-85).

75. What are the available ages?

We added to the text the published metamorphic ages, which are from 630 to 580 Ma (see Line 93-94).

90. Change "modern techniques in metamorphic petrology and geochronology" for the methods you used, such as pseudosection thermodynamic modeling and in-situ monazite petrochronology.

The suggested part was deleted and modified accordingly (see Line 110).

I still think that the aim of your work is too vague, please specify something like "to unravel the depth and timing of tectonic processes forcing the build of the ANS fold-and-thrust belt, such as tectonic burial and exhumation".

We modified the last paragraph of the introduction to be more specific as suggested (See Line 112-113).

111. "bodies" change for "plutons".

Done (see Line 133).

146-154. What are the main lithotypes of the Andrelandia Nappe? At least the ones you cite the ages and P-T conditions.

The Andrelândia Nappe main lithotypes were added (see Line 170-171).

155. This section is already your data? It should be called "Results" and then subdivided in sections such as "Field observations" or "Structures and stratigraphy". You also should write clearly that these are new data from field work performed in this study.

Done (see line 179-180)

156-159. If you want to keep these phrases, they should come in the Geological setting.

"Basement cores" instead of basement nucleus. "Allochthonous units"

We decided to keep this phrase in the field observations section, once it is a brief introduction of the study area, which will be linked with the other paragraphs of the section. The suggested modifications for "basement cores" and "Allochthonous Units" were done (see Lines 183-184).

162. Which minerals are kinematic indicators? Write even if you have a figure.

In this part of the text, we are presenting the field-based observations, then we preferred just adding information about macro-scale kinematic indicators (see Line 187).

173. Same as before, please specify the kinematic indicator.

Same as above, we prefer to give information, in this section, related to field observations. In section 3.2.1, where is described microstructural aspects of the Liberdade Nappe, we added information about which minerals are the kinematic indicators (see Line 233-234).

190. Make it a subsection of your Results section.

Done (see Line 215)

269. It's okay to use mineral abbreviations, but then you should be consistent and use it from the beginning, and including the meaning of abbreviations in your supplementary material.

To be consistent in the whole section, we deleted the mineral abbreviations. In the other sections, they are used and follow Whitney and Evans (2010) as indicated in the Line 228.

272. Use metamorphic paths to when you show the P-T-t paths with the pseudosections. Here, use "metamorphic phase" or "metamorphic assemblage".

Done (see Line 298).

292. Another subsection of "Results".

Done (see Line 319).

334-344. If you have EPMA geochemical composition of your metamorphic minerals, why don't you model the isopleths to show more accurate metamorphic conditions?

In the present work, we adopted as a thermobarometric strategy the iterative thermodynamic modeling (ITM, Lanari & Duesterhoeft 2019; Duesterhoeft & Lanari 2020; Lanari & Hermann 2021), which combines the advantages of both forward (e.g., pseudosection crossed with

mineral isopleths) and inverse thermodynamic models (e.g., multi-equilibrium thermobarometry). ITM builds a forward thermodynamic model and further, performs an iterative optimization through statistical routines that compare model outcomes (e.g., pseudosections and isopleths) and observations (e.g., mineral composition extracted from the compositional maps). The mineral compositions obtained through the EPMA were used to calibrate quantitative compositional maps (see Fig. 7 and 9). The compositions used in iterative optimization are indicated in red circles in the compositional maps (see Fig. 7, 9, and sup. Fig. file A2 e A3). These chosen mineral compositions were used for calculating the quality factor of mineral composition ( $Q_{\text{cmp}}$ ; see sup. Fig. file A4, A5, and A6). The  $Q_{\text{cmp}}$  will evaluate where in the  $P$ - $T$  diagram the chosen mineral composition will best match with the model. In other words, the ITM will show results of the modeled isopleths in a different graphical interface. Instead of displaying the mineral composition isolines and the user checks the match between them and the observed mineral composition, the ITM calculates the isopleths and then checks itself the probability of specific mineral composition being stable ( $Q_{\text{cmp}}=100\%$ ) in the  $P$ - $T$  diagram (see sup. Fig. file A4, A5, and A6). In a certain way, quality factors (for modes and mineral compositions), represented in quality factors maps, give an idea of the fit (and/or misfit) between modelled modes and mineral compositions (i.e., the isopleths) against the observed ones in the samples. In addition, we would like to point out that there is no work in the literature saying that the methodology applied in this work is less accurate than isopleth thermobarometry. On the contrary, we regard this methodology as a leading-edge method to extract as much as possible information on  $P$ - $T$ - $X$  sample's evolution and statistically check/visualizing the results with higher accuracy (see e.g. Lanari & Hermann 2021).

345-357. You cite intersections between mineral chemistry, but you don't show them in the figure. Please show the isopleths if you calculate them.

See the comment above regarding the compositional isopleths calculation (but please note how this is expressed in the quality factors maps). The areas where the thermodynamic model reproduces the plagioclase core and rim, muscovite, and garnet ( $Q_{\text{cmp}}=100\%$ ) compositions are delimited in Fig. 7b and 9b. In the supplementary figure A4, A5, and A6 are displayed the  $P$ - $T$  maps of the mineral chemistry composition quality factor ( $Q_{\text{cmp}}$ ).

390. Another subsection of "Results".

Done (see Line 417).

472. "two episodes of monazite growth"

Done (see Line 502).

475. After garnet crystallization.

Done (see Line 505).

477. Early prograde metamorphism. Exclude "path"

Done (see Line 507).

476-478. This phrase relates with the first metamorphic episode or with the second one?

I was added in text that the Th-rich are related to the  $M_{\text{LNI}}$  stage (see Line 508).

474-480. Please interpret your ages based on their range of dates, the mean age here is poor in significance once you have a clear gradual decrease of your ages. For minimum ages, use your younger date.

In our manuscript, we followed the recommendations of Williams et al. (2006) for reporting microprobe monazite ages, which require a different treatment compared to some isotopic techniques. For EMPA monazites geochronology is recommended that individual analysis be referred to as "measurements" or "analyses", but not as dates, or ages (which carries a geological meaning). According to Williams et al. (2006, Chemical Geology, vol. 225) pag. 5: "the essence of the method (EMPA monazite dating) is that numerous data points (analysis) are collected from each monazite compositional domain in order to produce a single date with an associated error". Therefore, the EMPA monazite geochronology approach requires that the

individual measurements are accumulated until an acceptable level of precision has been achieved (weighted mean age) (see e.g., Fig. 5 and 6 in Williams et al. (2006).

Additionally, the mean age 608 +/- 4 Ma appears here but not in the results, is it correct?

Sorry for the mistake, it was an oversight, the right age is 609±4 Ma (see Line 506).

Can you associate your older age with the S1 foliation?

Yes, we can. This information was added to the text (see Line 508).

484-491. Same about the minimum age, use your younger date in this context.

Add "Ma" to the age.

As explained above, it is necessary in EMPA monazite dating that the analyses of each compositional domain are combined using a weighted mean or other statistical procedure to place constraints on geological features (see Williams et al. 2006).

Also, time of deformation is very generic if you have several deformational episodes, repeat it's linked with S2 foliation, if it's your interpretation.

Done (see Line 511).

Also, if S2 formation in the Andrelandia Nappe forms during prograde metamorphism, I think it's inconsistent relating your S2 with the "decompression". I think conceptual discussion regarding tectonic processes generating foliations and metamorphic assemblages is lacking.

We related the LN S<sub>2</sub> foliation with decompression, and in opposite the AN S<sub>2</sub> fabric with prograde metamorphism. These temporal contrasts observed between the prograde and retrograde metamorphism between the nappes were further explained in section 4.3 by the mechanism of thrust load and decompression (see Line 612-617).

Can you estimate a geothermal gradient? You could then estimate the depth of metamorphic events using your P-T estimates, and this would enrich your discussion and Fig. 15.

We added the data of depth and the apparent geothermal gradient of both nappes (see Line 534-536 and 543-544), and Fig 14 and 15 were modified adding information of depth in the P-T diagrams.

502-505. Same observation regarding the minimum age, and this would change your abstract and other parts of your text in which you use the mean age. After this, clarify if the minimum age of your dated crystal is linked with MLN2 or MLN3 line 505.

See the comment above regarding the strategies to present the EMPA monazite ages.

509. Same observation as before about the minimum age.

See the comment above regarding the strategies to present the EMPA monazite ages.

515-539. These paragraphs are useful only if you discuss your data along with, that is the purpose of this chapter. Please give considerations showing why your data are important to disentangle, at least partially, the different interpretations previously given.

Our interpretation that the monazite populations are linked with the episodic growth during a single metamorphic loop of prograde and retrograde metamorphism differs from those that interpret them as related to two metamorphic events, one of high pressure and another of high temperature as a consequence of two different tectonic events (e.g., Brasilia and Ribeira collisions). To highlight this, we included a phrase explaining that the petrochronology study performed provided means for linking the monazite ages with episodic growth of monazites in a single metamorphic loop of burial and decompression in each of the nappes of the system, in the opposite of interpreting the spread of ages with multiple metamorphic loops (see Line 576-579).

Also, some of these phrases are conceptually wrong, such as "heating during exhumation", if you want to bring these kinds of phrases, you should discuss the significance of them.

This expression was modified to "heating during decompression" (see Line 562) to make it conceptually right.

I suggest excluding the section "Tectonic implications", once it's basically the same as "Tectonometamorphic evolution of the Andrelandia Nappe System (ANS)" and exclude phrases We prefer to leave the sections "Tectono-metamorphic evolution of the Andrelandia Nappe System (ANS)" and "Tectonic implications" as previously done. We do not think that both

sections are the same. In the tectono-metamorphic evolution of the ANS we present P-T-t-D paths of both studied nappes and compare our achievements with those from the literature. While the tectonic implications, we explained the geodynamic mechanism responsible for the P-T-t-D paths of the nappes.

541-543. For the next sentences, please bring them along with the discussion with previous data. See the justificative given above to let these sections separated.

567. Specify "decrease". Depth? Metamorphic P-T?

The phrase was modified to highlight that the decrease written is related to the metamorphic ages (see Line 606-610).

569-576. Cite Fig. 15 here. I suggest merging this paragraph and the next one, once they say the same thing, but the second with ages and contextualization within the regional geology.

Done (see 610-612).

577-593. This paragraph and the previous one, coupled with Fig. 15 are quite clear. So I suggest adjusting your abstract and rebuild part of your introduction based on the structural and metamorphic processes playing in the formation of accretionary wedges, more than with the general phrases that you bring in the introduction that are not really related with your work. Your focus is deep-seated processes forming fold-and-thrust belts, thus focus on that.

The suggested modifications of the abstract and introduction were done. We included in the introduction an explanation of two important mechanisms linked to the main topic of our work, the in-sequence flow of deep-seated rocks (see line 57-59) and the hot iron model (see line 62-64).

Also, it lacks some sentences saying what's the relevance of your work in a global context, or why your study is important for the general knowledge of fold-and-thrust belts etc. Otherwise the relevance of your work keeps too regional.

Two sentences were added to give a more global context for our work (see Lines 618-622). We tried to emphasize that the in-sequence thrust-and-fold architecture of the ANS is also described in several orogenic belts worldwide, suggesting that the mechanism of thrust-and-fold nappes propagation over recent accreted material can induce younger metamorphism and could be used to explain the structural and metamorphic record of collisional wedges.

584-606. Your conclusions are clearer than your abstract. Also in the discussion and conclusions you don't discuss single metamorphic event of multiple, as you does in the abstract in a confusing way. I suggest changing the focus in the abstract in a way to avoid misinterpretations.

We agree that we did not make clear in the text what we meant about the single metamorphic event. The way we wrote previously seemed that the whole ANS underwent a single metamorphic loop. We explained better this in the text (see Lines 576-579 and 586-589) and modified the abstract (see Line 28-31) to make clear that we are saying that each one of the nappes underwent one single metamorphic loop of burial and decompression, rather two loops (one of high pressure and a second of high temperature), as interpreted for some authors.

## ABSTRACT

The metamorphic and kinematic evolution of medium-high grade rocks of the Andrelândia Nappe System (ANS), the orogenic wedge of the Southern Brasília Orogen (SBO), was investigated in this work. Field and microstructural observations were combined with metamorphic petrology (i.e., iterative thermodynamic modeling) and monazite petrochronology to reconstruct the tectono-metamorphic history of the ANS rocks. The Liberdade Nappe experienced prograde metamorphism at *ca.* 610 Ma, achieving peak metamorphic conditions of *ca.* 650°C and 9.5-10 kbar. This stage was followed by isothermal decompression linked to tectonic transport toward SE, at *ca.* 570 Ma. On the contrary, the Andrelândia Nappe experienced prograde metamorphism later, at *ca.* 580 Ma, reaching peak metamorphic conditions of *ca.* 680°C and 11-12 kbar. The obtained results indicate that each nappe of the Andrelândia System records a single metamorphic cycle of burial and decompression, although it took place at different ages over a period of *ca.* 60 myr, from 630 to 570 Ma. The nappes experienced prograde and retrograde metamorphism whose ages progressively decreased toward the bottom of the nappe stack. We attribute this pattern to propagation of older buried material from the orogenic wedge (i.e., Liberdade Nappe), via thrust-and-fold, upon recently accreted rocks (i.e., Andrelândia Nappe), conducting a younger metamorphism event on the footwall of the ductile thrust nappes. This mechanism is consistent with the ANS in-sequence fold-and-thrust architecture.

### KEYWORDS:

Monazite petrochronology, iterative thermodynamic modeling, Brasília Orogen metamorphism, P-T-t-D paths

## **HIGHLIGHTS**

- Tectono-thermal history of Andrelândia Nappe System (ANS) was investigated.
- Each nappe of ANS records a single, diachronous, cycle of burial and decompression.
- Decompression in the hanging wall was coeval with burial in footwall rocks.
- In-sequence propagation of thrust-and-fold nappes drives younger metamorphic events.

[Click here to view linked References](#)

1 **In-sequence tectonic evolution of Ediacaran nappes in the southeastern branch of the**  
2 **Brasília Orogen (SE Brazil): constraints from metamorphic iterative thermodynamic**  
3 **modeling and monazite petrochronology**

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15 **ABSTRACT**

16 The metamorphic and kinematic evolution of medium-high grade rocks of the  
17 Andrelândia Nappe System (ANS), the orogenic wedge of the Southern Brasilia Orogen  
18 (SBO), was investigated in this work. Field and microstructural observations were  
19 combined with metamorphic petrology (i.e., iterative thermodynamic modeling) and  
20 monazite petrochronology to reconstruct the tectono-metamorphic history of the ANS

21 rocks. The Liberdade Nappe experienced prograde metamorphism at *ca.* 610 Ma, achieving  
22 peak metamorphic conditions of *ca.* 650°C and 9.5-10 kbar. This stage was followed by  
23 isothermal decompression linked to tectonic transport toward SE, at *ca.* 570 Ma. On the  
24 contrary, the Andrelândia Nappe experienced prograde metamorphism later, at *ca.* 580 Ma,  
25 reaching peak metamorphic conditions of *ca.* 680°C and 11-12 kbar. The obtained results  
26 indicate that each nappe of the Andrelândia System records a single metamorphic cycle of  
27 burial and decompression, although it took place at different ages over a period of *ca.* 60  
28 myr, from 630 to 570 Ma. The nappes experienced prograde and retrograde metamorphism  
29 whose ages progressively decreased toward the bottom of the nappe stack. We attribute this  
30 pattern to propagation of older buried material from the orogenic wedge (i.e., Liberdade  
31 Nappe), via thrust-and-fold, upon recently accreted rocks (i.e., Andrelândia Nappe),  
32 conducting a younger metamorphism event on the footwall of the ductile thrust nappes.  
33 This mechanism is consistent with the ANS in-sequence fold-and-thrust architecture.

34 **KEYWORDS:**

35 Monazite petrochronology, iterative thermodynamic modeling, Brasília Orogen  
36 metamorphism, P-T-t-D paths

37 **1. INTRODUCTION**

38 The growth of a mountain belt is controlled by the balance among accretion of  
39 crustal material, such as sediments and magma addition as well as thrust stacking, and  
40 removal by erosion, delamination, and post-orogenic extension (Beaumont et al., 2001;  
41 Davies et al., 1983; Jamieson and Beaumont, 2013; Vanderhaeghe, 2012; Whipple, 2009;  
42 Willett, 1999). An orogenic wedge is constituted by crustal material mainly detached from  
43 the subducted lithosphere, accreted, and stored within the orogenic system (Vanderhaeghe,

44 2012; Vanderhaeghe et al., 2003). During orogenesis, erosion, normal faulting, and ductile  
45 flow can lead to exhumation of the deep-seated rocks at the front of the crustal wedge  
46 (DeCelles and Mitra, 1995; England & Molnar, 1990; Ring et al., 1999; Vanderhaeghe et  
47 al., 2003). Deformation and ductile flow can follow an in-sequence pattern when they  
48 present progressive age decreases in the same direction of the tectonic transport (Weller et  
49 al., 2021). The accumulation of crustal material within an orogen enriched in radioactive  
50 heat-production elements, such as U, Th, and K, modifies its crustal geothermal gradient  
51 (England and Thompson, 1984; Rudnick and Fountain, 1995). Moreover, thrust stacking of  
52 hot rocks upon colder ones can also be a heat source for metamorphism in the footwall  
53 (“the hot iron model”; England & Molnar, 1993; Le Fort, 1975). Therefore, the deep-seated  
54 crustal rocks are able to record pressure ( $P$ ) and temperature ( $T$ ) changes during the  
55 development of an orogen as recorded by its kinematic and internal structure, providing  
56 valuable information to understand the deep dynamics of collisional wedges.

57         The Andrelândia Nappe System (ANS) is regarded as the Southern Brasilia Orogen  
58 (SBO) hinterland of an orogenic wedge. Its tectono-metamorphic evolution has been a  
59 target of intense debate during the past several decades. Some researchers (Coelho et al.,  
60 2017; Fontainha et al., 2020; Li et al., 2021; Trouw et al., 2013) argue that the ANS evolution  
61 was due to polymetamorphism related to two separate tectonic events during different  
62 orogenic cycles. The first event was related to high- $P$  metamorphic conditions testified by  
63 the HP-granulites and E/NE nappe stacking, owing to the Paranapanema and São Francisco  
64 Cratons collision in the period from *ca.* 630 to 600 Ma (Coelho et al., 2017; Li et al., 2021;  
65 Reno et al., 2012; Trouw et al., 2013). It was followed by a second orogenic event,  
66 characterized by medium pressure, greenschist- to amphibolite-facies conditions in the

67 staurolite and sillimanite zones, during NW-SE contraction at 600-560 Ma (Coelho et al.,  
68 2017; Fontainha et al., 2020; Heilbron et al., 2017; Trouw et al., 2013; Zuquim et al.,  
69 2011). This tectonic event is attributed to the Central Ribeira Orogeny (Fig. 1b). The  
70 second model proposes that the ANS evolution was due to a single orogenic cycle. The  
71 ANS tectono-metamorphic evolution is linked to the Paranapanema block collision against  
72 the São Francisco Craton (Campos Neto et al., 2011; Frugis et al., 2018; Westin et al.,  
73 2021). In this hypothesis, the sillimanite and staurolite presence documented by the ANS  
74 rocks would result from the decompression/exhumation of the nappe pile rather than testify  
75 a second tectono-thermal event. The available metamorphic ages, from 630 to 580 Ma,  
76 indicate a thrust propagation from WSW to ENE toward the São Francisco Craton southern  
77 edge (Westin et al., 2021 and references therein).

78         The reconstruction of Pressure-Temperature-time-Deformation (*P-T-t-D*) paths  
79 provide fundamental information to understand the tectonic and metamorphic events  
80 experienced by rocks accreted to the orogenic wedge. Primarily, the application of  
81 internally consistent databases to create phase equilibria models that can be used to  
82 constrain metamorphic conditions (Powell and Holland, 2008; Waters, 2019). This data can  
83 be linked with microstructural observations to set up the rock fabric relationships with the  
84 metamorphic mineral assemblage, i.e., the so-called blastesis-deformation relationships. In  
85 addition, the in-situ dating of accessory minerals, such as monazite, zircon, or titanite can  
86 provide ages for specific metamorphic reactions and deformation events (e.g., Bosse and  
87 Villa, 2019; Kohn et al., 2017; Williams and Jercinovic, 2012). This approach is one of the  
88 most effective ways to understand the complex frameworks of collisional belts (Carosi et  
89 al., 2018; Waters, 2019). In this contribution, we combine field and microstructural

90 observations with iterative metamorphic thermodynamic modeling and *in-situ* monazite  
91 geochronology. This integrative approach provides information about the timing of tectonic  
92 processes that drove the build of the ANS fold-and-thrust belt, such as tectonic burial and  
93 exhumation, and allowed the reconstruction of the tectono-metamorphic history of the ANS  
94 rocks.

## 95 **2. GEOLOGICAL SETTING**

96         The Brazilian-Pan African event is the name given to a series of diachronic  
97 collisions in the São Francisco-Congo Craton side of the West Gondwana paleocontinent  
98 (Cordani et al., 2003; Ganade De Araujo et al., 2014; Fig. 1). The Southern Brasilia Orogen  
99 (SBO) is one of the orogenic belts built during this tectonic event (Cordani et al., 2003; Fig.  
100 1 and 2). The SBO evolved from the lateral collision between the Paranapanema  
101 paleocontinent, the active margin, against the São Francisco paleocontinent, representing  
102 the SBO passive margin (Campos Neto, 2000; Campos Neto et al., 2011; Trouw et al.,  
103 2013, 2000).

104         The SBO final architecture resulted in an almost flat-lying fold-nappe pile, with top-  
105 to-the-east/northeast tectonic transport (Fig. 3). Three tectonic domains are recognized  
106 within the SBO (Campos Neto, 2000; Campos Neto et al., 2011, 2021; Trouw et al., 2013,  
107 2000; Fig. 2 and 3): (1) the active margin of the Paranapanema paleocontinent, constituted  
108 by the granulites and migmatites of the Socorro-Guaxupé Nappe, (2) the orogenic wedge  
109 hinterland, a pile of metasedimentary nappes of the Andrelândia Nappe System, (3) the  
110 passive margin related to the São Francisco paleocontinent, made by the psamo-pelitic  
111 sequences of the Carrancas and Lima Duarte Nappes. These tectonics domains are intruded

112 by leucogranites (Fig. 3) and A-type granitic rocks (i.e., Itu Granite Province, Pedra  
113 Branca, and Capituva Plutons; Fig. 2) interpreted as post-orogenic plutons.

114 The SBO is split into two segments by a tectonic window (Fig. 2) exposing the  
115 Archean-Paleoproterozoic migmatitic orthogneiss from the basement complexes (Cioffi et  
116 al., 2019, 2016; Westin et al., 2016). The Andrelândia Nappe System (ANS) is sandwiched  
117 among the UHT-HT metamorphic rocks of the Socorro-Guaxupé Nappe (Campos Neto and  
118 Caby, 1999; Motta et al., 2021; Rocha et al., 2017a; Tedeschi et al., 2018; Fig. 3) at the top  
119 and, by the low- to medium temperature metasedimentary rocks of the passive margin  
120 covers (Fig. 2 and Fig. 3), at the bottom. Internally, the ANS is divided from its uppermost  
121 structural level to the bottom by the Três Pontas-Varginha and Carmo da Cachoeira Nappes  
122 in the northern sector. In the southern sector, the ANS is segmented into the Pouso Alto (or  
123 Aiuruoca, Carvalhos, and Serra da Natureza Klippes equivalent), Liberdade, and  
124 Andrelândia Nappes (Fig. 3). Two characteristics are remarkable in the ANS: i) its inverted  
125 metamorphic pattern, in which rocks in the high-P granulite metamorphic facies structurally  
126 overlap those in amphibolite facies conditions (Campos Neto and Caby, 2000, 1999; Garcia  
127 and Campos Neto, 2003; Motta and Moraes, 2017; Trouw et al., 2000, 1998); ii) the  
128 decrease of metamorphic ages eastward, which is the same sense of the non-coaxial ductile  
129 flow (Campos Neto et al., 2011; Westin et al., 2021).

130 The Três Pontas-Varginha, Pouso Alto Nappe, and the Aiuruoca, Carvalhos, and  
131 Serra da Natureza Klippes, lay on the top of the ANS stack. They are made of K-  
132 feldspar+garnet+kyanite+rutile-bearing gneiss. These rocks attained metamorphic  
133 conditions of *ca.* 830°-900°C and 12-16 kbar in the high-pressure granulite facies

134 conditions (Campos Neto et al., 2010; Campos Neto and Caby, 2000; Cioffi et al., 2012;  
135 Fumes et al., 2021; Garcia and Campos Neto, 2003; Li et al., 2021; Reno et al., 2009).

136 The Liberdade Nappe (LN), the intermediate unit of the ANS, is composed of  
137 garnet+kyanite+ilmenite( $\pm$ sillimanite $\pm$ rutile)-bearing micaschist and paragneiss with  
138 subordinate quartzite, metabasite, and calc-silicate lenses. Metamorphic conditions, in  
139 metapelites, are constrained in the *P-T* range of 642-715°C and 6-10 kbar (Coelho et al.,  
140 2017; Motta and Moraes, 2017; Rodrigues et al., 2019; Santos et al., 2004). Zircon and  
141 monazite U-Pb dating retrieved ages around 620-615 Ma (Coelho et al., 2017; Motta and  
142 Moraes, 2017; Westin et al., 2021). Moreover, the metamafic rocks, interpreted as  
143 retroeclogites (Campos Neto and Caby, 1999; Coelho et al., 2017; Reno et al., 2009; Trouw  
144 et al., 2013), experienced *P-T* conditions around 700°-800°C and 12-16 kbar (Coelho et al.,  
145 2017; Reno et al., 2009; Tedeschi et al., 2017). The metamafic rocks present two clusters of  
146 metamorphic ages, the first around 680-660 Ma (Campos Neto et al., 2011; Reno et al.,  
147 2009), and the other around 630-625 Ma (Coelho et al., 2017; Tedeschi et al., 2017).

148 The Andrelândia (AN) and Carmo da Cachoeira Nappes are at the bottom of the  
149 ANS stack. They are internally constituted by, from the top to the base, micaschists  
150 intercalated with metapsamites, metawackes, and micaschists. The AN displays an inverted  
151 metamorphic gradient in which "peak" mineral assemblages vary from  
152 garnet+biotite+staurolite at its bottom to the kyanite+garnet+melt at the top. The  
153 Andrelândia and Carmo da Cachoeira Nappes attained peak conditions around 650-670°C  
154 and 9-10 kbar in *ca.* 600 Ma, followed by almost isothermal decompression in the time  
155 span of 600-575 Ma (Frugis et al., 2018; Marimon et al., 2022; Motta and Moraes, 2017;  
156 Reno et al., 2012; Santos et al., 2004; Westin et al., 2021).

157 **3. RESULTS**

158 *3.1 Field observations*

159 The study area is located in southeast Brazil, in the Minas Gerais state around Pouso  
160 Alto County. It comprises a geological section from SW to NE in the Andrelândia Nappe  
161 System southern sector (Figs. 2 and 4), highlighting all of its allochthonous units along  
162 with the basement cores of the nappe system.

163 The Pouso Alto Nappe has a spoon-shaped cylindrical SW-oriented synform, with  
164 W-SW plunging of the mineral and stretched lineations, and a general transport toward NE  
165 evidenced by asymmetric mafic boudin and *S-C* fabric kinematic indicators (Fig. 4a and b).  
166 The main lithotype described is a medium- to coarse-grained K-  
167 feldspar+garnet+kyanite+rutile(±ilmenite±biotite)-bearing gneiss.

168 The Liberdade Nappe is represented by fine- to medium-grained garnet+ilmenite  
169 (±sillimanite ±rutile±kyanite±staurolite)-bearing micaschist interlayered with quartzite.  
170 Micaschist displays a main spaced disjunctive schistosity, defined by biotite, white mica,  
171 and aluminum silicates shape preferred orientation (SPO). Intrafolial stretched isoclinal  
172 passive folds are observed. The ensemble of the foliation describes a large cylindrical  
173 synform with an SW-oriented B-axis in a type-3 superposition pattern (Ramsay, 1962) over  
174 recumbent isoclinal folding between the basement nucleus and the metasedimentary  
175 sequence (Fig. 3). The mineral (sillimanite/fibrolite and micas) lineations are mainly  
176 oriented to SE, which, coupled with some kinematics indicators (*S-C* fabric and  
177 asymmetrical strain shadow structures), point to an eastward transport of the nappe. The  
178 Pouso Alegre Complex is made by orthogneisses of a tonalite-granite series related to the  
179 Paleoproterozoic basement (Cioffi et al., 2016). A leucogranite body intrudes micaschist of

180 the Liberdade Nappe, the Alagoa migmatite, and the Pouso Alegre Complex (Fig. 3, 4a,  
181 and b).

182         The Andrelândia Nappe crops out in the north of the study area (Fig. 4a and b). It is  
183 made of grayish metawackes, and at its lithostratigraphic boundaries metapelites  
184 associations prevail. The main lithology described is a garnet+kyanite( $\pm$ staurolite)-bearing  
185 gneiss. The main foliation is a spaced disjunctive schistosity identified by SPO on white  
186 mica, biotite, and kyanite. The schistosity strikes ENE-WNW with dips varying from low  
187 to high angles, between 20°-80° toward the north. White mica, biotite, quartz, and kyanite  
188 are responsible for outlining the mineral and stretching lineation, which trends between  
189 N90°-N120° and plunges 10°-50° to E/SE. A kinematic change between the Pouso Alto  
190 Nappe, and the Liberdade and Andrelândia is noticed in the area. Whereas the upper nappe  
191 points to northeastward tectonic transport, the middle and lower suggest an east-  
192 southeastward direction.

### 193 *3.2 Petrography, microstructural relationships, and mineral chemistry*

194         In order to constrain the relationships between mineral growth and deformation  
195 (Fig. 5), several samples from Liberdade and Andrelândia Nappes were petrographically  
196 studied. One representative sample of each nappe was selected for performing full thin-  
197 sections maps acquired using the Scanning Electron Microscopy and Mineral Liberation  
198 Analyzer (SEM-MLA; supplementary figures A1). The location of samples is given in Fig.  
199 4a. An area of each thin-section mapped containing the inferred peak mineral assemblage,  
200 avoiding retrometamorphic textures where possible, was investigated using X-ray maps  
201 acquired by an electron probe micro-analyzer (EMPA). The analytical procedure employed  
202 for EMPA analysis is described in Appendix A. The X-ray maps were converted into oxide

203 weight percentage maps applying internal standards (Andrade et al., 2006) in the software  
204 XMapTools 3.4 (Lanari et al., 2014, 2019). Such areas were the basis for estimating the  
205 Local Bulk Composition (LBC) needed for petrological modeling (see section 5). The  
206 mineral abbreviations follow Whitney and Evans (2010).

### 207 3.2.1 Liberdade Nappe (LN)

208 The Liberdade Nappe micaschist is made up of quartz+plagioclase+white  
209 mica+biotite+garnet+ilmenite(±sillimanite±rutile+kyanite±staurolite). The LN displays a  
210 spaced disjunctive schistosity ( $S_2$ , Fig. 6a), and in some portions presents microstructures  
211 of tectonic transport such as a *S-C* fabric and isoclinal folds, made up mainly of white mica  
212 and sillimanite, denoting top-to-the-SE motion. Quartz has slightly lobate contacts (Fig.  
213 6a), and plagioclase has undulose extinction. The quartz features reveal that this mineral  
214 was recrystallized due to the grain boundary migration (GBM) regime and underwent the  
215 grain boundary area reduction (GBAR; Passchier and Trouw, 2005). Garnet porphyroblast  
216 has in several circumstances a skeletal microstructure (Fig. 6b). It also shows S-shaped  
217 inclusions made of quartz (Fig. 6c), defining an internal foliation that is not continuous  
218 with the external one. Then, garnet is regarded as a pre- to early-syn-tectonic mineral with  
219 respect to the  $S_2$  schistosity. Sillimanite is present as fibrolite, it replaces partial to  
220 completely garnet porphyroblasts, forming pseudomorphs (Fig. 6d), and also occurs along  
221 intrafolial isoclinal folds (Fig. 6e). Subidiomorphic relic of kyanite wrapped by white mica  
222 is observed (Fig. 6f). Staurolite, in a very low modal amount, is fine-grained and often  
223 related to garnet rims. Rutile is enclosed in garnet and in the matrix is usually rimmed by  
224 ilmenite.

225 The relationships among minerals suggest three metamorphic stages, here referred  
226 as  $M_{LN1}$ ,  $M_{LN2}$ , and  $M_{LN3}$ , for the Liberdade Nappe micaschist (Fig. 5). The  $M_{LN1}$  stage is  
227 pre- $S_2$ , related to prograde/peak metamorphism and it is characterized by  
228 quartz+plagioclase+white mica+biotite+garnet+rutile+kyanite(?) as the equilibrium  
229 assemblage in the rock. The  $M_{LN2}$  stage, in which quartz+plagioclase+white  
230 mica+biotite+garnet+kyanite(?)+ilmenite is inferred to be stable, represents a post-peak  
231 mineral assemblage. Finally, sillimanite and staurolite are regarded as phases that grew  
232 during the late stages of the metamorphic path ( $M_{LN3}$  and Syn- $S_2$ ).

233 Sample NESG-388 (Fig. 4a, supplementary figure A1) was selected for the LN  
234 mineral chemistry investigation and petrological modeling. The NESG-388 is a white  
235 mica+biotite+garnet+ilmenite-bearing mylonitic schist with minor sillimanite, rutile, and  
236 staurolite (Fig. 7a). Plagioclase is compositionally zoned, and its anorthite content increases  
237 from core to rim ( $X_{An}$  = 0.20-0.32) (Fig. 7b). Garnet end-members vary slightly from core  
238 to rim: almandine ( $X_{Alm}$ ) = 0.81-0.79, pyrope ( $X_{Prp}$ ) = 0.11-0.07, spessartine ( $X_{Sps}$ ) = 0.05-  
239 0.06 and grossular ( $X_{Grs}$ ) = 0.05-0.06 (Fig. 7c-f). The Ti (a.p.f.u) in biotite decreases toward  
240 the rim, ranging from 0.14 to 0.09, whereas the #Mg ( $Mg/Fe^{+2}+Mg$ ) ratio displays an  
241 inverse correlation, increasing toward the rims, varying from 0.37 to 0.43 (supplementary  
242 figures A2a and b). The  $Si^{4+}$  (a.p.f.u) of white mica varies from 3.04 to 3.12  
243 (supplementary figure A2d).

### 244 3.2.2 *Andrelândia Nappe*

245 The Andrelândia Nappe is constituted by the major phases:  
246 quartz+plagioclase+biotite+white mica+garnet+kyanite+ilmenite(±sillimanite±staurolite)  
247 and tourmaline+apatite+monazite+zircon+rutile as accessories. The AN has a  $S_2$  foliation

248 characterized by discontinuous millimetric compositional layers of granoblastic, made by  
249 quartz and plagioclase, and lepidoblastic, constituted by white mica and biotite with  
250 subordinate garnet and kyanite (Fig. 8a). The AN close to the contact with the Liberdade  
251 Nappe is affected by shearing and displays a mylonitic fabric (post-S<sub>2</sub>). The kinematic  
252 indicators described in the sheared gneisses are S-C fabric and white mica-fish, which point  
253 to a top-to-the-E/ESE tectonic transport. Quartz is a medium- to coarse-grained mineral  
254 with irregular and lobate boundaries, typical of the GBM recrystallization mechanism  
255 (Law, 2014).

256 Garnet is present as porphyroblast ( $\leq 2$  cm in size) (Fig. 8b). Discontinuous  
257 inclusion trails of opaque minerals within garnet, with respect to the S<sub>2</sub> fabric, testify to the  
258 inter-tectonic nature of this mineral (Fig. 8b and d). Thin graphite crystals, ilmenite, and  
259 rutile are the typical inclusions in garnet, and staurolite, quartz, plagioclase, biotite, and  
260 white mica are subordinate. Kyanite is a coarse-grained subidiomorphic crystal with a long  
261 axis aligned along the S<sub>2</sub> foliation (Fig. 8b). Twinning in kyanite is observed. Late fibrolite  
262 growth (post-S<sub>2</sub>) along shear bands and replacing biotite crystals are observed (Fig. 8c and  
263 d). Two generations of staurolite were observed, the first is characterized by tiny crystals  
264 enclosed in garnet, whereas the second one is in the matrix, often around garnet rims. A  
265 staurolite with biotite and sillimanite inclusions aligned with the external foliation, made by  
266 sillimanite, quartz, and biotite, denotes a syn-tectonic origin regarding the post-S<sub>2</sub> fabric  
267 (Fig. 8d). The contact between staurolite and garnet, as well as the abrupt change of the  
268 internal foliation of both minerals, suggest a pattern of porphyroblasts amalgamated (Fig.  
269 8d, e.g., Passchier and Trouw, 2005).

270 Based on the above description, three main stages of mineral equilibration were  
271 recognized (Fig. 5). The early prograde assemblage ( $M_{AN1}$ ), preserved in garnet core, is  
272 constituted by garnet(core)+quartz+plagioclase+biotite+white mica+staurolite+rutile. The  
273 peak assemblage ( $M_{AN2}$ ) is coeval with the  $S_2$  foliation and is marked by the appearance of  
274 kyanite and ilmenite and the consumption of staurolite and rutile. The  $M_{AN3}$  assemblage  
275 corresponds to retrograde metamorphic assemblage, characterized by a second growth of  
276 staurolite around garnet rims together with the late fibrolite appearance, and structures  
277 related to the tectonic transport (post- $S_2$  foliation).

278 Sample NESG-401 was chosen for a detailed chemical investigation (Fig. 4a,  
279 supplementary figure A1). The gneiss is composed of quartz+plagioclase+biotite+white  
280 mica+garnet+ilmenite and minor apatite (Fig. 9a). This sample is white mica-poor, which is  
281 restricted to the garnet strain shadow zones (supplementary figure A1 and Fig. 9a). The  
282 plagioclase is zoned, displaying Ca-poor cores ( $X_{An} -0.22$ ) and Ca-rich rims ( $X_{An} -0.32$ ).  
283 The highest Ca-content ( $X_{An} -0.34$ ) occurs in crystals that bound garnet (Fig. 9b). There  
284 are two garnet crystals in the X-ray mapped area. The large garnet porphyroblast displays a  
285 bell shape profile, whereas the smaller one presents an almost flat profile (Fig. 9c, d, e, and  
286 f). The garnet porphyroblast shows an increase in almandine and pyrope toward the rim,  
287 whereas spessartine and grossular display the inverse pattern (Core-  $X_{Alm}-0.6$ ,  $X_{Prp}-0.06$ ,  
288  $X_{Sps} -0.1$ ,  $X_{Grs}-0.22$ ; Rim-  $X_{Alm}-0.72$ ,  $X_{Prp}-0.13$ ,  $X_{Sps}-0.03$ ,  $X_{Grs}-0.08$ ) (Fig. 9c, d, e,  
289 and f). Spessartine displays a sharp increase in the outermost rim ( $X_{Sps}-0.09/0.1$ ) in both  
290 garnet crystals. The biotite composition varies according to its structural position. Crystals  
291 close to garnet have higher #Mg and lower Ti (a.p.f.u) compared to grains far from garnet  
292 (Bt near garnet  $X_{Mg}- 0.54-0.52$  and Ti(a.p.f.u)- 0.8-0.10; Bt in matrix  $X_{Mg}-0.5-0.51$  and

293 Ti(a.p.f.u)- 0.11-0.12) (supplementary figure A3a and b). The Si<sup>4+</sup> content in white mica is  
294 close to the muscovite end-member, between 3.00-3.08 a.p.f.u. (supplementary figure A3d).

### 295 3.3 *Iterative Thermodynamic Modeling (ITM) and P-T path*

296 The iterative thermodynamic modeling (ITM) integrated with quantitative  
297 compositional mapping was applied as the strategy for setting up the metamorphic history  
298 of the Andrelândia and Liberdade Nappes using the software Bingo-Antidote a XMapTools  
299 add-on (Duesterhoeft and Lanari, 2020; Lanari and Hermann, 2021). This approach  
300 provides a means of investigating rocks that were not fully re-equilibrated during their  
301 metamorphic paths. Through the quantitative compositional maps, areas/phases within a  
302 sample that best represents the reactive phases can be selected for the local bulk  
303 composition (LBC) calculation. Furthermore, the Bingo-Antidote software provides series  
304 of statistics routines that compare the model results with the observed mineral assemblage,  
305 modes, and phase compositions for the LBC studied. The bingo routines calculate the  
306 model quality, assessing as much as it matches with the LBC mineral assemblage ( $Q_{asm}$ ),  
307 mineral modes ( $Q_{mode}$ ), and mineral compositions ( $Q_{cmp}$ ). The quality factors  $Q_{asm}$ ,  $Q_{mode}$ ,  
308 and  $Q_{cmp}$  vary from 0%, which means there is no match between the model and LBC  
309 observations, and 100%, meaning that the model perfectly reproduces the LBC features. In  
310 addition, the antidote provides routines, for instance the recipe 14, to evaluate how the  
311 quality factors change within the model P-T(-X). The Andrelândia and Liberdade Nappes  
312 thin-section areas investigated for obtaining LBCs and mineral compositions ( $Q_{cmp}$ ) quality  
313 factors are displayed in Fig. 7a, 9a, supplementary figures A1, A2, and A3. The maps of  
314 quality factors from both samples are shown in supplementary figures A4, A5, and A6.

315 The isochemical diagrams were calculated for the local bulk composition (LBC)  
316 obtained by the Bingo-Antidote using the Theriak-Domino software (de Capitani and  
317 Petrakakis, 2010; de Capitani and Brown, 1987) to illustrate the stability of mineral fields.  
318 The calculations were performed in the chemical system MnO-Na<sub>2</sub>O-CaO-K<sub>2</sub>O-FeO-MgO-  
319 Al<sub>2</sub>O<sub>3</sub>-TiO<sub>2</sub>-SiO<sub>2</sub>-H<sub>2</sub>O. The water amount was chosen using recipe 14 of the antidote, a  
320 statistical routine that assesses how the quality factors ( $Q_{asm}$ ,  $Q_{mode}$ , and  $Q_{cmp}$ ), the mineral  
321 chemistry, and mode would vary along a given range of H<sub>2</sub>O, at fixed  $P$ - $T$  conditions. The  
322 diagrams were calculated for the  $P$ - $T$  range of 4-12 kbar and 550-725 °C. The database tc55  
323 (Holland and Powell, 1998), provided and employed in the Bingo-Antidote software, was  
324 used for the isochemical diagrams calculations. The respective solution models were  
325 utilized: feldspar (Baldwin et al., 2005), garnet (White et al., 2005), biotite (White et al.,  
326 2005), staurolite (Holland and Powell, 1998), cordierite (Holland and Powell, 1998), white  
327 mica (Coggon and Holland, 2002), ilmenite (White et al., 2007) and melt (White et al.,  
328 2007).

### 329 3.3.1 Sample NESG-388 - Liberdade Nappe

330 The calculated isochemical diagram for the Liberdade Nappe LBC is presented in  
331 Fig. 10a. The observed peak mineral assemblage, quartz+plagioclase+white  
332 mica+biotite+ilmenite, is stable in the penta-variant field constrained in the  $P$ - $T$  range of  
333 6.5-12 kbar and 600-670°C. Assuming the mineral phase equilibrium, the optimal  $P$ - $T$   
334 condition is expected to be achieved at 628°C and 7.5 kbar. At this condition, the quality  
335 factors for the mode ( $Q_{mode}$ ) is 92%, and the system mineral chemistry ( $Q_{cmp}$ ) is 86% (Fig.  
336 10b).

337 The mineral *P-T* chemistry composition maps are presented in supplementary figure  
338 A4. They display a more complex story used to trace the *P-T* path (Fig. 10b). The An-poor  
339 plagioclase core compositions ( $Q_{\text{cmp}}=100\%$ ) are stable in higher pressure, 8.5 kbar up to  
340 11.5 kbar, and in large temperature conditions, from 500°C to 700°C. On the contrary,  
341 plagioclase rim composition records a lower pressure condition, down to 8 kbar, and  
342 temperatures from 590°C to 660°C. Although the optimal *P-T* conditions obtained by the  
343 antidiote, peak conditions are better constrained by plagioclase rim composition ( $Q_{\text{cmp}}$   
344  $=100\%$ ), around 650°C and 9.5-10 kbar. The Na-Ca diffusion in plagioclase is considered  
345 slower than garnet Ca-Fe-Mg-Mn in temperatures above 600°C (Caddick et al., 2010;  
346 Lanari and Hermann, 2021). These described diffusional behaviors are the likely causes of  
347 plagioclase core records better the prograde conditions rather than garnet.

348 Plagioclase rim ( $Q_{\text{cmp}} =100\%$ ), and garnet ( $Q_{\text{cmp}} =90-100\%$ ) mineral chemistry  
349 compositions in addition with the mineral modes ( $Q_{\text{mode}} =100\%$ ) intersect at the hexa-  
350 variant field in which  $Qz+Pl+Bt+Grt+Ms+Ky+Ilm$  are the stable phases. The intersection is  
351 around 650°C and 7-7.5 kbar, suggesting an almost isothermal decompression path. Relics  
352 of kyanite are described in the LN (Fig. 6f), supporting that this mineral was stable at some  
353 moment of the LN *P-T* path. Lastly, the *P-T* path later stage is recorded by the  
354 compositional match between the plagioclase rim and muscovite ( $Pl-Q_{\text{cmp}} =100\%$ ;  $Ms-$   
355  $Q_{\text{cmp}} =95\%$ ) in the hexa-variant field where  $Qz+Pl+Grt+Bt+Ms+Ilm+Sil+H_2O$  are stable. A  
356 *P-T* path (Fig. 10b) is suggested based on the above mineral chemistry and mode optimal  
357 quality factors fields, and the  $M_{LN1}$ ,  $M_{LN2}$ , and  $M_{LN3}$  metamorphic stages described in  
358 section 4.1. The quantitative map of the Ti-in-biotite thermometer (Henry et al., 2005) was

359 applied (supplementary figure A2c). It displays values from 650 to 580°C consistent with  
360 the findings obtained by the ITM approach.

### 361 3.3.2 Sample NESG-401 – Andrelândia Nappe

362 Fig. 11a displays the isochemical diagram built for the Andrelândia Nappe LBC that  
363 better represents the peak-to post-peak conditions. Bulk compositions that consider phases  
364 that are not fully equilibrated in the system, such as minerals relics or displaying  
365 compositional zoning, can affect the thermodynamic models quality (Lanari and Engi,  
366 2017). Once one garnet of the LBC is strongly zoned and likely its core was unreactive at  
367 peak condition, for avoiding the question described above, the garnet core area was  
368 subtracted and is not considered in the bulk composition. Although, the isochemical  
369 diagram taking into account the garnet core composition and the  $P$ - $T$  stability field map for  
370 garnet core composition (garnet core  $Q_{\text{cmp}}$ ) are provided in the supplementary figure A5.  
371 Therefore, the  $M_{\text{ANI}}$  stage, which corresponds to a mineral assemblage preserved in the  
372 garnet core, does not appear in the suggested  $P$ - $T$  path.

373 The peak mineral assemblage,  $Qz+Pl+Bt+Grt+Ky+Ms+Ilm+H_2O$ , was constrained  
374 in the quadri-variant field delimited in the  $P$ - $T$  range of 620°C-675°C and 7-10 kbar. The  
375 optimal  $P$ - $T$  condition obtained is 676°C and 8.1 kbar with  $Q_{\text{cmp}}=92\%$  and  $Q_{\text{mode}}=95\%$   
376 (Fig. 11b). The mineral phases chemical composition of sample NESG-401 preserves three  
377 stages of the metamorphic path, the prograde, decompression, and cooling (Fig. 11b),  
378 which were traced using  $P$ - $T$  stability field maps (supplementary figure A6). The prograde  
379 path was traced taking into account the compositions of garnet mantle ( $Q_{\text{cmp}}=100\%$ ),  
380 which records early stages of amphibolite facies around 550-570°C and 8-9 kbar,  
381 plagioclase core ( $Q_{\text{cmp}}=100\%$ ), and white mica ( $Q_{\text{cmp}}=85-80\%$ ). Indeed, the antidote

382 optimal conditions calculations seem to underestimate the peak condition. The plagioclase  
383 core and white mica chemical composition provide a better constrain, crossing at *ca.*  
384 660°C-670°C and 11.5-12 kbar, at these conditions, Qz+Pl+Bt+Grt+Ky+Ms+Ilm are the  
385 stable phases ( $M_{AN2}$  stage). An almost isothermal decompression is suggested based on the  
386 mineral modes ( $Q_{mode}=95-100\%$ ) field of stability, which is at lower pressure of 6-8 kbar  
387 but at almost the same temperature range, from 625 to 680 °C. At last, garnet rim chemical  
388 composition ( $Q_{cmp}=80\%$ ) provided information about the AN cooling stage. It is  
389 equilibrated at 550°C and 4.5 kbar in the stability field of Qz+Pl+Grt+Bt+Ilm+St+Sil  
390 ( $M_{AN3}$  stage; Fig. 11b). The Ti-in-biotite thermometer map (supplementary figure A3c)  
391 displays temperatures ranging from 630 to 560 °C, in agreement with the retrograde  
392 temperature conditions obtained by ITM.

### 393 3.4 EMPA monazite petrochronology

394 To constrain the timing of the metamorphic and deformation events, *in-situ* U-(Th)-  
395 Pb monazite chemical dating was carried out by EMPA (e.g., Dumond et al., 2015;  
396 Williams and Jercinovic, 2002, 2012). The analytical procedures are described in appendix  
397 A.

#### 398 3.4.1 Sample NESG-388 – Liberdade Nappe

399 Monazites from sample NESG-388 are between quartz, plagioclase, white mica, and  
400 biotite from the matrix. Ten crystals were chosen to perform X-ray maps and trace element  
401 analysis. The results are illustrated in Fig. 12 and supplementary table A2. Most of the  
402 crystals display an elongated shape parallel to the mylonitic foliation, varying in size from  
403 70 to 250  $\mu\text{m}$ , except the Mnz 4, associated with ilmenite which shows an irregular lobate  
404 shape. In some crystals, small quartz (e.g., Mnz 4, Mnz 5, and Mnz 6) inclusions were

405 observed, but most of the monazites are inclusions free. The monazites display a sectorial  
406 core-rim internal zoning (e.g., Mnz 1, 2, 6 and 7). A remarkable feature that might be  
407 highlighted is the core and rim zonation pattern that is well-aligned (e.g., Mnz1, 2, 6, 8, and  
408 10) with the main foliation, suggesting a pre-to syn-mylonitic growth related to the rock  
409 fabric. In addition, the Mnz 7 occurred on the S-plane of a *S-C* fabric.

410 Three chemical domains are distinguished based on the X-ray maps, mainly of Y  
411 and Th distribution (Fig. 12a, b, and c). Domain 1, characterized by high-Th and low-Y  
412 cores, is small patchy (e.g., Mnz 9), and straight (e.g., Mnz 2). The Y<sub>2</sub>O<sub>3</sub> content (wt%)  
413 varies from 1.02 to 1.39, and the ThO<sub>2</sub> (wt%) values are very spread, ranging from 4.00 to  
414 6.95. Domain 2 is related to core characterized by low-Y and -Th. The Y<sub>2</sub>O<sub>3</sub> (wt%) and  
415 ThO<sub>2</sub> (wt%) amounts vary respectively in a narrow range of 0.93-1.22 and 2.29-3.80. The  
416 third domain (domain 3) is associated with monazite rims showing high-Y, in which the  
417 Y<sub>2</sub>O<sub>3</sub> (wt%) amounts are spread in a broad range from 1.62 up to 2.61, and ThO<sub>2</sub> (wt%)  
418 variation is concentrated between 3.18-3.59.

419 In total, 84 EMPA spot analyses were acquired in the different chemical domains  
420 for chemical dating calculation. Obtained dates span from 640 to 540 Ma. Domain 1,  
421 characterized by high-Th and low-Y core, dates range from 640±21Ma to 588±19 Ma.  
422 Domain 2, with low-Th and Y cores, has dates spread from 613 Ma±36 Ma to 550±33 Ma.  
423 Owing to the dates from domains 1 and domain 2 are relative to core, they were plotted in  
424 the same weighted average diagram (Fig. 12d) and yielded a mean age of 609±4 Ma (n=55;  
425 MSWD=1.6). Domain 3, related to high-Y rims, has dates from 590±28 Ma to 540±26 Ma  
426 and yields a mean weighted average age of 567±5 Ma (n=33; MSWD=1.19; Fig. 12e).

427 3.4.2 Sample NESG-401 – Andrelândia Nappe

428 Fig. 13a displays the mapped monazite crystals (n=8) from sample NESG-401, the  
429 elements analysis spots position, and the results of chemical dating. The monazites occur  
430 between the matrix minerals, hosted in quartz, plagioclase, biotite, and white mica ( Mnz 1,  
431 3 and 5), one crystal is enclosed in kyanite (Mnz 4), and three are located in apatite rims  
432 (Mnz 2, 5 and 8). The size of crystals varies from 50  $\mu\text{m}$  up to 100  $\mu\text{m}$ . Monazite shape  
433 varies from rounded to elongated. Quartz inclusions are observed in Mnz 1 and Mnz 7.  
434 Regarding the monazite compositional zoning, they are very homogenous. The crystals  
435 display intermediate  $\text{Y}_2\text{O}_3$  contents varying from 1.3 to 2.9 wt% and variable Th amounts,  
436 varying the  $\text{ThO}_2$  between 1.9 and 5.4 wt% (Fig. 13a, b, and c). The exception is  
437 represented by rims significantly enriched in Th (with  $\text{ThO}_2$  content between 6.7-13.1 wt%)  
438 observed in crystals associated with apatite (Fig. 13c).

439 A total of 56 EMPA spot analyses were carried out. The obtained U-(Th)-Pb  
440 chemical dates range from  $612\pm 23$  Ma to  $535\pm 28$  Ma. The dates are plotted in the weighted  
441 average diagram (Fig. 13d), and they yield a mean age of  $579\pm 6$  Ma (MSWD=3.5). Of  
442 particular interest is the crystal enclosed in kyanite (Mnz 4), which can report worthy  
443 information about tectonic and metamorphic events undergone by this rock since the  
444 kyanite is considered coeval with the  $S_2$  foliation. The dates vary from  $605\pm 22$  Ma to  
445  $558\pm 25$  Ma and yield a mean age of  $589\pm 19$  Ma (MSWD=2.3; Fig. 13e).

446 **4. DISCUSSION**

447 *4.1 Monazite chemical dating interpretation*

448 The in-situ monazite dating combined with the X-ray maps (e.g., Y and Th) allows  
449 correlating monazite growth episodes with metamorphic reactions and deformation stages

450 (Bosse and Villa, 2019; Spear and Pyle, 2002; Williams and Jercinovic, 2002, 2012). The Y  
451 and HREE concentration in monazite mostly depend on the garnet presence in the system,  
452 once this mineral is the preferential sink for these elements (Spear and Pyle, 2002).  
453 Whereas the Th concentration is controlled by a Th-rich phase breakdown responsible for  
454 releasing this element in the system, preferentially partitioned into monazite structure  
455 (Benetti et al., 2021; Kohn and Malloy, 2004; Williams et al., 2022). Moreover, monazite  
456 can be a fabric-forming mineral in deformed rocks and behaves as a porphyroclast rotated  
457 and with inclusion trails (Dumond et al., 2008, 2022). Therefore, the *in-situ* dating allows  
458 us to relate the monazite chemical zonation with its microstructural position, providing  
459 means to constrain the deformation time.

460           At sub-solidus conditions, two main metamorphic reactions will control the  
461 monazite chemistry. Firstly, the allanite breakdown is responsible for releasing most of the  
462 REE necessary for the monazite precipitation (Gasser et al., 2012; Janots et al., 2008; Kohn  
463 and Malloy, 2004; Spear and Pyle, 2010). This reaction occurs between the greenschist-to  
464 amphibolite facies transition, at temperature conditions around 550°C (Gasser et al., 2012;  
465 Janots et al., 2008; Spear and Pyle, 2010). If monazite grows at these conditions before  
466 garnet growth, the monazite will display intermediate- to high-Y and HREE content. In  
467 contrast, when monazite grows in equilibrium with garnet, the monazite tends to be  
468 depleted in Y and HREE since these elements are strongly partitioned in garnet. In addition,  
469 due to allanite being a Th-rich mineral, the monazite that grows soon after its breakdown  
470 tends to be Th-enriched (Benetti et al., 2021; Kohn and Malloy, 2004). Another monazite  
471 generation is expected during the rock decompression path, in which garnet breakdown

472 releases Y and HREE in the system, and the monazite precipitating from this reaction will  
473 display enriched signatures in these elements (Gasser et al., 2012; Kohn et al., 2005).

474         Considering the monazite behavior during the sub-solidus metamorphism and  
475 deformation described above, two episodes of monazite growth can be identified in the  
476 sample NESG-388 from the Liberdade Nappe. The first episode is correlated with Y-  
477 depleted cores and a wide range of Th amounts (domains 1 and 2). These dates are  
478 associated with prograde metamorphism ( $M_{LN1}$  stage) in which monazite grew after garnet  
479 crystallization in the system and yielded mean chemical age of  $609\pm 4$  Ma. The Th-enriched  
480 domains (domain 1) can likely be linked to the early prograde metamorphism (early  $M_{LN1}$   
481 stage), soon after the allanite-to-monazite transition, releasing Th in the system and  
482 reproducing the oldest dates. The weighted mean age of  $567\pm 5$  Ma, represented by Y-  
483 enriched monazite rims (domain 3), is interpreted as linked with garnet resorption during  
484 the rock decompression ( $M_{LN2}$  and  $M_{LN3}$ ). Furthermore, the growth orientation of some  
485 high-Y rims aligned with the  $S_2$  foliation (e.g., Mnz 1 and 2), and the crystal in the S-C  
486 band (Mnz 7) rotated during the shearing suggest that the decompression was coeval with  
487 the development of the  $S_2$  fabric related with the SE tectonic transport.

488         The monazites grains from the sample NESG-401 of the Andrelândia Nappe are  
489 homogenous with intermediate Y and Th-depleted. They are interpreted as growing coeval  
490 with the garnet during the prograde metamorphism ( $M_{AN2}$  stage), at a minimum age of  
491  $579\pm 6$  Ma. The Mnz 4 is enclosed in kyanite and parallel to the AN  $S_2$  fabric, providing  
492 time constraint for the foliation-forming deformation coeval with kyanite growth during the  
493  $P$ - $T$  path. This single crystal yields mean age of  $589\pm 19$  (n=6), consequently interpreted as  
494 corresponding to the time of the  $S_2$  deformation, and taking into account the age standard

495 deviation, is considered contemporary to the prograde metamorphism ( $M_{AN2}$  stage). Rims  
496 highly enriched in Th (Mnz 2, 5, and 8) are attributable to exchange reactions between  
497 apatite and monazite and have no signatures that can associate them with any significant  
498 tectono-metamorphic event.

#### 499 4.2 *Tectono-metamorphic evolution of the Andrelândia Nappe System (ANS)*

500 The microstructural descriptions,  $P$ - $T$  path traced through thermodynamic  
501 metamorphic modeling, and monazite petrochronological data presented here help elucidate  
502 the complex ANS framework in the southern sector of the SBO. The Liberdade and  
503 Andrelândia Nappes evolved from a clockwise sub-solidus  $P$ - $T$  path characterized by burial  
504 and heating, followed by nearly isothermal decompression, and lastly, cooling and  
505 decompression. The Liberdade Nappe (NESG-388)  $M_{LN1}$  stage assemblage (Qz-Pl-Grt-Bt-  
506 Ms-Ilm) records peak conditions at *ca.* 650°C and 9.5-10 kbar and has a minimum age of  
507 609±4 Ma (Fig. 14a). The peak conditions indicate that the LN rocks were buried by 36  
508 km, corresponding to the middle and lower depth of a thickened crust with an apparent  
509 geothermal gradient of 18°C/km (Fig. 14a). The further stages,  $M_{LN2}$  (Qz-Pl-Grt-Bt-Ms-  
510 Ilm-Ky(?)) and the  $M_{LN3}$  (Qz-Pl-Grt-Bt-Ms-Ilm-Sil-St), represent respectively the  
511 isothermal decompression and decompression/cooling episodes related to the LN migration  
512 toward SE, whose the minimum age is constrained at 567±5 Ma (Fig. 14a).

513 The Andrelândia Nappe sample (NESG-401) records a burial and heating episode in  
514 the kyanite stability field during the prograde metamorphism, from ~550°C and 9.0-9.5  
515 kbar up to ~680 °C and 11-12 kbar ( $M_{AN2}$  stage; Fig. 14a). The  $P$ - $T$  data suggest an  
516 apparent geothermal gradient of 16°C/km and burial into crustal depths of 43 km (Fig. 14a).  
517 The minimum age for the prograde metamorphism was estimated at 579±6 Ma, and within

518 the uncertainties is considered coeval with the S<sub>2</sub> deformation event underwent by this rock.  
519 It was followed by an almost isothermal decompression, in which the pressure conditions  
520 decreased from 12 kbar down to 8.0-7.0 kbar (Fig.14a). Lastly, the M<sub>AN3</sub> stage related to  
521 staurolite and sillimanite appearance in the system was constrained in the *P-T* range of 670-  
522 550°C and 8.0-4.5 kbar (Fig. 14a).

523 A compilation of literature *P-T* paths from the Andrelândia and Liberdade Nappes is  
524 provided in Fig. 14a. Different approaches were adopted by Coelho et al. (2017), Motta and  
525 Moraes (2017), Reno et al. (2012), and Santos et al. (2004), such as inverse and forward  
526 thermodynamic modeling. Considering the different methods-related uncertainties, peak  
527 conditions constrained for the Andrelândia and Liberdade Nappes in this contribution agree  
528 with those previously reported. However, there are differences between the *P-T* path traced  
529 here and those interpreted by these authors. For instance, Reno et al. (2021) suggested two  
530 episodes of isobaric cooling separated by a near-isothermal decompression phase to the  
531 Carmo da Cachoeira Nappe, the Andrelândia Nappe equivalent in the SBO northern sector.  
532 Moreover, Santos et al. (2004) considered that Andrelândia Nappe underwent heating  
533 during decompression, while the Liberdade Nappe evolved from an isothermal  
534 decompression. These *P-T* path contrasts can be assigned to different interpretations  
535 regarding blastesis-deformation relationships and distinct approaches used by each of the  
536 authors and the present work.

537 Fig. 14b is a summary of the available metamorphic ages for the Andrelândia and  
538 Liberdade Nappes using monazite and zircon U-Pb geochronology techniques. The oldest  
539 ages of the Liberdade Nappe, at *ca.* 680-670 Ma, reported by Campos Neto et al. (2011)  
540 and Reno et al. (2009), are related to metamafic rocks and interpreted as the HP

541 metamorphism age experienced by these rocks. Regarding the LN and AN micaschists and  
542 gneisses, the previously published ages by Coelho et al. (2017), Frugis et al. (2018),  
543 Marimon et al (2022), Motta and Moraes (2017), and Westin et al. (2021) and those  
544 reported in this work are widespread in a time range *ca.* 60 Ma, from 630 to 570 Ma. The  
545 geochronology data from the literature, calculated by different methods (e.g., isocron age,  
546 concordia age, and weighted average age), are comprised within the spread of chemical  
547 dates acquired here. However, in this study, the monazite petrochronology results indicate  
548 that each nappe experienced episodic growth during a single metamorphic cycle of burial  
549 (prograde metamorphism) and decompression (retrograde metamorphism), rather than  
550 being affected by polymetamorphism events.

#### 551 4.3 *Tectonic implications*

552 Our present findings shed new light on some critical points regarding the tectono-  
553 metamorphic events experienced by the ANS. The first point is related to the Andrelândia  
554 and Liberdade Nappes *P-T* paths. Microstructural observations and thermodynamic  
555 modeling show that the staurolite and sillimanite in the matrix are related to decompression  
556 and cooling stages. Furthermore, the suggested metamorphic paths to the LN and AN  
557 pointed out that the baric and thermic peaks occur almost simultaneously. These  
558 information in conjunction with monazite petrochronology indicate that likely each one of  
559 the nappes underwent a single metamorphic loop of burial and decompression.

560 The second critical point concerns the timing constraints of metamorphism and  
561 deformation. The Liberdade Nappe attained prograde, amphibolite facies, within the  
562 kyanite stability field at minimum age of *ca.* 610 Ma, nearly 30 Ma before the Andrelândia  
563 Nappe (Fig. 15 b, c, and d). Although the sample from Andrelândia Nappe does not have

564 dates related to exhumation, the spread dates from the Liberdade Nappe linked with the  
565 exhumation mostly overlap the prograde monazite dates in the Andrelândia Nappe,  
566 structurally below. Hence, it is possible to claim that when the Liberdade Nappe onset its  
567 decompression path, the Andrelândia Nappe was still experiencing prograde conditions and  
568 was likely exhumed afterward compared to the Liberdade Nappe (Fig. 15c). In other words,  
569 the dates younger than 610 Ma in the Liberdade Nappe are related to its exhumation and  
570 tectonic transport toward SE (Fig. 15c and d). In contrast, this time span is linked with  
571 prograde burial metamorphic conditions (coeval with kyanite growth) in the Andrelândia  
572 Nappe (Fig. 15c). The Pouso Alto Nappe, the upper structural level of the ANS in the  
573 southern part of the SBO, yields a minimums age of *ca.* 620 Ma and of *ca.* 610 Ma, for  
574 respectively the prograde metamorphism, and melt crystallization related to cooling and  
575 decompression (Fig. 15a and b; Benetti et al., in prep; Benetti, 2022). Therefore, the spread  
576 of ages from 630 Ma to 570 Ma (Fig. 15) within the ANS records a pattern of age decrease,  
577 toward lower structural levels, of the prograde and retrograde metamorphic ages during the  
578 protracted metamorphism of the SBO (Fig 15). The spatial arrangement and decrease of the  
579 metamorphic ages toward the bottom of the ANS stack outline an in-sequence fold-and-  
580 thrust architecture of the orogenic wedge (Fig. 15). This framework would have been  
581 developed through the inner material incorporated at the wedge being detached, shortened,  
582 and propagated over the incoming material, similar to what is proposed by Platt (1986) to  
583 the dynamics of orogenic wedges. Then, the rocks from the older nappes (i.e., Liberdade  
584 Nappe) were decompressed via thrust and folding over the younger ones (i.e., Andrelândia  
585 Nappe) that likely experienced their peak metamorphism as a consequence of loading of the  
586 overlying nappe. Analogue in-sequence fold-and-thrust architectures are described in other  
587 orogenic belts such as the Caledonian, Trans-Hudson, Grenville, Himalayan, and

588 Appalachian orogens (Beaumont et al., 2006; Carosi et al., 2016; Weller et al., 2021). This  
589 suggests that the mechanism described above is an important mechanism controlling the  
590 structural and metamorphic style of collisional wedges. Fig. 15 illustrates the proposed  
591 tectono-metamorphic evolution for the nappes of the Southern Brasília Orogen. The  
592 collision-related metamorphic event evolved from 630 to 570 Ma based on zircon,  
593 monazite, and titanite U-Pb ages and monazite-EPMA ages (Campos Neto et al., 2010;  
594 Coelho et al., 2017; Frugis et al., 2018; Fumes et al., 2021; Li et al. 2021; Marimon et al.,  
595 2020, 2022; Motta et al., 2021; Rocha et al., 2017; Westin et al., 2021). The Andrelândia  
596 Nappe System underwent high-pressure metamorphic conditions during the collision  
597 between the São Francisco (passive margin) and Paranapanema (active margin) paleoplates  
598 (Fig. 15). The crustal material was stored and sunk within the orogenic wedge hinterland  
599 until 620 Ma when the first nappe of the system, the Pouso Alto, started its decompression  
600 path with tectonic transport toward northeast (Fig. 15a and b). After *ca.* 610 Ma, the  
601 Liberdade Nappe follows an upward flow toward east/southeast, laterally to the south  
602 margin of the São Francisco Craton, over the Andrelândia Nappe (Fig. 15c). The final stage  
603 of the SBO continental collision took place after 580-570 Ma, coeval with the  
604 decompression and exhumation path of the Andrelândia and Carrancas Nappes (Fig., 15d;  
605 Campos Neto et al., 2010, 2020; Carvalho et al., 2020; Cioffi et al., 2019; Coelho et al.,  
606 2017; Frugis et al., 2018; Reno et al., 2009, 2012, Tedeschi et al., 2017; Westin et al.,  
607 2021).

## 608 **5. CONCLUSION**

609 The *P-T-t-D* data provided here document the metamorphic and deformation history  
610 of the Andrelândia and Liberdade Nappes. The Liberdade Nappe experienced prograde

611 burial metamorphism at *ca.* 610 Ma and achieved peak conditions at ~650°C and 9.5-10  
612 kbar. This stage was followed by a near-isothermal decompression and further cooling with  
613 a minimum age of *ca.* 570 Ma. Meanwhile, the Andrelândia Nappe structurally below the  
614 Liberdade Nappe underwent prograde metamorphism nearly 30 Ma later, at *ca.* 580 Ma,  
615 reaching the peak condition at *ca.* 680°C and 11.5-12 kbar. The data document an in-  
616 sequence fold-and-thrust architecture, in which the metamorphic ages decrease toward  
617 lower structural levels of the stack. This framework would have evolved through older  
618 material incorporated into the inner parts of the orogenic wedge has been detached and  
619 propagated via thrust-and-fold nappes upon recently accreted rocks, leading to a younger  
620 metamorphism event on the footwall of the ductile thrust.

## 621 **APPENDIX A – ANALYTICAL METHODS**

622         The equipment employed in the trace elements, quantitative mineral analyses, and  
623 compositional maps is a JEOL JXA-8230 Electron Probe Micro Analyzer (EPMA)  
624 equipped with five wavelengths dispersive spectrometry (WDS) detectors hosted at the  
625 Department of Geology at the State of São Paulo University (UNESP). The compositional  
626 maps were obtained through X-rays maps, which were further classified and calibrated  
627 using the internal standardization procedure and the pseudo-background correction  
628 available in the XMapTools 3.4 (Lanari et al., 2014, 2019). The X-ray maps for Mg, Na,  
629 Ca, K, and Fe were acquired by the WDS detectors, whereas for Al, Si, P, S, Ti, Mn, and Zr  
630 by the energy dispersive-spectrometry (EDS). The x-ray maps were carried out with an  
631 accelerating voltage of 15Kv, a current beam of 100nA, and a dwell of 100 ms.  
632 Representative analysis of silicates obtained within the X-maps perimeter used for the  
633 calibrations are available in the supplementary table file A1.

634 Monazite U-(Th)-Pb chemistry dating was performed using the same equipment  
635 cited above. The crystals were first identified through full thin-sections maps acquired  
636 using the Scanning Electron Microscopy and Mineral Liberation Analyzer (SEM-MLA).  
637 Considering the monazite structural position and textural relationships some crystals were  
638 selected to perform high-resolution compositional X-ray maps of Y, Al, Th, U, Pb, Si, Ca,  
639 Fe, La, and Ce. The acquisition conditions were 15 kV, 100 nA, 100 ms dwell time, and 10  
640  $\mu\text{m}$  electron beam size and step. Trace elements spots analyses were performed in the  
641 different domains identified with helping of the X-ray maps. The analytical procedure  
642 follows the strategies of Fumes et al. (2021). The moacyr monazite standard was used after  
643 each 10 to 20 punctual analyses, and their results are displayed in the supplementary figure  
644 file A7. The background was estimated in all analyzed spots. Spectral interference  
645 corrections considered matrix correction factors and were performed offline. Interference  
646 corrections and age calculations were performed using the Age\_Cor program (Vlach,  
647 2010). The dates were plotted in the weighted average diagram using the Isoplot program  
648 (Ludwig, 2008).

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## 975 **FIGURES CAPTIONS**

976 Figure 1 - a) Western Gondwana reconstruction by Westin et al. (2021). The blue square  
977 marks the cratonic blocks involved in the Southern Brasilia Orogen (SBO) development.

978 (1) Transbrasiliano-Kandi Lineament. Continental cratons: A-Amazon; CC- Congo; KA-  
979 Kazai; LA- Luis Alves; P- Pampia; Pp- Paranapanema; Pb- Parnaíba; WA-RA- Ria Apa;  
980 RP- Rio de la Plata; SH- Sahara; SF- São Francisco; SL- São Luis; b) Orogenic belts of  
981 Central and Southeast Brazil (Westin et al., 2021). Red square is the SBO position.

982 Figure 2 - Southern Brasilia Orogen (SBO) tectonic map modified after Campos Neto et al.  
983 (2020). The black square marks the study area location.

984 Figure 3 – Cross-section A-B (see Fig. 2) illustrating the tectonic architecture of the south  
985 sector of the Southern Brasilia Orogen.

986 Figure 4 - a) Geological map of Pouso Alto county; b) Geological cross-section of the area  
987 and stereographic projections of collected structural data.

988 Figure 5 - Blastesis-deformation relationships in the Liberdade and Andrelândia Nappes.

989 Figure 6 - Liberdade Nappe (LN) photomicrographs. a) Spaced disjunctive schistosity ( $S_2$ )  
990 defined by biotite and white mica shape preferential orientation (SPO). Quartz displays  
991 moderately irregular contacts (UTM 521535/7560145); b) Skeletal garnet and decussate  
992 fibrolite (UTM 521535/7560145); c) Garnet porphyroblast with S-shaped internal foliation  
993 (UTM 521535/7560145); d) Garnet pseudomorph replaced completely by fibrolite (UTM  
994 521535/7560145); e) Isoclinal fold marked by fibrolite orientation (UTM 519472/  
995 7549550); f) Kyanite relic overgrown by white mica (UTM 5110028/7561820).

996 Figure 7 - Quantitative compositional maps for the sample NESG-388 of the Liberdade  
997 Nappe: a) Mineral map of the investigated thin-section area showing the mineral phases in  
998 the mapped area; b) Anorthite (XAn) content in plagioclase map; c)-f) Almandine (XAlm),

999 grossular (XGr<sub>s</sub>), pyrope (XPrp) and spessartine (XSps) zoning in garnet. The red circles  
1000 indicate the area used to perform the Q<sub>cmp</sub> maps for garnet, and plagioclase (core and rim).  
1001 Figure 8 - Andrelândia Nappe (AN) photomicrographs. a) Compositional banding,  
1002 alternating layers made by quartz and plagioclase, and those constituted by white mica and  
1003 biotite with subordinate garnet and kyanite (UTM 513937/7565930); b) Garnet  
1004 porphyroblast with opaque inclusion trails defying the internal foliation (Pre-S<sub>2</sub>), and  
1005 kyanite aligned according to the external S<sub>2</sub> foliation (UTM 516960/7565691); c) Fibrolite  
1006 growth along a shear bands (UTM 516960/7565691); d) Garnet with opaque inclusion trails  
1007 oblique to the external foliation (post-S<sub>2</sub>) made by sillimanite, quartz, and biotite. Staurolite  
1008 with internal foliation continuous with the external one. Note the fibrolite replacing biotite  
1009 crystals (UTM 516960/7565691).

1010 Figure 9 - Quantitative compositional maps for sample NESG-401 of the Andrelândia  
1011 Nappe; a) Mineral map of the investigated thin-section area showing the mineral phases in  
1012 the mapped area; b) Anorthite (XAn) content in plagioclase map; c)-f) Almandine (XAlm),  
1013 grossular (XGr<sub>s</sub>), pyrope (XPrp) and spessartine (XSps) zoning in garnet. The red circles  
1014 indicate the area used to perform the Q<sub>cmp</sub> maps for garnet (mantle and rim), and  
1015 plagioclase (core and rim).

1016 Figure 10 – a) *P-T* isochemical phase diagram in the MnNCKFMASHT system for the  
1017 Liberdade Nappe (NESG-388); b) *P-T* path based on optimal conditions of mineral  
1018 chemistry composition (Q<sub>cmp</sub>) and mode (Q<sub>mode</sub>) maps. The red star corresponds to the  
1019 optimal *P-T* conditions obtained by the antidote.

1020 Figure 11 – a) *P-T* isochemical phase diagram in the MnNCKFMASHT system for the  
1021 Andrelândia Nappe (NESG-401); b) *P-T* path based on optimal conditions for mineral  
1022 chemistry composition ( $Q_{\text{cmp}}$ ) and mode ( $Q_{\text{mode}}$ ) maps. The red star corresponds to the  
1023 optimal *P-T* conditions obtained by the antidote.

1024 Figure 12– Liberdade Nappe (sample NESG-388): a) BSE images, X-ray maps (Y and Th)  
1025 of monazites showing structural position, textural relationships, and internal zoning; b)  
1026  $Y_2O_3$  (wt%) vs. age plot; c)  $ThO_2$  (wt%) vs. age plot; d) weighted average diagram for  
1027 monazite core dates (domain 1 and 2); e) weighted average diagram for monazite rim dates  
1028 (domain 3).

1029 Figure 13 – Andrelândia Nappe (sample NESG-401): a) BSE images, X-ray maps (Y and  
1030 Th) of monazites showing structural position, textural relationships, and internal zoning; b)  
1031  $Y_2O_3$  (wt%) vs. age plot; c)  $ThO_2$  (wt%) vs. age plot; d) weighted average diagram for  
1032 monazite core dates; e) weighted average diagram for monazite enclosed in Ky.

1033 Figure 14 – a) Summary of Andrelândia Nappe System (ANS) *P-T* paths. Grey dotted lines  
1034 display different geothermal gradients trends. Solidus curve from Spear et al. (1999) in the  
1035 NaKFMASH system; b) summary of the monazite and zircon U-Pb metamorphic ages from  
1036 the Liberdade and Andrelândia Nappes.

1037 Figure 15 – Tectono-metamorphic model for the evolution of the SBO nappes. a) 630 to  
1038 620 Ma: Early prograde metamorphism in the collisional wedge and Pouso Alto Nappe  
1039 burial and heating stage; b) 620 to 610 Ma: Onset of the decompression path in the  
1040 collisional wedge. Pouso Alto Nappe decompression and melt crystallization stage, while  
1041 the Liberdade Nappe was buried and heated; c) 610 to 580 Ma: Liberdade Nappe onset its

1042 upward isothermal decompression path over the Andrelândia Nappe, which was heated and  
1043 buried; d) <580-570 Ma: Final stage of the SBO continental collision coeval with the  
1044 Andrelândia and Carrancas Nappes decompression and cooling stages. The *P-T-t* paths are  
1045 based on Benetti. (2022), Campos Neto et al. (2021), Coelho et al. (2017), Fumes et al.,  
1046 (2021), Li et al. (2021), Marimon et al. (2020, 2022), Motta and Moraes (2017), Motta et al.  
1047 (2021), Rocha et al. (2017), Westin et al. (2021).

#### 1048 **SUPPLEMENTARY FIGURE FILE A**

1049 Figure A1 - Full thin-sections maps acquired using the Scanning Electron Microscopy and  
1050 Mineral Liberation Analyzer (SEM-MLA). The black square represents the local bulk  
1051 composition (LBC) investigated. a) Sample NESG-388 from Liberdade Nappe; b) Sample  
1052 NESG-401 from Andrelândia Nappe.

1053 Figure A2 – Quantitative compositional maps for the sample NESG-388 from Liberdade  
1054 Nappe. a) Map of Ti content in biotite (a.p.f.u); b) Map of #Mg in biotite; c) Map of Ti in  
1055 biotite thermometer of Henry et al. (2005); d) Map of Si<sup>+4</sup> content in white mica (a.p.f.u).  
1056 Red circle indicates the area used to perform the  $Q_{\text{cmp}}$  maps.

1057 Figure A3 – Quantitative compositional maps for the sample NESG-401 from Andrelândia  
1058 Nappe. a) Map of Ti content in biotite (a.p.f.u); b) Map of #Mg in biotite; c) Map of Ti in  
1059 biotite thermometer of Henry et al. (2005); d) Map of Si<sup>+4</sup> content in white mica (a.p.f.u).  
1060 Red circle indicates the area used to perform the  $Q_{\text{cmp}}$  maps.

1061 Figure A4- Maps of quality factors by Antidote for Liberdade Nappe. a)  $Q_{\text{asm}}$ ; b)  $Q_{\text{mode}}$ ; c)  
1062  $Q_{\text{cmp}}$  for the LBC bulk composition; d)  $Q_{\text{cmp}}$  for garnet composition; e)  $Q_{\text{cmp}}$  for plagioclase

1063 core composition; f)  $Q_{\text{cmp}}$  for plagioclase rim composition; g)  $Q_{\text{cmp}}$  for white mica  
1064 composition; h)  $Q_{\text{cmp}}$  for biotite composition.

1065 Figure A5- a) *P-T* isochemical phase diagram in the MnNCKFMASHT system for the  
1066 Andrelândia Nappe (NESG-401) for LBC including garnet core composition; b) Map of  
1067 quality factor  $Q_{\text{cmp}}$  by Antidote for AN garnet core composition.

1068 Figure A6 - Maps of quality factors by Antidote for Andrelândia Nappe. a)  $Q_{\text{asm}}$ ; b)  $Q_{\text{mode}}$ ;  
1069 c)  $Q_{\text{cmp}}$  for the LBC bulk composition; d)  $Q_{\text{cmp}}$  for garnet mantle composition; e)  $Q_{\text{cmp}}$  for  
1070 garnet rim composition; f)  $Q_{\text{cmp}}$  for white mica composition; g)  $Q_{\text{cmp}}$  for plagioclase core  
1071 composition; h)  $Q_{\text{cmp}}$  for plagioclase rim composition; i)  $Q_{\text{cmp}}$  for biotite composition.

1072 Figure A7 – Weighted mean plot for Moacyr monazite standard.

#### 1073 **SUPPLEMENTARY TABLE FILE A**

1074 Table A1- Representative Electron Microprobe (EMP) analyses of minerals from samples  
1075 NESG-388 and NESG-401. (b.d.l. - below detection limit).

1076 Table A2 - Monazite chemical composition from sample NESG-388 and NESG-401  
1077 (normalized to 4O), (b.d.l- below detection limit).

1 **In-sequence tectonic evolution of Ediacaran nappes in the southeastern branch of the**  
2 **Brasília Orogen (SE Brazil): constraints from metamorphic iterative thermodynamic**  
3 **modeling and monazite petrochronology**

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15 **ABSTRACT**

16 **The metamorphic and kinematic evolution** of medium-high grade rocks **of forming the**  
17 ~~hinterland of the orogenic wedge are able to record pressure ( $P$ ) and temperature ( $T$ )~~  
18 ~~changes during the orogen development, as well as its kinematic history. The~~ Andrelândia  
19 Nappe System (ANS), ~~is the hinterland~~ **orogenic wedge** of the Southern Brasilia Orogen  
20 (SBO), **was investigated in this work** ~~and its tectono-metamorphic evolution has been a~~

21 ~~subject of intense debate in the past decades.~~ Field and microstructural observations were  
22 combined with metamorphic petrology (i.e., iterative thermodynamic modeling) and  
23 monazite petrochronology to reconstruct the tectono-metamorphic history of the ANS  
24 rocks. The Liberdade Nappe ~~attained~~ **experienced** prograde metamorphism at *ca.* 610 Ma,  
25 achieving peak metamorphic conditions of  $\sim ca.$  650°C and 9.5-10 kbar. This stage was  
26 followed by isothermal decompression linked to tectonic transport toward SE, at *ca.* 570  
27 Ma. On the contrary, the Andrelândia Nappe experienced prograde metamorphism later, at  
28 *ca.* 580 Ma, reaching peak metamorphic conditions of *ca.* 680°C and 11-12 kbar. The  
29 obtained results indicate that ~~each~~ **the** nappe of the Andrelândia System ~~record~~ **records** a  
30 single metamorphic cycle of burial and decompression, although it took place at different  
31 ages over a period of *ca.* 60 ~~Ma~~ **myr**, from 630 to 570 Ma. **The nappes experienced prograde**  
32 **and retrograde metamorphism whose ages progressively decreased toward the bottom of**  
33 **the nappe stack.** ~~The different ages of when the nappes experienced prograde and~~  
34 ~~retrograde metamorphism followed a progressive decrease toward the bottom of the stack.~~  
35 **We attribute this pattern** ~~This would have occurred~~ owing to propagation of older **buried**  
36 material from ~~inner parts of~~ the orogenic wedge (**i.e., Liberdade Nappe**), via thrust-and-  
37 fold, upon recently accreted rocks (**i.e., Andrelândia Nappe**), conducting a younger  
38 metamorphism event **on the footwall of the ductile thrust nappes** ~~external parts of the~~  
39 ~~wedge.~~ This mechanism **is consistent** with ~~the ANS~~ **would be responsible to outline an the**  
40 in-sequence fold-and-thrust architecture ~~of the ANS.~~

41 **KEYWORDS:**

42 Monazite petrochronology, iterative thermodynamic modeling, Brasília Orogen  
43 metamorphism, P-T-t-D paths

## 44 1. INTRODUCTION

45 The growth of a mountain belt is controlled by the balance among accretion of  
46 crustal material, such as sediments and magma addition **as well as thrust stacking**, and  
47 removal by erosion, **tectonic delamination**, and post-orogenic **thinning extension**  
48 **(Beaumont et al., 2001; Davies et al., 1983; Jamieson and Beaumont, 2013; Vanderhaeghe,**  
49 **2012; Whipple, 2009; Willett, 1999)**. ~~External (e.g., climate) and internal (e.g., structure~~  
50 ~~and geodynamic) factors, controlling mountain building, play a main role in modifying the~~  
51 ~~architecture of the orogenic wedge of a collisional belt (DeCelles and Mitra, 1995)~~. An  
52 orogenic wedge is constituted by crustal material mainly detached from the subducted  
53 lithosphere, accreted, and stored within the orogenic system (Vanderhaeghe, 2012;  
54 Vanderhaeghe et al., 2003). During orogenesis, **erosion, normal faulting, and ductile flow**  
55 **can lead** ~~balance of the orogen active forces leads to~~ **exhumation of the deep-seated rocks at**  
56 **the front of the crustal wedge (DeCelles and Mitra, 1995; England & Molnar, 1990; Ring et**  
57 **al., 1999; Vanderhaeghe et al., 2003)**. **Deformation and ductile flow can follow an in-**  
58 **sequence pattern when they present progressive age decreases in the same direction of the**  
59 **tectonic transport (Weller et al., 2021)**. ~~Moreover,~~ **the** accumulation of crustal material  
60 within an orogen enriched in radioactive heat-production elements, such as U, Th, and K,  
61 modifies its crustal geothermal gradient (England and Thompson, 1984; Rudnick and  
62 Fountain, 1995). **Moreover, thrust stacking of hot rocks upon colder ones can also be a heat**  
63 **source for metamorphism in the footwall (“the hot iron model”; England & Molnar, 1993;**  
64 **Le Fort, 1975)**. ~~Therefore, The aforementioned observations demonstrate that the deep-~~  
65 ~~seated crustal rocks, stored within an orogenic wedge,~~ are able to record pressure ( $P$ ) and  
66 temperature ( $T$ ) **changes during the development of an orogen as recorded by its kinematic**  
67 **and internal structure, providing valuable information to understand the deep dynamics of**

68 ~~collisional wedges, an orogen development as well as its kinematics history and crust~~  
69 ~~internal structure. Hence, the study of the deformation and metamorphic conditions of~~  
70 ~~deep-seated crustal rocks stored in an orogenic wedge is fundamental to comprehending the~~  
71 ~~tectonic and geodynamic evolution of ancient and young orogenic belts.~~

72         The Andrelândia Nappe System (ANS) is regarded as the Southern Brasília Orogen  
73 (SBO) hinterland of an orogenic wedge. Its tectono-metamorphic evolution has been a  
74 target of intense debate in during the past several decades. ~~Indeed,~~ Some researchers  
75 (Coelho et al., 2017; Fontainha et al., 2020; Li et al., 2021; Trouw et al., 2013) argue that the  
76 ANS evolution was due to polymetamorphism related to two separate tectonic events  
77 during different orogenic cycles. ~~results of a polymetamorphic evolution related to two~~  
78 ~~separate tectono-metamorphic events from different orogenic cycles.~~ The first event is was  
79 related to high-P metamorphic conditions testified by the HP-granulites and E/NE nappe  
80 stacking, owing to the Paranapanema and São Francisco Cratons collision in the period  
81 from *ca.* 630 to 600 Ma (Coelho et al., 2017; Li et al., 2021; Reno et al., 2012; Trouw et al.,  
82 2013). It was followed by a second orogenic event, characterized by medium pressure,  
83 greenschist- to amphibolite-facies conditions in the staurolite and sillimanite zones, during  
84 NW-SE contraction at 600-560 Ma (Coelho et al., 2017; Fontainha et al., 2020; Heilbron et  
85 al., 2017; Trouw et al., 2013; Zuquim et al., 2011), ~~with NW-SE shortening direction, and~~  
86 ~~ages from 600 to 560 Ma. This second episode would be related~~ This tectonic event is  
87 attributed to the Central Ribeira Orogeny (Fig. 1b). The second ~~viewpoint~~ model proposes  
88 that the ANS evolution ~~results~~ was due to from a single orogenic cycle. ~~According to them,~~  
89 The ANS tectono-metamorphic evolution is linked to the Paranapanema block collision  
90 against the São Francisco Craton (Campos Neto et al., 2011; Frugis et al., 2018; Westin et

91 al., 2021). In this hypothesis, the sillimanite and staurolite presence documented by the  
92 ANS rocks would result from the decompression/exhumation of the nappe pile rather than  
93 testify a second tectono-thermal event. The available metamorphic ages, **from 630 to 580**  
94 **Ma**, indicate a thrust propagation from WSW to ENE toward the São Francisco Craton  
95 southern edge (Westin et al., 2021 and references therein).

96 The reconstruction of Pressure-Temperature-time-Deformation (*P-T-t-D*) paths  
97 provide ~~elementary~~ **fundamental** information to understand the tectonic and metamorphic  
98 events experienced by rocks accreted to the orogenic wedge. Primarily, the application of  
99 internally consistent databases **to create phase equilibria models that can be** ~~to build~~  
100 ~~pseudosection has been~~ used to constrain metamorphic conditions (Powell and Holland,  
101 2008; Waters, 2019). This data can be linked with microstructural observations to set up the  
102 rock fabric relationships with the metamorphic mineral assemblage, i.e., the so-called  
103 blastesis-deformation relationships (~~Passchier & Trouw, 2005~~). In addition, the in-situ  
104 dating of accessory minerals, such as monazite, zircon, or titanite **can provide ages for**  
105 **specific metamorphic reactions and deformation events**, ~~can be bound to metamorphic~~  
106 ~~reactions and deformation events~~ (e.g., Bosse and Villa, 2019; Kohn et al., 2017; Williams  
107 and Jercinovic, 2012). This approach ~~is~~ **has been proven to be** one of the most effective  
108 ways to understand the **complex frameworks of** collisional belts ~~complex frameworks~~  
109 (Carosi et al., 2018; Waters, 2019). In this contribution, we combine field and  
110 microstructural observations with **iterative metamorphic thermodynamic modeling** ~~modern~~  
111 ~~techniques in metamorphic petrology~~ and ***in-situ* monazite** geochronology. This integrative  
112 approach provides ~~the necessary~~ **information about the timing of tectonic processes that**

113 drove the build of the ANS fold-and-thrust belt, such as tectonic burial and exhumation,  
114 and allowed the reconstruction of the tectono-metamorphic history of the ANS rocks.

## 115 2. GEOLOGICAL SETTING

116 The Brazilian-Pan African event is the name given to a series of diachronic  
117 collisions in the São Francisco-Congo Craton side of the West Gondwana paleocontinent  
118 (Cordani et al., 2003; Ganade De Araujo et al., 2014; Fig. 1). The Southern Brasilia Orogen  
119 (SBO) is one of the orogenic belts built during this tectonic event (Cordani et al., 2003; Fig.  
120 1 and 2). The SBO evolved from the lateral collision between the Paranapanema  
121 paleocontinent, the active margin, against the São Francisco paleocontinent, representing  
122 the SBO passive margin (Campos Neto, 2000; Campos Neto et al., 2011; Trouw et al.,  
123 2013, 2000).

124 The SBO final architecture resulted in an almost flat-lying fold-nappe pile, with top-  
125 to-the-east/northeast tectonic transport (Fig. 3). Three tectonic domains are recognized  
126 within the SBO (Campos Neto, 2000; Campos Neto et al., 2011, 2021; Trouw et al., 2013,  
127 2000; Fig. 2 and 3): (1) the active margin of the Paranapanema paleocontinent, constituted  
128 by the granulites and migmatites of the Socorro-Guaxupé Nappe, (2) the orogenic wedge  
129 hinterland, a pile of metasedimentary nappes of the Andrelândia Nappe System, (3) the  
130 passive margin related to the São Francisco paleocontinent, made by the psamo-pelitic  
131 sequences of the Carrancas and Lima Duarte Nappes. These tectonics domains are intruded  
132 by leucogranites (Fig. 3) and A-type granitic rocks (i.e., Itu Granite Province, Pedra  
133 Branca, and Capituva Plutons; Fig. 2) interpreted as post-orogenic plutonsbodies.

134 The SBO is split into two segments by a tectonic window (Fig. 2) exposing the  
135 Archean-Paleoproterozoic migmatitic orthogneiss from the basement complexes (Cioffi et

136 al., 2019, 2016; Westin et al., 2016). The Andrelândia Nappe System (ANS) is sandwiched  
137 among the UHT-HT metamorphic rocks of the Socorro-Guaxupé Nappe (Campos Neto and  
138 Caby, 1999; Motta et al., 2021; Rocha et al., 2017a; Tedeschi et al., 2018; Fig. 3) at the top  
139 and, by the low- to medium temperature metasedimentary rocks of the passive margin  
140 covers (Fig. 2 and Fig. 3), at the bottom. Internally, the ANS is divided from its uppermost  
141 structural level to the bottom by the Três Pontas-Varginha and Carmo da Cachoeira Nappes  
142 in the northern sector. In the southern sector, the ANS is segmented into the Pouso Alto (or  
143 Aiuruoca, Carvalhos, and Serra da Natureza Klippes equivalent), Liberdade, and  
144 Andrelândia Nappes (Fig. 3). Two characteristics are remarkable in the ANS: i) its inverted  
145 metamorphic pattern, in which rocks in the high-P granulite metamorphic facies structurally  
146 overlap those in amphibolite facies conditions (Campos Neto and Caby, 2000, 1999; Garcia  
147 and Campos Neto, 2003; Motta and Moraes, 2017; Trouw et al., 2000, 1998); ii) the  
148 decrease of metamorphic ages eastward, which is the same sense of the non-coaxial ductile  
149 flow (Campos Neto et al., 2011; Westin et al., 2021).

150         The Três Pontas-Varginha, Pouso Alto Nappe, and the Aiuruoca, Carvalhos, and  
151 Serra da Natureza Klippes, lay on the top of the ANS stack. They are made of K-  
152 feldspar+garnet+kyanite+rutile-bearing gneiss. These rocks attained metamorphic  
153 conditions of *ca.* 830°-900°C and 12-16 kbar in the high-pressure granulite facies  
154 conditions (Campos Neto et al., 2010; Campos Neto and Caby, 2000; Cioffi et al., 2012;  
155 Fumes et al., 2021; Garcia and Campos Neto, 2003; Li et al., 2021; Reno et al., 2009).

156         The Liberdade Nappe (LN), the intermediate unit of the ANS, is composed of  
157 garnet+kyanite+ilmenite(±sillimanite±rutile)-bearing micaschist and paragneiss with  
158 subordinate quartzite, metabasite, and calc-silicate lenses. Metamorphic conditions, in

159 metapelites, are constrained in the *P-T* range of 642-715°C and 6-10 kbar (Coelho et al.,  
160 2017; Motta and Moraes, 2017; Rodrigues et al., 2019; Santos et al., 2004). Zircon and  
161 monazite U-Pb dating retrieved ages around 620-615 Ma (Coelho et al., 2017; Motta and  
162 Moraes, 2017; Westin et al., 2021). Moreover, the metamafic rocks, interpreted as  
163 retroeclogites (Campos Neto and Caby, 1999; Coelho et al., 2017; Reno et al., 2009; Trouw  
164 et al., 2013), experienced *P-T* conditions around 700°-800°C and 12-16 kbar (Coelho et al.,  
165 2017; Reno et al., 2009; Tedeschi et al., 2017). The metamafic rocks present two clusters of  
166 metamorphic ages, the first around 680-660 Ma (Campos Neto et al., 2011; Reno et al.,  
167 2009), and the other around 630-625 Ma (Coelho et al., 2017; Tedeschi et al., 2017).

168         The Andrelândia (AN) and Carmo da Cachoeira Nappes are at the bottom of the  
169 ANS stack. They are internally ~~constituted by, divided into three lithostratigraphic units.~~  
170 ~~From the top to the base, they are:~~ **micaschists intercalated with metapsamites Rio**  
171 **Capivari, metawackes from the Santo Antonio, and micaschists from the Serra da Boa**  
172 ~~Vista.~~ The AN displays an inverted metamorphic gradient in which "peak" mineral  
173 assemblages vary from garnet+~~biotite~~**biotite**+staurolite at its bottom to the  
174 kyanite+garnet+melt at the top. The Andrelândia and Carmo da Cachoeira Nappes attained  
175 peak conditions around 650-670°C and 9-10 kbar in *ca.* 600 Ma, followed by almost  
176 isothermal decompression in the time span of 600-575 Ma (Frugis et al., 2018; **Marimon et**  
177 **al., 2022**; Motta and Moraes, 2017; Reno et al., 2012; Santos et al., 2004; Westin et al.,  
178 2021).

179 **3. RESULTS**

180 *3.1 Field observations*

181 The study area is located in southeast Brazil, in the Minas Gerais state around Pouso  
182 Alto County. It comprises a geological section from SW to NE in the Andrelândia Nappe  
183 System southern sector (Figs. 2 and 4), highlighting all of its **allochthonous units** along  
184 with the basement ~~nucleus~~ **cores** of the nappe system.

185 The Pouso Alto Nappe has a spoon-shaped cylindrical SW-oriented synform, with  
186 W-SW plunging of the mineral and stretched lineations, and a general transport toward NE  
187 evidenced by **asymmetric mafic boudin and S-C fabric** kinematic indicators (Fig. 4a and b).  
188 The main lithotype described is a medium- to coarse-grained K-  
189 feldspar+garnet+kyanite+rutile(±ilmenite±biotite)-bearing gneiss.

190 The Liberdade Nappe is represented by fine- to medium-grained garnet+ilmenite  
191 (±sillimanite ±rutile±kyanite±staurolite)-bearing micaschist interlayered with quartzite.  
192 Micaschist displays a main spaced disjunctive schistosity, defined by biotite, white mica,  
193 and aluminum silicates shape **preferred** orientation (SPO). Intrafolial stretched isoclinal  
194 passive folds are observed. The ensemble of the foliation describes a large cylindrical  
195 synform with an SW-oriented B-axis in a type-3 superposition pattern (Ramsay, 1962) over  
196 recumbent isoclinal folding between the basement nucleus and the metasedimentary  
197 sequence (Fig. 3). The mineral (sillimanite/fibrolite and micas) lineations are mainly  
198 oriented to SE, which, coupled with some kinematics indicators (*S-C fabric* and  
199 asymmetrical ~~pressure~~ **strain** shadow structures), point to **an** eastward transport of the  
200 nappe. The Pouso Alegre Complex is made by orthogneisses of a tonalite-granite series  
201 related to the Paleoproterozoic basement (Cioffi et al., 2016). A leucogranite body intrudes

202 micaschist of the Liberdade Nappe, the Alagoa migmatite, and the Pouso Alegre Complex  
203 (Fig. 3, 4a, and b).

204 The Andrelândia Nappe crops out in the north of the study area (Fig. 4a and b). It is  
205 made of grayish metawackes, and at its lithostratigraphic boundaries metapelites  
206 associations prevail. The main lithology described is a garnet+kyanite( $\pm$ staurolite)-bearing  
207 gneiss. The main foliation is a spaced disjunctive schistosity identified by SPO on white  
208 mica, biotite, and kyanite. The schistosity strikes ENE-WNW with dips varying from low  
209 to high angles, between 20°-80° toward the north. White mica, biotite, quartz, and kyanite  
210 are responsible for outlining the mineral and stretching lineation, which trends between  
211 N90°-N120° and plunges 10°-50° to E/SE. A kinematic change between the Pouso Alto  
212 Nappe, and the Liberdade and Andrelândia is noticed in the area. Whereas the upper nappe  
213 points to northeastward tectonic transport, the middle and lower suggest an east-  
214 southeastward direction.

### 215 3.2 *Petrography, microstructural relationships, and mineral chemistry*

216 In order to constrain the relationships between mineral growth and deformation  
217 (Fig. 5), several samples from Liberdade and Andrelândia Nappes were petrographically  
218 studied. One representative sample of each nappe was selected for performing full thin-  
219 sections maps acquired using the Scanning Electron Microscopy and Mineral Liberation  
220 Analyzer (SEM-MLA) (supplementary figures A1). The location of samples is given in  
221 Fig. 4a. An area of each thin-section mapped containing the inferred peak mineral  
222 assemblage, avoiding retrometamorphic textures where possible, was investigated using X-  
223 ray maps acquired by an electron probe micro-analyzer (EMPA). The analytical procedure  
224 employed for EMPA analysis is described in Appendix A. The X-ray maps were converted

225 into oxide weight percentage maps applying internal standards (Andrade et al., 2006) in the  
226 software XMapTools 3.4 (Lanari et al., 2014, 2019). Such areas were the basis for  
227 estimating the Local Bulk Composition (LBC) needed for petrological modeling (see  
228 section 5). The mineral abbreviations follow Whitney and Evans (2010).

### 229 3.2.1 Liberdade Nappe (LN)

230 The Liberdade Nappe micaschist is made up of quartz+plagioclase+white  
231 mica+biotite+garnet+ilmenite(±sillimanite±rutile+kyanite±staurolite). The LN displays a  
232 spaced disjunctive schistosity ( $S_2$ , Fig. 6a), and in some portions presents **microstructures**  
233 of tectonic transport such as a *S-C* fabric and isoclinal folds, **made up mainly of white mica**  
234 **and sillimanite**, denoting top-to-the-SE motion. Quartz has slightly lobate contacts (Fig.  
235 6a), and plagioclase has undulose extinction. The quartz features reveal that this mineral  
236 was recrystallized due to the grain boundary migration (GBM) regime and underwent the  
237 grain boundary area reduction (GBAR; Passchier and Trouw, 2005). Garnet porphyroblast  
238 has in several circumstances a skeletal microstructure (Fig. 6b). It also shows S-shaped  
239 inclusions made of quartz (Fig. 6c), defining an internal foliation that is not continuous  
240 with the external one. Then, garnet is regarded as a pre- to early-syn-tectonic mineral with  
241 respect to the  $S_2$  schistosity. Sillimanite is present as fibrolite, it replaces partial to  
242 completely garnet porphyroblasts, forming pseudomorphs (Fig. 6d), and also occurs along  
243 intrafolial isoclinal folds (Fig. 6e). Subidiomorphic relic of kyanite wrapped by white mica  
244 is observed (Fig. 6f). Staurolite, in a very low modal amount, is fine-grained and often  
245 related to garnet rims. Rutile is enclosed in garnet and in the matrix is usually rimmed by  
246 ilmenite.

247           The relationships among minerals suggest three metamorphic stages, here referred  
248 as  $M_{LN1}$ ,  $M_{LN2}$ , and  $M_{LN3}$ , for the Liberdade Nappe micaschist (Fig. 5). The  $M_{LN1}$  stage is  
249 pre- $S_2$ , related to prograde/peak metamorphism and it is characterized by  
250 quartz+plagioclase+white mica+biotite+garnet+rutile+kyanite(?) as the equilibrium  
251 assemblage in the rock. The  $M_{LN2}$  stage, in which quartz+plagioclase+white  
252 mica+biotite+garnet+kyanite(?)+ilmenite is inferred to be stable, represents a post-peak  
253 mineral assemblage. Finally, sillimanite and staurolite are regarded as phases that grew  
254 during the late stages of the metamorphic path ( $M_{LN3}$  and Syn- $S_2$ ).

255           Sample NESG-388 (Fig. 4a, supplementary figure A1) was selected for the LN  
256 mineral chemistry investigation and petrological modeling. The NESG-388 is a white  
257 mica+biotite+garnet+ilmenite-bearing mylonitic schist with minor sillimanite, rutile, and  
258 staurolite (Fig. 7a). Plagioclase is compositionally zoned, and its anorthite content increases  
259 from core to rim ( $X_{An} = 0.20-0.32$ ) (Fig. 7b). Garnet end-members vary slightly from core  
260 to rim: almandine ( $X_{Alm}$ )=0.81-0.79, pyrope ( $X_{Prp}$ )=0.11-0.07, spessartine ( $X_{Sps}$ ) =0.05-  
261 0.06 and grossular ( $X_{Grs}$ )=0.05-0.06 (Fig. 7c-f). The Ti (a.p.f.u) in biotite decreases toward  
262 the rim, ranging from 0.14 to 0.09, whereas the #Mg ( $Mg/Fe^{+2}+Mg$ ) ratio displays an  
263 inverse correlation, increasing toward the rims, varying from 0.37 to 0.43 (supplementary  
264 figures A2a and b). The  $Si^{4+}$  (a.p.f.u) of white mica varies from 3.04 to 3.12  
265 (supplementary figure A2d).

### 266 3.2.2           *Andrelândia Nappe*

267           The Andrelândia Nappe is constituted by the major phases:  
268 quartz+plagioclase+biotite+white mica+garnet+kyanite+ilmenite(±sillimanite±staurolite)  
269 and tourmaline+apatite+monazite+zircon+rutile as accessories. The AN has a  $S_2$  foliation

270 characterized by discontinuous millimetric compositional layers of granoblastic, made by  
271 quartz and plagioclase, and lepidoblastic, constituted by white mica and biotite with  
272 subordinate garnet and kyanite (Fig. 8a). The AN close to the contact with the Liberdade  
273 Nappe is affected by shearing and displays a mylonitic fabric (post-S<sub>2</sub>). The kinematic  
274 indicators described in the sheared gneisses are S-C fabric and white mica-fish, which point  
275 to a top-to-the-E/ESE tectonic transport. Quartz is a medium- to coarse-grained mineral  
276 with irregular and lobate ~~contacts~~ boundaries, typical of the GBM recrystallization  
277 mechanism (Law, 2014).

278 Garnet is present as porphyroblast ( $\leq 2$  cm in size) (Fig. 8b). Discontinuous  
279 inclusion trails of opaque minerals within garnet, with respect to the S<sub>2</sub> fabric, testify to the  
280 inter-tectonic nature of this mineral (Fig. 8b and d). Thin graphite crystals, ilmenite, and  
281 rutile are the typical inclusions in garnet, and staurolite, quartz, plagioclase, biotite, and  
282 white mica are subordinate. Kyanite is a coarse-grained subidiomorphic crystal with a long  
283 axis aligned along the S<sub>2</sub> foliation (Fig. 8b). Twinning in kyanite is observed. Late fibrolite  
284 growth (post-S<sub>2</sub>) along shear bands and replacing biotite crystals are observed (Fig. 8c and  
285 d). Two generations of staurolite were observed, the first is characterized by tiny crystals  
286 enclosed in garnet, ~~Whereas~~ whereas the second ~~one~~ is in the matrix, often around garnet  
287 rims. A staurolite with biotite and sillimanite inclusions aligned with the external foliation,  
288 made by sillimanite, quartz, and biotite, denotes a syn-tectonic origin regarding the post-S<sub>2</sub>  
289 fabric (Fig. 8d). The contact between staurolite and garnet, as well as the abrupt change of  
290 the internal foliation of both minerals, suggest a pattern of porphyroblasts amalgamated  
291 (Fig. 8d, e.g., Passchier and Trouw, 2005).

292 Based on the above description, three main stages of mineral equilibration were  
293 recognized (Fig. 5). The early prograde assemblage ( $M_{AN1}$ ), preserved in garnet core, is  
294 constituted by  
295 ~~Grt(core)+Qz+Pl+Bt+Ms+St+Rt~~ garnet(core)+quartz+plagioclase+biotite+white  
296 mica+staurolite+rutile. The peak assemblage ( $M_{AN2}$ ) is coeval with the  $S_2$  foliation and is  
297 marked by the appearance of kyanite and ilmenite and the consumption of staurolite and  
298 rutile. The  $M_{AN3}$  assemblage corresponds to retrograde metamorphic path assemblage,  
299 characterized by a second growth of staurolite around garnet rims together with the late  
300 fibrolite appearance, and structures related to the tectonic transport (post- $S_2$  foliation).

301 Sample NESG-401 was chosen for a detailed chemical investigation (Fig. 4a,  
302 supplementary figure A1). The gneiss is composed of quartz+plagioclase+biotite+white  
303 mica+garnet+ilmenite ~~Qz+Pl+Bt+Ms+Grt+Ilm~~ and minor apatite (Fig. 9a). This sample is  
304 white mica-poor, which is restricted to the garnet strain shadow zones (supplementary  
305 figure A1 and Fig. 9a). The plagioclase is zoned, displaying Ca-poor cores ( $X_{An} -0.22$ ) and  
306 Ca-rich rims ( $X_{An} -0.32$ ). The highest Ca-content ( $X_{An} -0.34$ ) occurs in crystals that  
307 bound garnet (Fig. 9b). There are two garnet crystals in the X-ray mapped area. The large  
308 garnet porphyroblast displays a bell shape profile, whereas the smaller one presents an  
309 almost flat profile (Fig. 9c, d, e, and f). The garnet porphyroblast shows an increase in  
310 almandine and pyrope toward the rim, whereas spessartine and grossular display the inverse  
311 pattern (Core-  $X_{Alm} -0.6$ ,  $X_{Prp} -0.06$ ,  $X_{Sps} -0.1$ ,  $X_{Grs} -0.22$ ; Rim-  $X_{Alm} -0.72$ ,  $X_{Prp} -0.13$ ,  
312  $X_{Sps} -0.03$ ,  $X_{Grs} -0.08$ ) (Fig. 9c, d, e, and f). Spessartine displays a sharp increase in the  
313 outermost rim ( $X_{Sps} -0.09/0.1$ ) in both garnet crystals. The biotite composition varies  
314 according to its structural position. Crystals close to garnet have higher #Mg and lower Ti

315 (a.p.f.u) compared to grains far from garnet (Bt near garnet XMg- 0.54-0.52 and Ti(a.p.f.u)-  
316 0.8-0.10; Bt in matrix XMg-0.5-0.51 and Ti(a.p.f.u)- 0.11-0.12) (supplementary figure A3a  
317 and b). The Si<sup>4+</sup> content in white mica is close to the muscovite end-member, between 3.00-  
318 3.08 a.p.f.u. (supplementary figure A3d).

### 319 3.3 *Iterative Thermodynamic Modeling (ITM) and P-T path*

320 The iterative thermodynamic modeling (ITM) integrated with quantitative  
321 compositional mapping was applied as the strategy for setting up the metamorphic history  
322 of the Andrelândia and Liberdade Nappes using the software Bingo-Antidote a XMapTools  
323 add-on (Duesterhoeft and Lanari, 2020; Lanari and Hermann, 2021). This approach  
324 provides a means of investigating rocks that were not fully re-equilibrated during their  
325 metamorphic paths. Through the quantitative compositional maps, areas\phases within a  
326 sample that best represents the reactive phases can be selected for the local bulk  
327 composition (LBC) calculation. Furthermore, the Bingo-Antidote software provides series  
328 of statistics routines that compare the model results with the observed mineral assemblage,  
329 modes, and phase compositions for the LBC studied. The bingo routines calculate the  
330 model quality, assessing as much as it matches with the LBC mineral assemblage ( $Q_{asm}$ ),  
331 mineral modes ( $Q_{mode}$ ), and mineral compositions ( $Q_{cmp}$ ). The quality factors  $Q_{asm}$ ,  $Q_{mode}$ ,  
332 and  $Q_{cmp}$  vary from 0%, which means there is no match between the model and LBC  
333 observations, and 100%, meaning that the model perfectly reproduces the LBC features. In  
334 addition, the antidote provides routines, for instance the recipe 14, to evaluate how the  
335 quality factors change within the model P-T(-X). The Andrelândia and Liberdade Nappes  
336 thin-section areas investigated for obtaining LBCs and mineral compositions ( $Q_{cmp}$ ) quality

337 factors are displayed in Fig. 7a, 9a, supplementary figures A1, A2, and A3. The maps of  
338 quality factors from both samples are shown in supplementary figures A4, A5, and A6.

339 The isochemical diagrams were calculated for the local bulk composition (LBC)  
340 obtained by the Bingo-Antidote using the Theriak-Domino software (de Capitani and  
341 Petrakakis, 2010; de Capitani and Brown, 1987) to illustrate the stability of mineral fields.  
342 The calculations were performed in the chemical system MnO-Na<sub>2</sub>O-CaO-K<sub>2</sub>O-FeO-MgO-  
343 Al<sub>2</sub>O<sub>3</sub>-TiO<sub>2</sub>-SiO<sub>2</sub>-H<sub>2</sub>O. The water amount was chosen using recipe 14 of the antidote, a  
344 statistical routine that assesses how the quality factors ( $Q_{asm}$ ,  $Q_{mode}$ , and  $Q_{cmp}$ ), the mineral  
345 chemistry, and mode would vary along a given range of  $H_2O\theta$ , at fixed  $P$ - $T$  conditions.  
346 The diagrams were calculated for the  $P$ - $T$  range of 4-12 kbar and 550-725 °C. The database  
347 tc55 (Holland and Powell, 1998), provided and employed in the Bingo-Antidote software,  
348 was used for the isochemical diagrams calculations. The respective solution models were  
349 utilized: feldspar (Baldwin et al., 2005), garnet (White et al., 2005), biotite (White et al.,  
350 2005), staurolite (Holland and Powell, 1998), cordierite (Holland and Powell, 1998), white  
351 mica (Coggon and Holland, 2002), ilmenite (White et al., 2007) and melt (White et al.,  
352 2007).

### 353 3.3.1 Sample NESG-388 - Liberdade Nappe

354 The calculated isochemical diagram for the Liberdade Nappe LBC is presented in  
355 Fig. 10a. The observed peak mineral assemblage, quartz+plagioclase+white  
356 mica+biotite+ilmenite, is stable in the penta-variant field constrained in the  $P$ - $T$  range of  
357 6.5-12 kbar and 600-670°C. Assuming the mineral phase equilibrium, the optimal  $P$ - $T$   
358 condition is expected to be achieved at 628°C and 7.5 kbar. At this condition, the quality

359 factors for the mode ( $Q_{\text{mode}}$ ) is 92%, and the system mineral chemistry ( $Q_{\text{cmp}}$ ) is 86% (Fig.  
360 10b).

361 The mineral  $P$ - $T$  chemistry composition maps are presented in supplementary figure  
362 A4. They display a more complex story used to trace the  $P$ - $T$  path (Fig. 10b). The An-poor  
363 plagioclase core compositions ( $Q_{\text{cmp}}=100\%$ ) are stable in higher pressure, 8.5 kbar up to  
364 11.5 kbar, and in large temperature conditions, from 500°C to 700°C. On the contrary,  
365 plagioclase rim composition records a lower pressure condition, down to 8 kbar, and  
366 temperatures from 590°C to 660°C. Although the optimal  $P$ - $T$  conditions obtained by the  
367 antidiote, peak conditions are better constrained by plagioclase rim composition ( $Q_{\text{cmp}}$   
368  $=100\%$ ), around 650°C and 9.5-10 kbar. The Na-Ca diffusion in plagioclase is considered  
369 slower than garnet Ca-Fe-Mg-Mn in temperatures above 600°C (Caddick et al., 2010;  
370 Lanari and Hermann, 2021). These described diffusional behaviors are the likely causes of  
371 plagioclase core records better the prograde conditions rather than garnet.

372 Plagioclase rim ( $Q_{\text{cmp}}=100\%$ ), and garnet ( $Q_{\text{cmp}}=90$ -100%) mineral chemistry  
373 compositions in addition with the mineral modes ( $Q_{\text{mode}}=100\%$ ) intersect at the hexa-  
374 variant field in which  $\text{Qz}+\text{Pl}+\text{Bt}+\text{Grt}+\text{Ms}+\text{Ky}+\text{Ilm}$  are the stable phases. The intersection is  
375 around 650°C and 7-7.5 kbar, suggesting an almost isothermal decompression path. Relics  
376 of kyanite are described in the LN (Fig. 6f), supporting that this mineral was stable at some  
377 moment of the LN  $P$ - $T$  path. Lastly, the  $P$ - $T$  path later stage is recorded by the  
378 compositional match between the plagioclase rim and muscovite ( $\text{Pl}-Q_{\text{cmp}}=100\%$ ;  $\text{Ms}-$   
379  $Q_{\text{cmp}}=95\%$ ) in the hexa-variant field where  $\text{Qz}+\text{Pl}+\text{Grt}+\text{Bt}+\text{Ms}+\text{Ilm}+\text{Sil}+\text{H}_2\text{O}$  are stable. A  
380  $P$ - $T$  path (Fig. 10b) is suggested based on the above mineral chemistry and mode optimal  
381 quality factors fields, and the  $M_{\text{LN}1}$ ,  $M_{\text{LN}2}$ , and  $M_{\text{LN}3}$  metamorphic stages described in

382 section 4.1. The quantitative map of the Ti-in-biotite thermometer (Henry et al., 2005) was  
383 applied (supplementary figure A2c). It displays values from 650 to 580°C consistent with  
384 the findings obtained by the ITM approach.

### 385 3.3.2 Sample NESG-401 – Andrelândia Nappe

386 Fig. 11a displays the isochemical diagram built for the Andrelândia Nappe LBC that  
387 better represents the peak-to post-peak conditions. Bulk compositions that consider phases  
388 that are not fully equilibrated in the system, such as minerals relics or displaying  
389 compositional zoning, can affect the thermodynamic models quality (Lanari and Engi,  
390 2017). Once one garnet of the LBC is strongly zoned and likely its core was unreactive at  
391 peak condition, for avoiding the question described above, the garnet core area was  
392 subtracted and is not considered in the bulk composition. Although, the isochemical  
393 diagram taking into account the garnet core composition and the  $P$ - $T$  stability field map for  
394 garnet core composition (garnet core  $Q_{\text{cmp}}$ ) are provided in the supplementary figure A5.  
395 Therefore, the  $M_{\text{ANI}}$  stage, which corresponds to a mineral assemblage preserved in the  
396 garnet core, does not appear in the suggested  $P$ - $T$  path.

397 The peak mineral assemblage,  $\text{Qz}+\text{Pl}+\text{Bt}+\text{Grt}+\text{Ky}+\text{Ms}+\text{Ilm}+\text{H}_2\text{O}$ , was constrained  
398 in the quadri-variant field delimited in the  $P$ - $T$  range of 620°C-675°C and 7-10 kbar. The  
399 optimal  $P$ - $T$  condition obtained is 676°C and 8.1 kbar with  $Q_{\text{cmp}}=92\%$  and  $Q_{\text{mode}}=95\%$   
400 (Fig. 11b). The mineral phases chemical composition of sample NESG-401 preserves three  
401 stages of the metamorphic path, the prograde, decompression, and cooling (Fig. 11b),  
402 which were traced using  $P$ - $T$  stability field maps (supplementary figure A6). The prograde  
403 path was traced taking into account the compositions of garnet mantle ( $Q_{\text{cmp}}=100\%$ ),  
404 which records early stages of amphibolite facies around 550-570°C and 8-9 kbar,

405 plagioclase core ( $Q_{\text{cmp}} = 100\%$ ), and white mica ( $Q_{\text{cmp}} = 85-80\%$ ). Indeed, the antidote  
406 optimal conditions calculations seem to underestimate the peak condition. The plagioclase  
407 core and white mica chemical composition provide a better constrain, crossing at *ca.*  
408  $660^{\circ}\text{C}-670^{\circ}\text{C}$  and 11.5-12 kbar, at these conditions,  $\text{Qz}+\text{Pl}+\text{Bt}+\text{Grt}+\text{Ky}+\text{Ms}+\text{Ilm}$  are the  
409 stable phases ( $M_{\text{AN}2}$  stage). An almost isothermal decompression is suggested based on the  
410 mineral modes ( $Q_{\text{mode}} = 95-100\%$ ) field of stability, which is at lower pressure of 6-8 kbar  
411 but at almost the same temperature range, from 625 to 680  $^{\circ}\text{C}$ . At last, garnet rim chemical  
412 composition ( $Q_{\text{cmp}} = 80\%$ ) provided information about the AN cooling stage. It is  
413 equilibrated at  $550^{\circ}\text{C}$  and 4.5 kbar in the stability field of  $\text{Qz}+\text{Pl}+\text{Grt}+\text{Bt}+\text{Ilm}+\text{St}+\text{Sil}$   
414 ( $M_{\text{AN}3}$  stage; Fig. 11b). The Ti-in-biotite thermometer map (supplementary figure A3c)  
415 displays temperatures ranging from 630 to 560  $^{\circ}\text{C}$ , in agreement with the retrograde  
416 temperature conditions obtained by ITM.

### 417 3.4 EMPA monazite petrochronology

418 To constrain the timing of the metamorphic and deformation events, *in-situ* U-(Th)-  
419 Pb monazite chemical dating was carried out by EMPA (e.g., Dumond et al., 2015;  
420 Williams and Jercinovic, 2002, 2012). The analytical procedures are described in appendix  
421 A.

#### 422 3.4.1 Sample NESG-388 – Liberdade Nappe

423 Monazites from sample NESG-388 are between quartz, plagioclase, white mica, and  
424 biotite from the matrix. Ten crystals were chosen to perform X-ray maps and trace element  
425 analysis. The results are illustrated in Fig. 12 and supplementary table A2. Most of the  
426 crystals display an elongated shape parallel to the mylonitic foliation, varying in size from  
427 70 to 250  $\mu\text{m}$ , except the Mnz 4, associated with ilmenite which shows an irregular lobate

428 shape. In some crystals, small quartz (e.g., Mnz 4, Mnz 5, and Mnz 6) inclusions were  
429 observed, but most of the monazites are inclusions free. The monazites display a sectorial  
430 core-rim internal zoning (e.g., Mnz 1, 2, 6 and 7). A remarkable feature that might be  
431 highlighted is the core and rim zonation pattern that is well-aligned (e.g., Mnz1, 2, 6, 8, and  
432 10) with the main foliation, suggesting a pre-to syn-mylonitic growth related to the rock  
433 fabric. In addition, the Mnz 7 occurred on the S-plane of a *S-C* fabric.

434 Three chemical domains are distinguished based on the X-ray maps, mainly of Y  
435 and Th distribution (Fig. 12a, b, and c). Domain 1, characterized by high-Th and low-Y  
436 cores, is small patchy (e.g., Mnz 9), and straight (e.g., Mnz 2). The Y<sub>2</sub>O<sub>3</sub> content (wt%)  
437 varies from 1.02 to 1.39, and the ThO<sub>2</sub> (wt%) values are very spread, ranging from 4.00 to  
438 6.95. Domain 2 is related to core characterized by low-Y and -Th. The Y<sub>2</sub>O<sub>3</sub> (wt%) and  
439 ThO<sub>2</sub> (wt%) amounts vary respectively in a narrow range of 0.93-1.22 and 2.29-3.80. The  
440 third domain (domain 3) is associated with monazite rims showing high-Y, in which the  
441 Y<sub>2</sub>O<sub>3</sub> (wt%) amounts are spread in a broad range from 1.62 up to 2.61, and ThO<sub>2</sub> (wt%)  
442 variation is concentrated between 3.18-3.59.

443 In total, 84 ~~punctual~~ EMPA spot analyses were acquired in the different chemical  
444 domains for chemical dating calculation. Obtained dates span from 640 to 540 Ma. Domain  
445 1, characterized by high-Th and low-Y core, dates range from 640±21Ma to 588±19 Ma.  
446 Domain 2, with low-Th and Y cores, has dates spread from 613 Ma±36 Ma to 550±33 Ma.  
447 Owing to the dates from domains 1 and domain 2 are relative to core, they were plotted in  
448 the same weighted average diagram (Fig. 12d) and yielded a mean age of 609±4 Ma (n=55;  
449 MSWD=1.6). Domain 3, related to high-Y rims, has dates from 590±28 Ma to 540±26 Ma  
450 and yields a mean weighted average age of 567±5 Ma (n=33; MSWD=1.19; Fig. 12e).

### 451 3.4.2 Sample NESG-401 – Andrelândia Nappe

452 Fig. 13a displays the mapped monazite crystals (n=8) from sample NESG-401, the  
453 elements analysis spots position, and the results of chemical dating. The monazites occur  
454 between the matrix minerals, hosted in quartz, plagioclase, biotite, and white mica ( Mnz 1,  
455 3 and 5), one crystal is enclosed in kyanite (Mnz 4), and three are located in apatite rims  
456 (Mnz 2, 5 and 8). The size of crystals varies from 50  $\mu\text{m}$  up to 100  $\mu\text{m}$ . Monazite shape  
457 varies from rounded to elongated. Quartz inclusions are observed in Mnz 1 and Mnz 7.  
458 Regarding the monazite compositional zoning, they are very homogenous. The crystals  
459 display intermediate  $\text{Y}_2\text{O}_3$  contents varying from 1.3 to 2.9 wt% and variable Th amounts,  
460 varying the  $\text{ThO}_2$  between 1.9 and 5.4 wt% (Fig. 13a, b, and c). The exception is  
461 represented by rims significantly enriched in Th (with  $\text{ThO}_2$  content between 6.7-13.1 wt%)  
462 observed in crystals associated with apatite (Fig. 13c).

463 A total of 56 ~~chemical spots~~ of EMPA **spot analyses** were carried out. The obtained  
464 U-(Th)-Pb chemical dates range from  $612\pm 23$  Ma to  $535\pm 28$  Ma. The dates are plotted in  
465 the weighted average diagram (Fig. 13d), and they yield a mean age of  $579\pm 6$  Ma  
466 (MSWD=3.5). Of particular interest is the crystal enclosed in kyanite (Mnz 4), which can  
467 report worthy information about tectonic and metamorphic events undergone by this rock  
468 since the kyanite is considered coeval with the  $S_2$  foliation. The dates vary from  $605\pm 22$  Ma  
469 to  $558\pm 25$  Ma and yield a mean age of  $589\pm 19$  Ma (MSWD=2.3; Fig. 13e).

## 470 4. DISCUSSION

### 471 4.1 Monazite chemical dating interpretation

472 The in-situ monazite dating combined with the X-ray ~~trace elements~~ maps (e.g., Y  
473 and Th) allows correlating monazite growth episodes with metamorphic reactions and

474 deformation stages (Bosse and Villa, 2019; Spear and Pyle, 2002; Williams and Jercinovic,  
475 2002, 2012). The Y and HREE concentration in monazite mostly depends on the garnet  
476 presence in the system, once this mineral is the preferential sink for these elements (Spear  
477 and Pyle, 2002). Whereas the Th concentration is controlled by a Th-rich phase breakdown  
478 responsible for releasing this element in the system, preferentially partitioned into monazite  
479 structure (Benetti et al., 2021; Kohn and Malloy, 2004; Williams et al., 2022). Moreover,  
480 monazite can be a fabric-forming mineral in deformed rocks and behaves as a  
481 porphyroclast rotated and with inclusion trails (Dumond et al., 2008, 2022). Therefore, the  
482 *in-situ* dating allows us to relate the monazite **chemical zonation** with its microstructural  
483 position, providing means to constrain the deformation time.

484 At sub-solidus conditions, two main metamorphic reactions will control the  
485 monazite chemistry. Firstly, the allanite breakdown is responsible for releasing most of the  
486 REE necessary for the monazite precipitation (Gasser et al., 2012; Janots et al., 2008; Kohn  
487 and Malloy, 2004; Spear and Pyle, 2010). This reaction occurs between the greenschist-to  
488 amphibolite facies transition, at temperature conditions around 550°C (Gasser et al., 2012;  
489 Janots et al., 2008; Spear and Pyle, 2010). **If monazite grows at these conditions before**  
490 **garnet growth, the monazite will display** ~~At these conditions, if monazite grows coeval or~~  
491 ~~previous than garnet is a stable phase, the monazite will display~~ intermediate- to high-Y  
492 **and HREE content.** In contrast, **when monazite grows in equilibrium with garnet, the**  
493 **monazite tends to be depleted in Y and HREE since these elements are strongly partitioned**  
494 **in garnet.** ~~if garnet is already a reactive phase, the Y will be partitioned toward it, and the~~  
495 ~~monazite will be Y-depleted~~ In addition, due to allanite being a Th-rich mineral, the  
496 monazite that grows soon after its breakdown tends to be Th-enriched (Benetti et al., 2021;

497 Kohn and Malloy, 2004). Another monazite generation is expected during the rock  
498 decompression path, in which garnet breakdown releases Y and HREE in the system, and  
499 the monazite precipitating from this reaction will display enriched signatures in these  
500 elements (Gasser et al., 2012; Kohn et al., 2005).

501           Considering the monazite behavior during the sub-solidus metamorphism and  
502 deformation described above, two episodes of ~~its~~ **monazite** growth can be identified in the  
503 sample NESG-388 from the Liberdade Nappe. The first episode is correlated with Y-  
504 depleted cores and a wide range of Th amounts (domains 1 and 2). These dates are  
505 associated with prograde metamorphism (**M<sub>LN1</sub> stage**) in which monazite grew **after** ~~post~~-  
506 garnet crystallization in the system and yielded mean chemical age of **6098±4** Ma. The Th-  
507 enriched domains (domain 1) can likely be linked to the early prograde **metamorphism**~~path~~  
508 (**early M<sub>LN1</sub> stage**), soon after the allanite-to-monazite transition, releasing Th in the system  
509 and reproducing the oldest dates. The weighted mean age of **567±5** Ma, represented by Y-  
510 enriched monazite rims (domain 3), is interpreted as linked with garnet resorption during  
511 the rock decompression (**M<sub>LN2</sub> and M<sub>LN3</sub>**). Furthermore, the growth orientation of some  
512 high-Y rims aligned with the S<sub>2</sub> foliation (e.g., Mnz 1 and 2), and the crystal in the S-C  
513 band (Mnz 7) rotated during the shearing suggest that the decompression was coeval with  
514 the development of the S<sub>2</sub> fabric related with the SE tectonic transport.

515           The monazites **grains** from the sample NESG-401 of the Andrelândia Nappe are  
516 homogenous with intermediate Y and Th-depleted. They are interpreted as growing coeval  
517 with the garnet during the prograde metamorphism (**M<sub>AN2</sub> stage**), at a minimum age of  
518 **579±6** Ma. The Mnz 4 is enclosed in kyanite and parallel to the AN S<sub>2</sub> fabric, providing  
519 time constraint for the foliation-forming deformation coeval with kyanite growth during the

520 *P-T* path. This single crystal yields mean age of  $589\pm 19$  (n=6), consequently interpreted as  
521 corresponding to the time of the  $S_2$  deformation, and taking into account the age standard  
522 deviation, is considered contemporary to the prograde metamorphism ( $M_{AN2}$  stage). Rims  
523 highly enriched in Th (Mnz 2, 5, and 8) are attributable to exchange reactions between  
524 apatite and monazite and have no signatures that can associate them with any significant  
525 tectono-metamorphic event.

#### 526 4.2 Tectono-metamorphic evolution of the Andrelândia Nappe System (ANS)

527 The microstructural descriptions, *P-T* path traced through thermodynamic  
528 metamorphic modeling, and monazite petrochronological data presented here help  
529 contribute to elucidate the complex ANS framework in the southern sector of the SBO. The  
530 Liberdade and Andrelândia Nappes evolved from a clockwise sub-solidus *P-T* path  
531 characterized by burial and heating, followed by nearly isothermal decompression, and  
532 lastly, cooling and decompression. The Liberdade Nappe (NESG-388)  $M_{LN1}$  stage  
533 assemblage (Qz-Pl-Grt-Bt-Ms-Ilm) records peak conditions at *ca.* 650°C and 9.5-10 kbar  
534 and has a minimum age of  $609\pm 4$  Ma (Fig. 14a). The peak conditions indicate that the LN  
535 rocks were buried by 36 km, corresponding to the middle and lower depth of a thickened  
536 crust with apparent geothermal gradient of 18°C/km (Fig. 14a). The further stages,  $M_{LN2}$   
537 (Qz-Pl-Grt-Bt-Ms-Ilm-Ky(?)) and the  $M_{LN3}$  (Qz-Pl-Grt-Bt-Ms-Ilm-Sil-St), represent  
538 respectively the isothermal decompression and decompression/cooling episodes related to  
539 the LN migration toward SE, whose the minimum age is constrained at  $567\pm 5$  Ma (Fig.  
540 14a).

541 The Andrelândia Nappe sample (NESG-401) records a burial and heating episode in  
542 the kyanite stability field during the prograde metamorphism, from ~550°C and 9.0-9.5

543 kbar up to ~680 °C and 11-12 kbar ( $M_{AN2}$  stage; Fig. 14a). The *P-T* data suggest an  
544 apparent geothermal gradient of 16°C/km and burial into crustal depths of 43 km (Fig. 14a).  
545 The minimum age for the prograde metamorphism was estimated at  $579 \pm 6$  Ma, and within  
546 the uncertainties is considered coeval with the  $S_2$  deformation event underwent by this rock.  
547 It was followed by an almost isothermal decompression, in which the pressure conditions  
548 decreased from 12 kbar down to 8.0-7.0 kbar (Fig. 14a). Lastly, the  $M_{AN3}$  stage related to  
549 staurolite and sillimanite appearance in the system was constrained in the *P-T* range of 670-  
550 550°C and 8.0-4.5 kbar (Fig. 14a).

551 A compilation of literature *P-T* paths from the Andrelândia and Liberdade Nappes is  
552 provided in Fig. 14a. ~~Even though the Different approaches were adopted by Coelho et al.~~  
553 ~~(2017), Motta and Moraes (2017), Reno et al. (2012), and Santos et al. (2004) the other~~  
554 ~~authors, such as (e.g., inverse and forward thermodynamic modeling. and~~ Considering the  
555 different methods-related uncertainties, peak conditions constrained for the Andrelândia  
556 and Liberdade Nappes in this contribution agree with those previously reported by ~~Coelho~~  
557 ~~et al. (2017), Motta and Moraes (2017), Reno et al. (2012), and Santos et al. (2004).~~  
558 However, there are differences between the *P-T* path traced here and those interpreted by  
559 these authors. For instance, Reno et al. (2021) suggested two episodes of isobaric cooling  
560 separated by a near-isothermal decompression phase to the Carmo da Cachoeira Nappe, the  
561 Andrelândia Nappe equivalent in the SBO northern sector. Moreover, Santos et al. (2004)  
562 considered that Andrelândia Nappe underwent heating during ~~decompression~~ exhumation,  
563 while the Liberdade Nappe evolved from an isothermal decompression. These *P-T* path  
564 contrasts can be assigned to different interpretations regarding blastesis-deformation  
565 relationships and distinct approaches used by each of the authors and the present work.

566 Fig. 14b is a summary of the available metamorphic ages for the Andrelândia and  
567 Liberdade Nappes using monazite and zircon U-Pb geochronology techniques. The oldest  
568 ages of the Liberdade Nappe, at *ca.* 680-670 Ma, reported by Campos Neto et al. (2011)  
569 and Reno et al. (2009), are related to metamafic rocks and interpreted as the HP  
570 metamorphism age experienced by these rocks. Regarding the LN and AN micaschists and  
571 gneisses, the previously published ages by Coelho et al. (2017), Frugis et al. (2018),  
572 Marimon et al (2022), Motta and Moraes (2017), and Westin et al. (2021) and those  
573 reported in this work are widespread in a time range *ca.* 60 Ma, from 630 to 570 Ma. The  
574 geochronology data from the literature, calculated by different methods (e.g., isocron age,  
575 concordia age, and weighted average age), are comprised within the spread of chemical  
576 dates acquired here. **However, in this study, the monazite petrochronology results indicate**  
577 **that each nappe experienced episodic growth during a single metamorphic cycle of burial**  
578 **(prograde metamorphism) and decompression (retrograde metamorphism), rather than**  
579 **being affected by polymetamorphism events.**

#### 580 4.3 *Tectonic implications*

581 Our present findings shed new light on some critical points regarding the tectono-  
582 metamorphic events experienced by the ANS. The first point is related to the Andrelândia  
583 and Liberdade Nappes *P-T* paths. Microstructural observations and thermodynamic  
584 modeling show that the staurolite and sillimanite in the matrix are related to decompression  
585 and cooling stages. Furthermore, the suggested metamorphic paths to the LN and AN  
586 pointed out that the baric and thermic peaks occur almost simultaneously. These  
587 information **in conjunction with monazite petrochronology** indicate that likely **each one of**

588 the nappes ~~these rocks~~ underwent a single metamorphic ~~eye~~ **loop** of burial and  
589 decompression.

590 The second critical point concerns the ~~time~~ **timing** constraints of metamorphism and  
591 deformation. The Liberdade Nappe attained prograde, amphibolite facies, within the  
592 kyanite stability field at minimum age of *ca.* 610 Ma, nearly 30 Ma before the Andrelândia  
593 Nappe (Fig. 15 b, c, and d). Although the sample from Andrelândia Nappe does not have  
594 dates related to exhumation, the spread dates from the Liberdade Nappe linked with the  
595 exhumation mostly overlap the prograde monazite dates in the Andrelândia Nappe,  
596 structurally below. Hence, it is possible to claim that when the Liberdade Nappe onset its  
597 decompression path, the Andrelândia Nappe was still experiencing prograde conditions and  
598 was likely exhumed afterward compared to the Liberdade Nappe (Fig. 15c). In other words,  
599 the dates younger than 610 Ma in the Liberdade Nappe are related to its exhumation and  
600 tectonic transport toward SE (Fig. 15c and d). In contrast, this time span is linked with  
601 prograde burial metamorphic conditions (coeval with kyanite growth) in the Andrelândia  
602 Nappe (Fig. 15c). The Pouso Alto Nappe, the upper structural level of the ANS in the  
603 southern part of the SBO, yields a minimums age of *ca.* 620 Ma and of *ca.* 610 Ma, for  
604 respectively the prograde metamorphism, and melt crystallization related to cooling and  
605 decompression (Fig. 15a and b; Benetti et al., in prep; Benetti, 2022). Therefore, the spread  
606 of ages from 630 Ma to 570 Ma (Fig. 15) within the ANS records a ~~temporal~~ **pattern of age**  
607 **decrease**, toward lower structural levels, ~~variation of when the nappes attended their~~  
608 prograde and retrograde metamorphic ages ~~stage~~ during the protracted metamorphism of  
609 the SBO ~~and follow a pattern of progressive decrease toward lower structural levels of the~~  
610 ~~system~~ (Fig 15). The spatial arrangement and decrease of the metamorphic ages toward the

611 bottom of the ANS stack outline an in-sequence fold-and-thrust architecture of the orogenic  
612 wedge (Fig. 15). This ANS framework would have been developed through the inner  
613 material incorporated at the wedge being detached, shortened, and propagated over the  
614 incoming material, similar to what is proposed by Platt (1986) to the dynamics of orogenic  
615 wedges. Then, the rocks from the older nappes (i.e., Liberdade Nappe) were decompressed  
616 via thrust and folding over the younger ones (i.e., Andrelândia Nappe) that likely  
617 experienced their peak metamorphism as a consequence of loading of the overlying nappe.  
618 Analogue in-sequence fold-and-thrust architectures are described in other orogenic belts  
619 such as the Caledonian, Trans-Hudson, Grenville, Himalayan, and Appalachian orogens  
620 (Beaumont et al., 2006; Carosi et al., 2016; Weller et al., 2021). This suggests that the  
621 mechanism described above is an important mechanism controlling the structural and  
622 metamorphic style of collisional wedges. Fig. 15 illustrates the proposed tectono-  
623 metamorphic evolution for the nappes of the Southern Brasília Orogen. The collision-  
624 related metamorphic event evolved from 630 to 570 Ma based on zircon, monazite, and  
625 titanite U-Pb ages and monazite-EPMA ages (Campos Neto et al., 2010; Coelho et al.,  
626 2017; Frugis et al., 2018; Fumes et al., 2021; Li et al. 2021; Marimon et al., 2020, 2022;  
627 Motta et al., 2021; Rocha et al., 2017; Westin et al., 2021, submitted). The Andrelândia  
628 Nappe System underwent high-pressure metamorphic conditions during the collision  
629 between the São Francisco (passive margin) and Paranapanema (active margin) paleoplates  
630 (Fig. 15). The crustal material was stored and sunk within the orogenic wedge hinterland  
631 until 620 Ma when the first nappe of the system, the Pouso Alto, started its decompression  
632 path with tectonic transport toward northeast (Fig. 15a and b). After ca. 610 Ma, the  
633 Liberdade Nappe follows an upward flow toward east/southeast, laterally to the south  
634 margin of the São Francisco Craton, over the Andrelândia Nappe (Fig. 15c). The final stage

635 of the SBO continental collision took place after 580-570 Ma, coeval with the  
636 decompression and exhumation path of the Andrelândia and Carrancas Nappes (Fig., 15d;  
637 Campos Neto et al., 2010, 2020; Carvalho et al., 2020; Cioffi et al., 2019; Coelho et al.,  
638 2017; Frugis et al., 2018; Reno et al., 2009, 2012, Tedeschi et al., 2017; Westin et al., 2021,  
639 submitted).

## 640 5. CONCLUSION

641 The *P-T-t-D* data provided here document the metamorphic and deformation history  
642 of the Andrelândia and Liberdade Nappes. The Liberdade Nappe experienced prograde  
643 burial metamorphism at *ca.* 610 Ma and achieved peak conditions at ~650°C and 9.5-10  
644 kbar. This stage was followed by a near-isothermal decompression and further cooling with  
645 a minimum age of *ca.* 570 Ma. Meanwhile, the Andrelândia Nappe structurally below the  
646 Liberdade Nappe underwent prograde metamorphism nearly 30 Ma later, at *ca.* 580 Ma,  
647 reaching the peak condition at *ca.* 680°C and 11.5-12 kbar. The data document an in-  
648 sequence fold-and-thrust architecture, in which the metamorphic ages decrease toward  
649 lower structural levels of the stack. This framework would have evolved through older  
650 material incorporated into the inner parts of the orogenic wedge has been detached and  
651 propagated via thrust-and-fold nappes upon recently accreted rocks, leading to a younger  
652 metamorphism event on **the footwall of the ductile thrust** ~~external parts of the wedge.~~

## 653 APPENDIX A – ANALYTICAL METHODS

654 The equipment employed in the trace elements, quantitative mineral analyses, and  
655 compositional maps is a JEOL JXA-8230 Electron Probe Micro Analyzer (EPMA)  
656 equipped with five wavelengths dispersive spectrometry (WDS) detectors hosted at the  
657 Department of Geology at the State of São Paulo University (UNESP). The compositional

658 maps were obtained through X-rays maps, which were further classified and calibrated  
659 using the internal standardization procedure and the pseudo-background correction  
660 available in the XMapTools 3.4 (Lanari et al., 2014, 2019). The X-ray maps for Mg, Na,  
661 Ca, K, and Fe were acquired by the WDS detectors, whereas for Al, Si, P, S, Ti, Mn, and Zr  
662 by the energy dispersive-spectrometry (EDS). The x-ray maps were carried out with an  
663 accelerating voltage of 15Kv, a current beam of 100nA, and a dwell of 100 ms.  
664 Representative analysis of silicates obtained within the X-maps perimeter used for the  
665 calibrations are available in the supplementary table file A1.

666 Monazite U-(Th)-Pb chemistry dating was performed using the same equipment  
667 cited above. The crystals were first identified through full thin-sections maps acquired  
668 using the Scanning Electron Microscopy and Mineral Liberation Analyzer (SEM-MLA).  
669 Considering the monazite structural position and textural relationships some crystals were  
670 selected to perform high-resolution compositional X-ray maps of Y, Al, Th, U, Pb, Si, Ca,  
671 Fe, La, and Ce. The acquisition conditions were 15 kV, 100 nA, 100 ms dwell time, and 10  
672  $\mu\text{m}$  electron beam size and step. Trace elements spots analyses were performed in the  
673 different domains identified with helping of the X-ray maps. The analytical procedure  
674 follows the strategies of Fumes et al. (2021). The moacyr monazite standard was used after  
675 each 10 to 20 punctual analyses, and their results are displayed in the supplementary figure  
676 file A7. The background was estimated in all analyzed spots. Spectral interference  
677 corrections considered matrix correction factors and were performed offline. Interference  
678 corrections and age calculations were performed using the Age\_Cor program (Vlach,  
679 2010). The dates were plotted in the weighted average diagram using the Isoplot program  
680 (Ludwig, 2008).

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### 1013 **FIGURES CAPTIONS**

1014 Figure 1 - a) Western Gondwana reconstruction by Westin et al. (2021). The blue square  
1015 marks the cratonic blocks involved in the Southern Brasilia Orogen (SBO) development.  
1016 (1) Transbrasiliano-Kandi Lineament. Continental cratons: A-Amazon; CC- Congo; KA-  
1017 Kazai; LA- Luis Alves; P- Pampia; Pp- Paranapanema; Pb- Parnaíba; WA-RA- Ria Apa;  
1018 RP- Rio de la Plata; SH- Sahara; SF- São Francisco; SL- São Luis; b) Orogenic belts of  
1019 Central and Southeast Brazil (Westin et al., 2021). Red square is the SBO position.

1020 Figure 2 - Southern Brasilia Orogen (SBO) tectonic map modified after Campos Neto et al.  
1021 (2020). The black square marks the study area location.

1022 Figure 3 – Cross-section A-B (see Fig. 2) illustrating the tectonic architecture of the south  
1023 sector of the Southern Brasilia Orogen.

1024 Figure 4 - a) Geological map of Pouso Alto county; b) Geological cross-section of the area  
1025 and stereographic projections of collected structural data.

1026 Figure 5 - Blastesis-deformation relationships in the Liberdade and Andrelândia Nappes.

1027 Figure 6 - Liberdade Nappe (LN) photomicrographs. a) Spaced disjunctive schistosity ( $S_2$ )  
1028 defined by biotite and white mica shape preferential orientation (SPO). Quartz displays  
1029 moderately irregular contacts (UTM 521535/7560145); b) Skeletal garnet and decussate  
1030 fibrolite (UTM 521535/7560145); c) Garnet porphyroblast with S-shaped internal foliation  
1031 (UTM 521535/7560145); d) Garnet pseudomorph replaced completely by fibrolite (UTM  
1032 521535/7560145); e) Isoclinal fold marked by fibrolite orientation (UTM 519472/  
1033 7549550); f) Kyanite relic overgrown by white mica (UTM 5110028/7561820).

1034 Figure 7 - Quantitative compositional maps for the sample NESG-388 of the Liberdade  
1035 Nappe: a) Mineral map of the investigated thin-section area showing the mineral phases in  
1036 the mapped area; b) Anorthite (XAn) content in plagioclase map; c)-f) Almandine (XAlm),  
1037 grossular (XGrs), pyrope (XPrp) and spessartine (XSps) zoning in garnet. The red circles  
1038 indicate the area used to perform the  $Q_{cmp}$  maps for garnet, and plagioclase (core and rim).

1039 Figure 8 - Andrelândia Nappe (AN) photomicrographs. a) Compositional banding,  
1040 alternating layers made by quartz and plagioclase, and those constituted by white mica and  
1041 biotite with subordinate garnet and kyanite (UTM 513937/7565930); b) Garnet  
1042 porphyroblast with opaque inclusion trails defying the internal foliation (Pre- $S_2$ ), and  
1043 kyanite aligned according to the external  $S_2$  foliation (UTM 516960/7565691); c) Fibrolite  
1044 growth along a shear bands (UTM 516960/7565691); d) Garnet with opaque inclusion trails  
1045 oblique to the external foliation (post- $S_2$ ) made by sillimanite, quartz, and biotite. Staurolite

1046 with internal foliation continuous with the external one. Note the fibrolite replacing biotite  
1047 crystals (UTM 516960/7565691).

1048 Figure 9 - Quantitative compositional maps for sample NESG-401 of the Andrelândia  
1049 Nappe; a) Mineral map of the investigated thin-section area showing the mineral phases in  
1050 the mapped area; b) Anorthite (XAn) content in plagioclase map; c)-f) Almandine (XAlm),  
1051 grossular (XGrs), pyrope (XPrp) and spessartine (XSps) zoning in garnet. The red circles  
1052 indicate the area used to perform the  $Q_{\text{cmp}}$  maps for garnet (mantle and rim), and  
1053 plagioclase (core and rim).

1054 Figure 10 – a)  $P$ - $T$  isochemical phase diagram in the MnNCKFMASHT system for the  
1055 Liberdade Nappe (NESG-388); b)  $P$ - $T$  path based on optimal conditions of mineral  
1056 chemistry composition ( $Q_{\text{cmp}}$ ) and mode ( $Q_{\text{mode}}$ ) maps. The red star corresponds to the  
1057 optimal  $P$ - $T$  conditions obtained by the antidote.

1058 Figure 11 – a)  $P$ - $T$  isochemical phase diagram in the MnNCKFMASHT system for the  
1059 Andrelândia Nappe (NESG-401); b)  $P$ - $T$  path based on optimal conditions for mineral  
1060 chemistry composition ( $Q_{\text{cmp}}$ ) and mode ( $Q_{\text{mode}}$ ) maps. The red star corresponds to the  
1061 optimal  $P$ - $T$  conditions obtained by the antidote.

1062 Figure 12– Liberdade Nappe (sample NESG-388): a) BSE images, X-ray maps (Y and Th)  
1063 of monazites showing structural position, textural relationships, and internal zoning; b)  
1064  $Y_2O_3$  (wt%) vs. age plot; c)  $ThO_2$  (wt%) vs. age plot; d) weighted average diagram for  
1065 monazite core dates (domain 1 and 2); e) weighted average diagram for monazite rim dates  
1066 (domain 3).

1067 Figure 13 – Andrelândia Nappe (sample NESG-401): a) BSE images, X-ray maps (Y and  
1068 Th) of monazites showing structural position, textural relationships, and internal zoning; b)  
1069  $Y_2O_3$  (wt%) vs. age plot; c)  $ThO_2$  (wt%) vs. age plot; d) weighted average diagram for  
1070 monazite core dates; e) weighted average diagram for monazite enclosed in Ky.

1071 Figure 14 – a) Summary of Andrelândia Nappe System (ANS)  $P$ - $T$  paths. Grey dotted lines  
1072 display different geothermal gradients trends. Solidus curve from Spear et al. (1999) in the  
1073 NaKFMASH system; b) summary of the monazite and zircon U-Pb metamorphic ages from  
1074 the Liberdade and Andrelândia Nappes.

1075 Figure 15 – Tectono-metamorphic model for the evolution of the SBO nappes. a) 630 to  
1076 620 Ma: Early prograde metamorphism in the collisional wedge and Pouso Alto Nappe  
1077 burial and heating stage; b) 620 to 610 Ma: Onset of the decompression path in the  
1078 collisional wedge. Pouso Alto Nappe decompression and melt crystallization stage, while  
1079 the Liberdade Nappe was buried and heated; c) 610 to 580 Ma: Liberdade Nappe onset its  
1080 upward isothermal decompression path over the Andrelândia Nappe, which was heated and  
1081 buried; d) <580-570 Ma: Final stage of the SBO continental collision coeval with the  
1082 Andrelândia and Carrancas Nappes decompression and cooling stages. The  $P$ - $T$ - $t$  paths are  
1083 based on Benetti. (2022), Campos Neto et al. (2021), Coelho et al. (2017), Fumes et al.,  
1084 (2021), Li et al. (2021), Marimon et al. (2020, 2022), Motta and Moraes (2017), Motta et al.  
1085 (2021), Rocha et al. (2017), Westin et al. (2021, ~~submitted~~).

#### 1086 **SUPPLEMENTARY FIGURE FILE A**

1087 Figure A1 - Full thin-sections maps acquired using the Scanning Electron Microscopy and  
1088 Mineral Liberation Analyzer (SEM-MLA). The black square represents the local bulk

1089 composition (LBC) investigated. a) Sample NESG-388 from Liberdade Nappe; b) Sample  
1090 NESG-401 from Andrelândia Nappe.

1091 Figure A2 – Quantitative compositional maps for the sample NESG-388 from Liberdade  
1092 Nappe. a) Map of Ti content in biotite (a.p.f.u); b) Map of #Mg in biotite; c) Map of Ti in  
1093 biotite thermometer of Henry et al. (2005); d) Map of  $\text{Si}^{+4}$  content in white mica (a.p.f.u).  
1094 Red circle indicates the area used to perform the  $Q_{\text{cmp}}$  maps.

1095 Figure A3 – Quantitative compositional maps for the sample NESG-401 from Andrelândia  
1096 Nappe. a) Map of Ti content in biotite (a.p.f.u); b) Map of #Mg in biotite; c) Map of Ti in  
1097 biotite thermometer of Henry et al. (2005); d) Map of  $\text{Si}^{+4}$  content in white mica (a.p.f.u).  
1098 Red circle indicates the area used to perform the  $Q_{\text{cmp}}$  maps.

1099 Figure A4- Maps of quality factors by Antidote for Liberdade Nappe. a)  $Q_{\text{asm}}$ ; b)  $Q_{\text{mode}}$ ; c)  
1100  $Q_{\text{cmp}}$  for the LBC bulk composition; d)  $Q_{\text{cmp}}$  for garnet composition; e)  $Q_{\text{cmp}}$  for plagioclase  
1101 core composition; f)  $Q_{\text{cmp}}$  for plagioclase rim composition; g)  $Q_{\text{cmp}}$  for white mica  
1102 composition; h)  $Q_{\text{cmp}}$  for biotite composition.

1103 Figure A5- a)  $P$ - $T$  isochemical phase diagram in the MnNCKFMASHT system for the  
1104 Andrelândia Nappe (NESG-401) for LBC including garnet core composition; b) Map of  
1105 quality factor  $Q_{\text{cmp}}$  by Antidote for AN garnet core composition.

1106 Figure A6 - Maps of quality factors by Antidote for Andrelândia Nappe. a)  $Q_{\text{asm}}$ ; b)  $Q_{\text{mode}}$ ;  
1107 c)  $Q_{\text{cmp}}$  for the LBC bulk composition; d)  $Q_{\text{cmp}}$  for garnet mantle composition; e)  $Q_{\text{cmp}}$  for  
1108 garnet rim composition; f)  $Q_{\text{cmp}}$  for white mica composition; g)  $Q_{\text{cmp}}$  for plagioclase core  
1109 composition; h)  $Q_{\text{cmp}}$  for plagioclase rim composition; i)  $Q_{\text{cmp}}$  for biotite composition.

1110 Figure A7 – Weighted mean plot for Moacyr monazite standard.

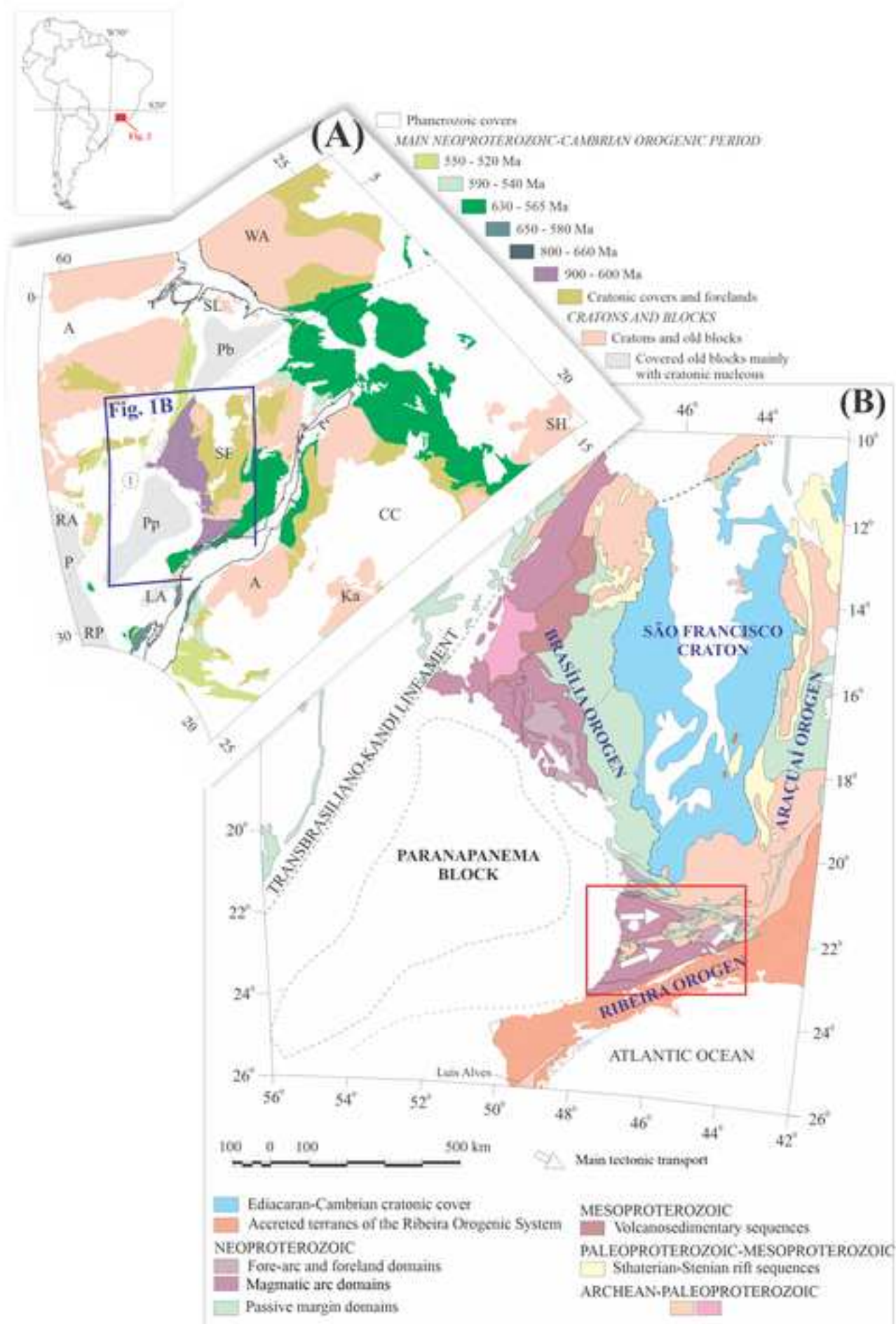
1111 **SUPPLEMENTARY TABLE FILE A**

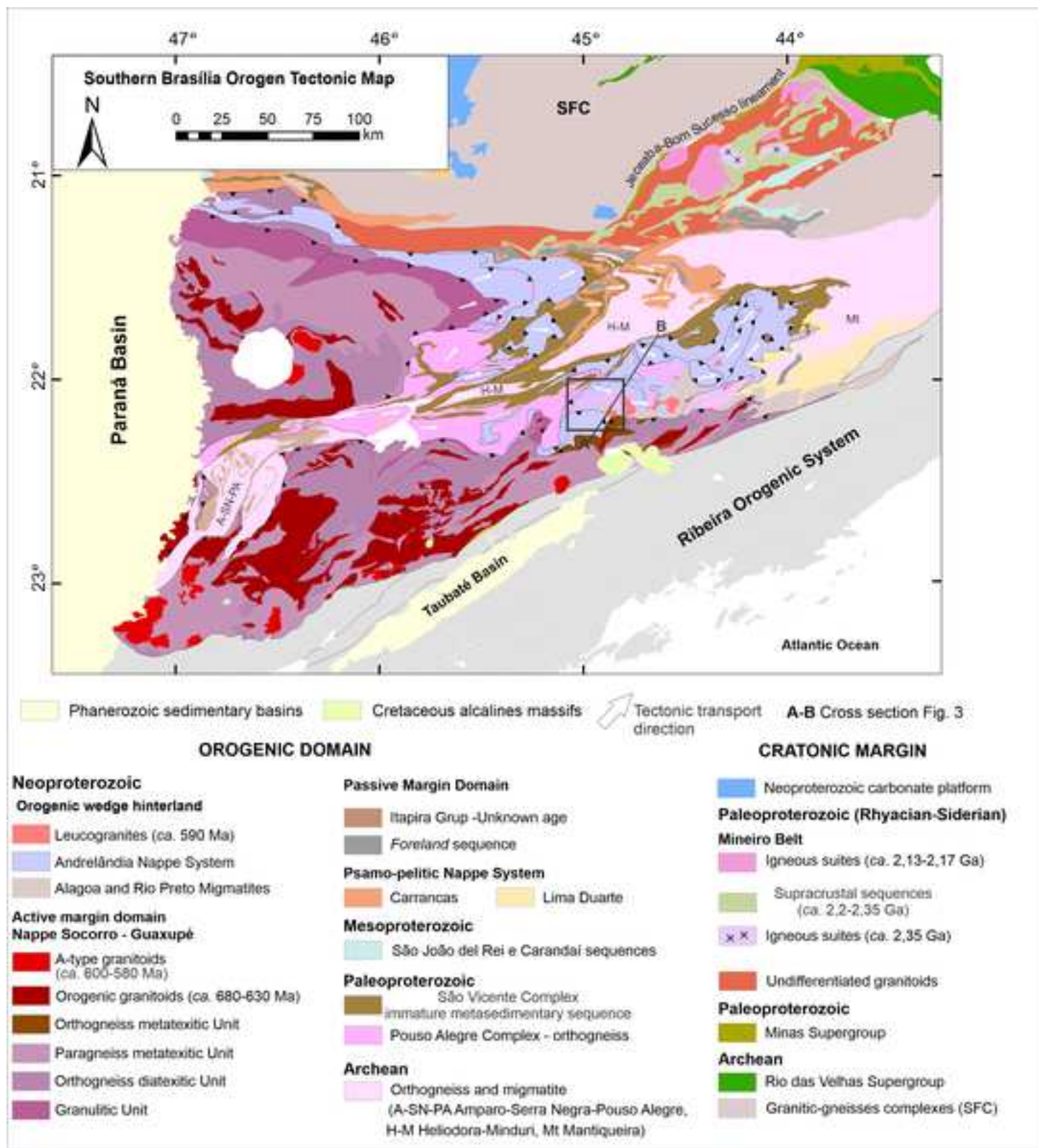
1112 Table A1- Representative Electron Microprobe (EMP) analyses of minerals from samples

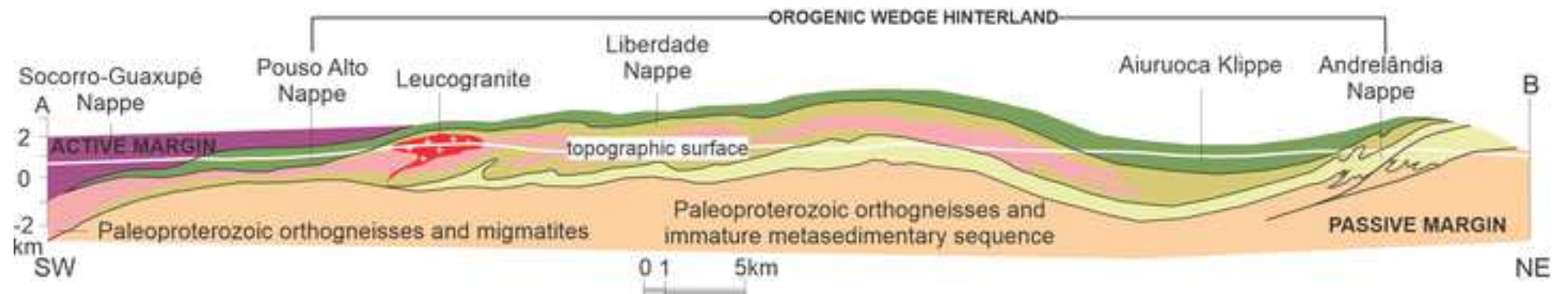
1113 NESG-388 and NESG-401. (b.d.l. - below detection limit).

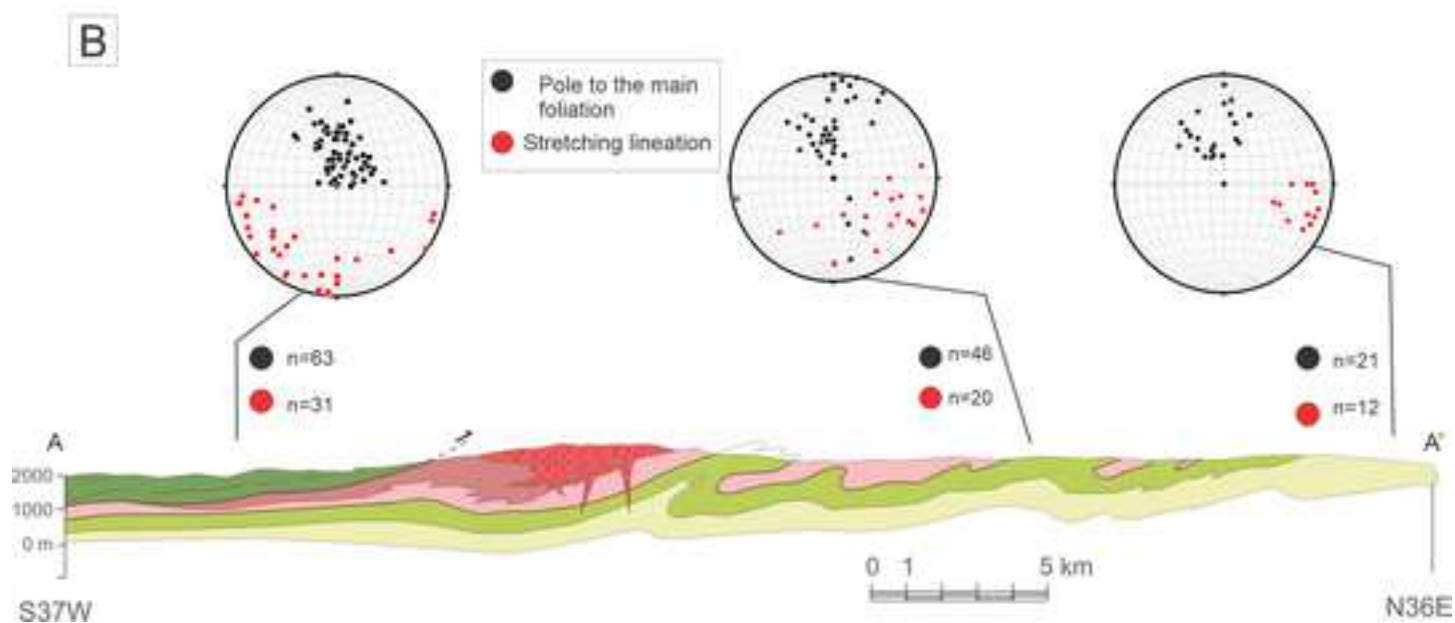
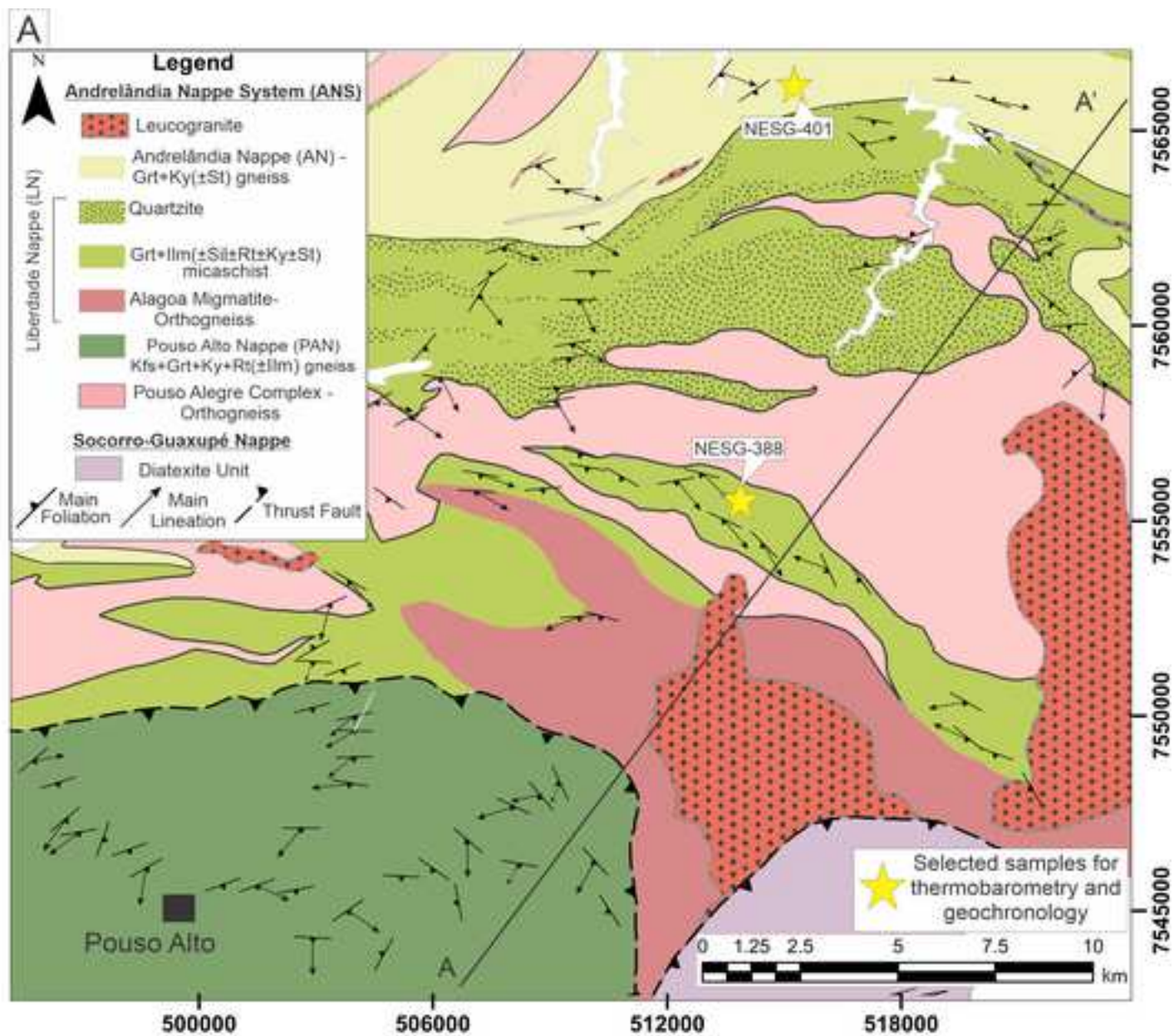
1114 Table A2 - Monazite chemical composition from sample NESG-388 and NESG-401

1115 (normalized to 4O), (b.d.l- below detection limit).

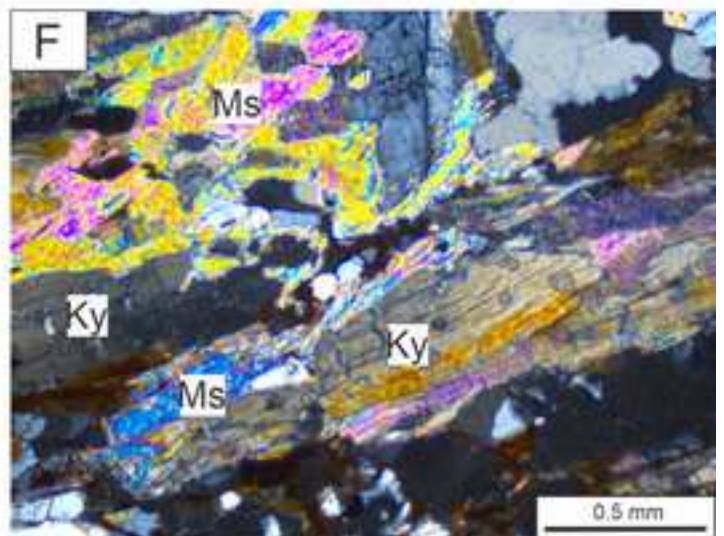
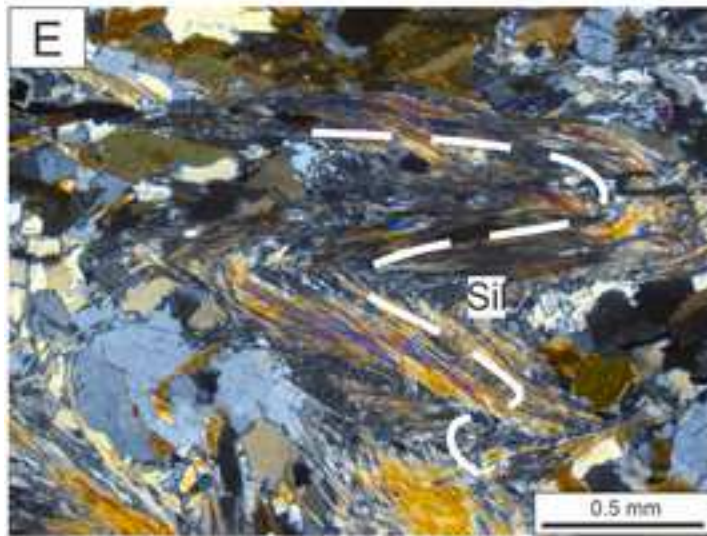
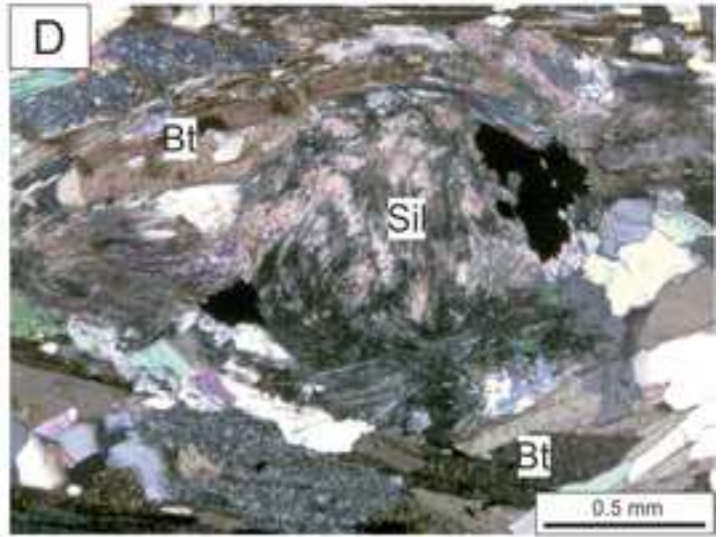
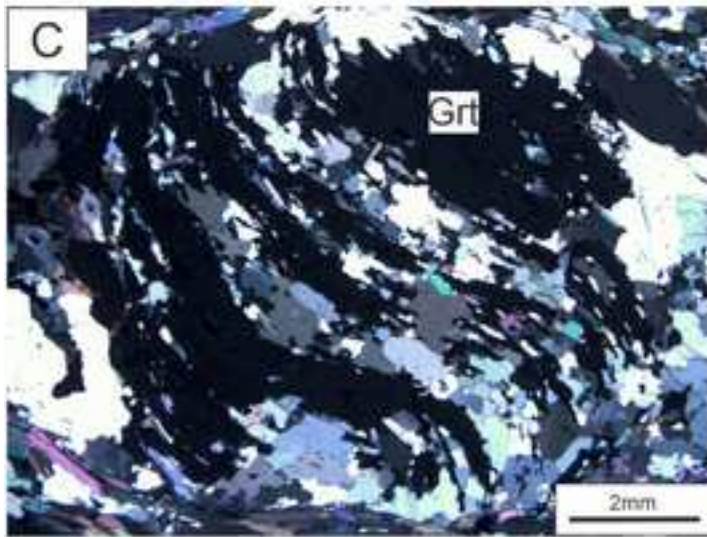
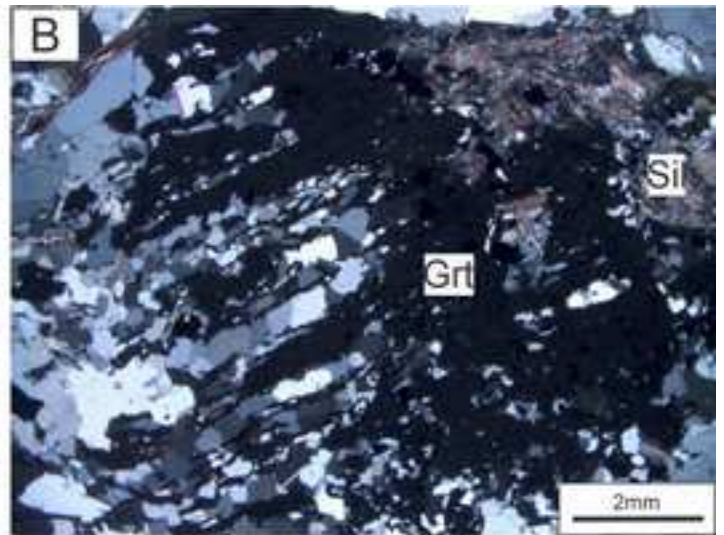
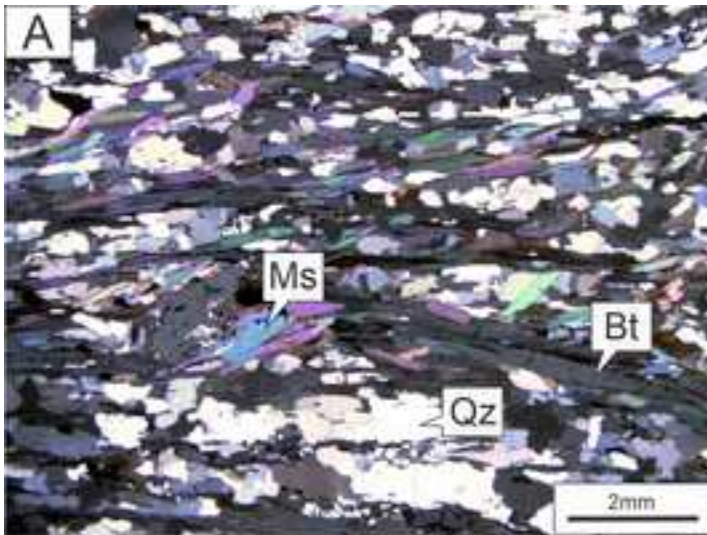


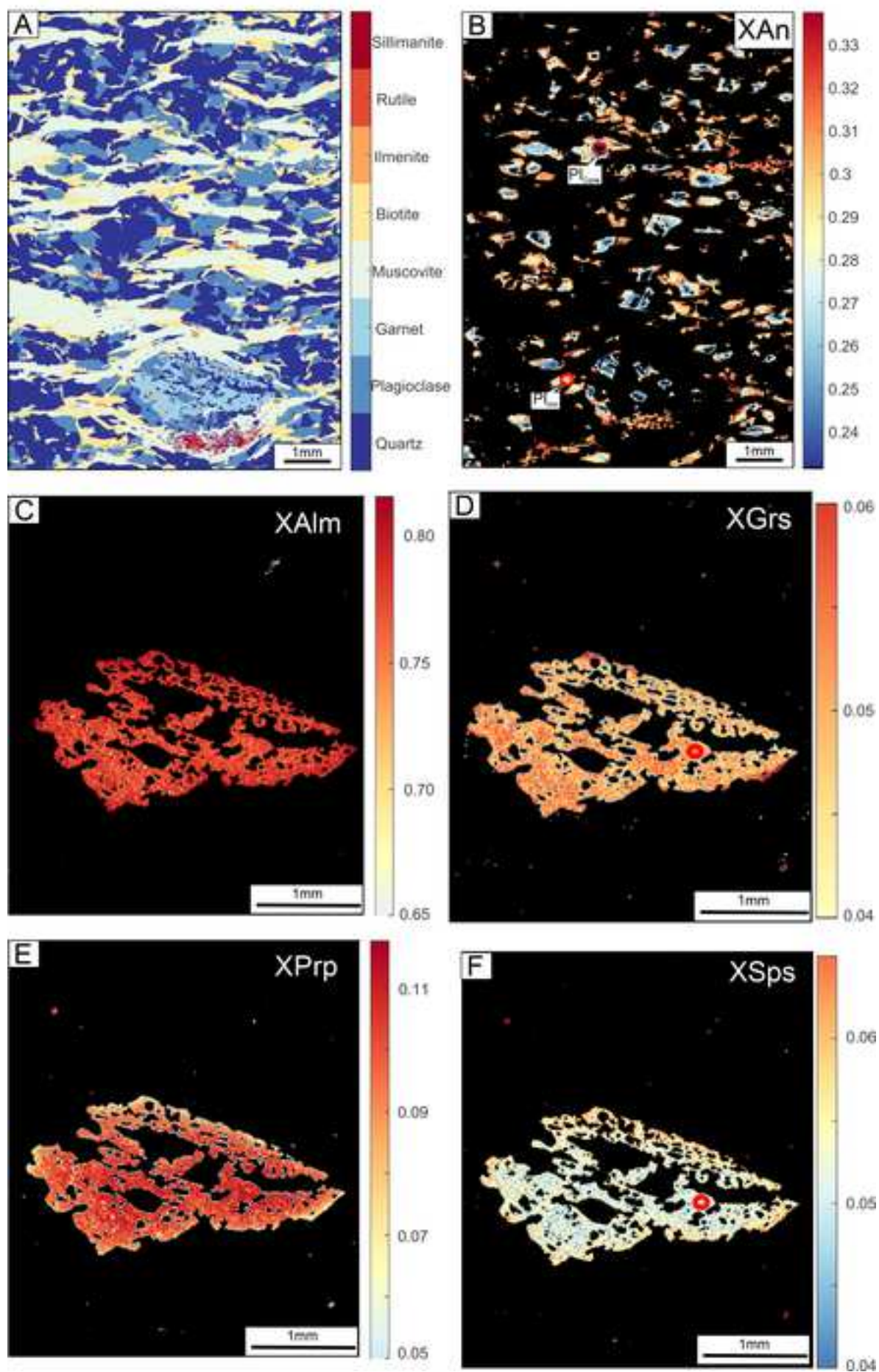


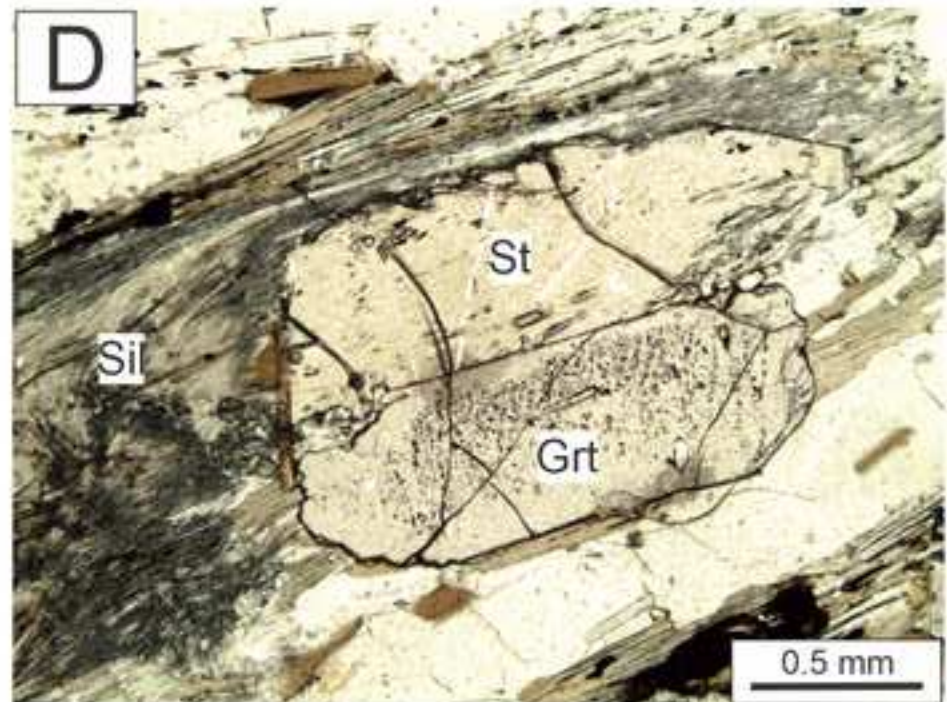
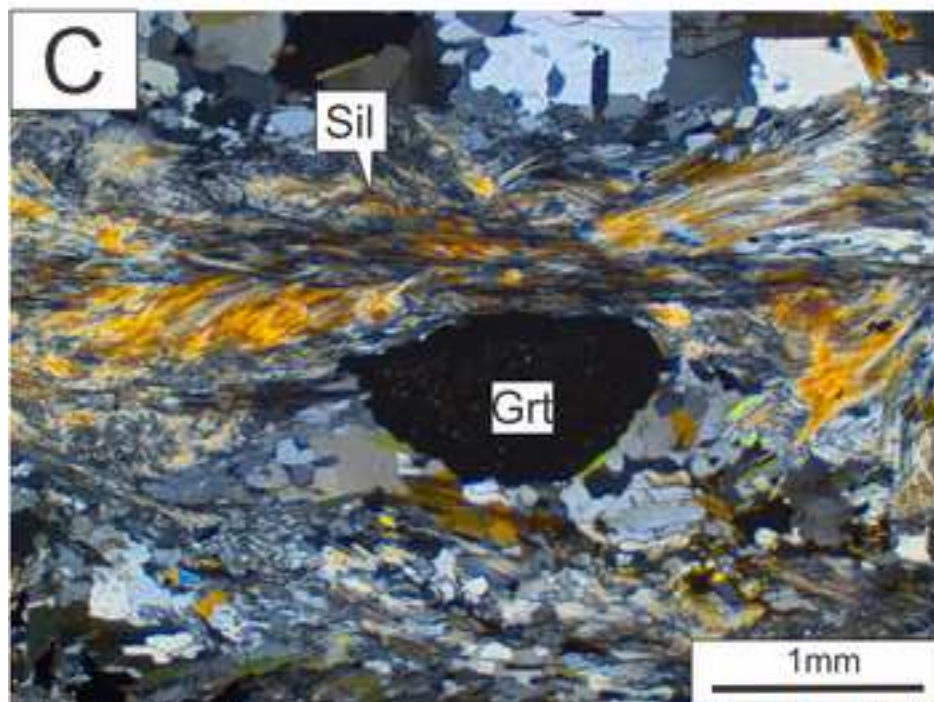
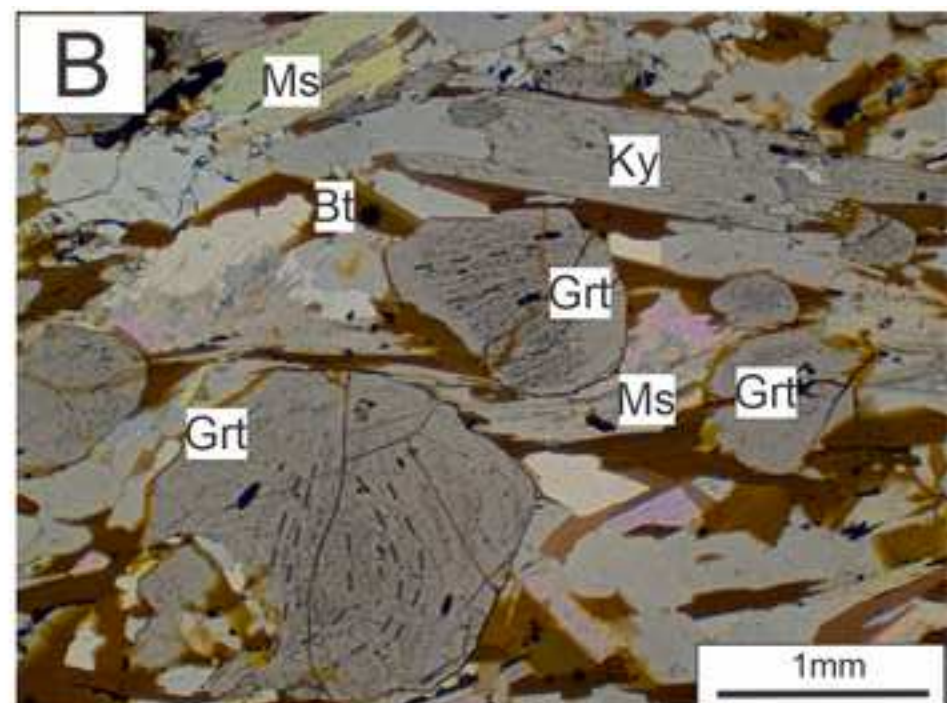
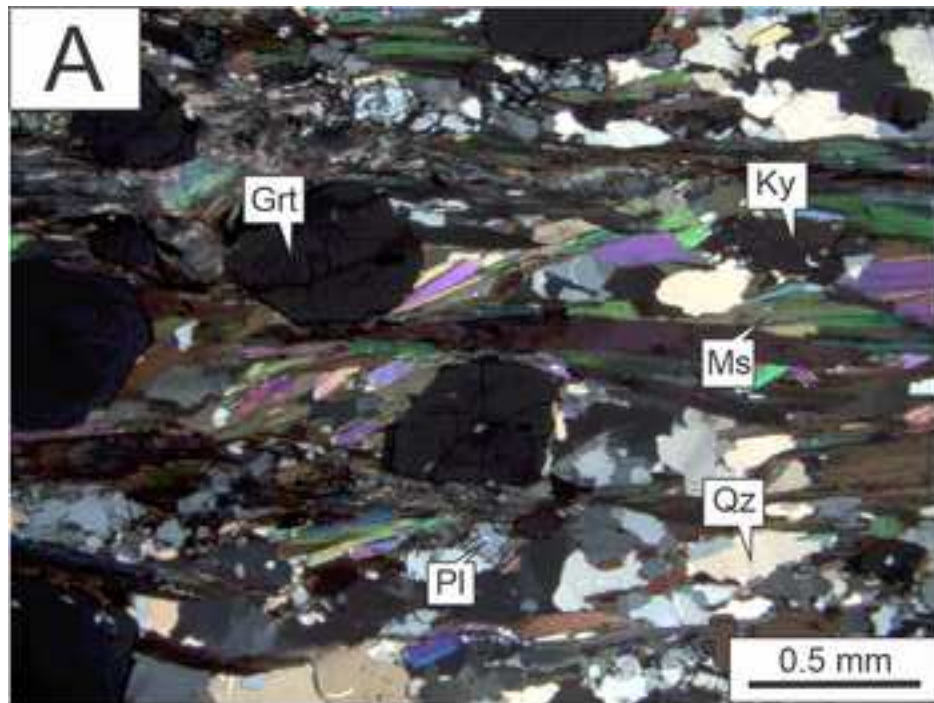




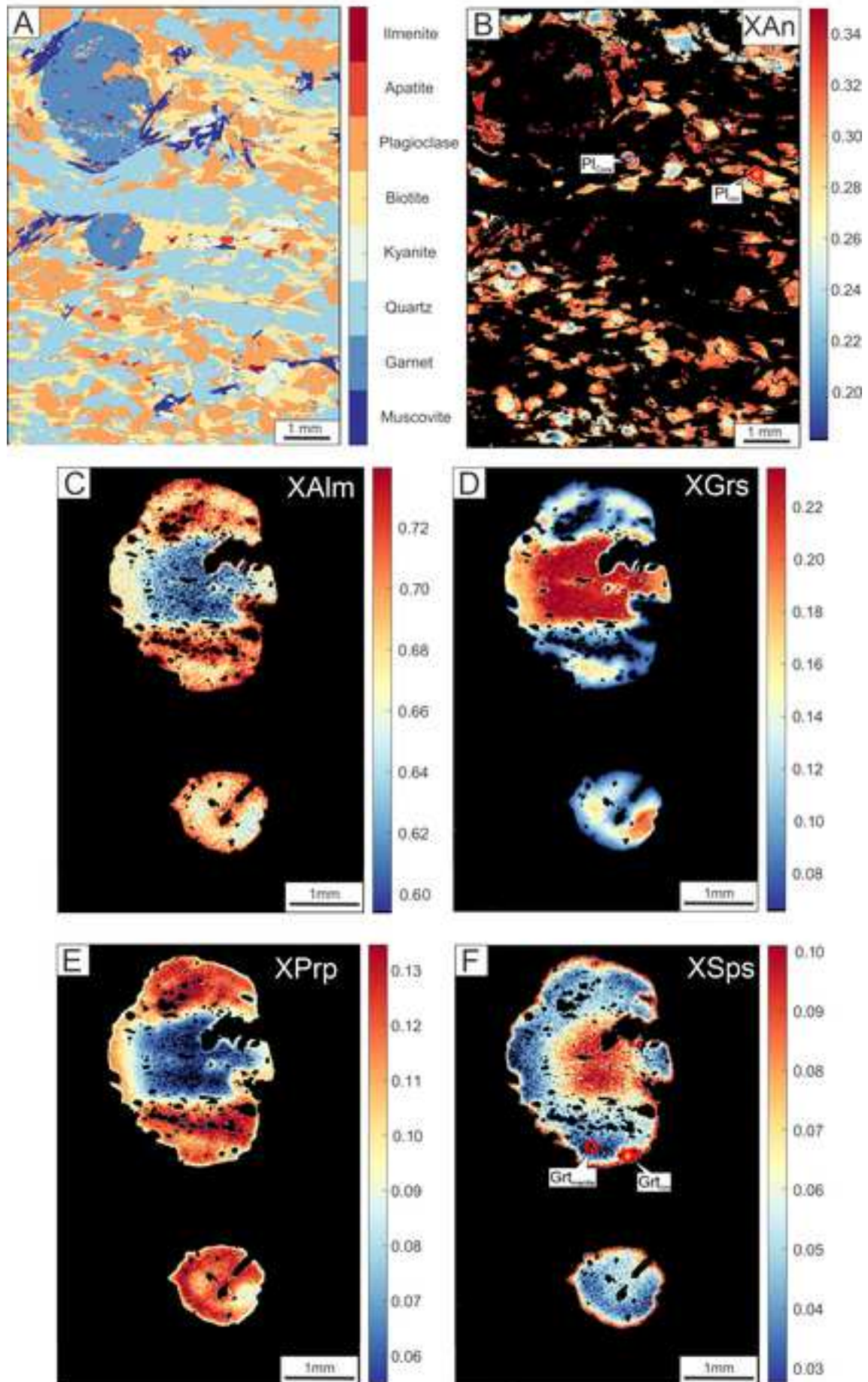
	Phase	$M_{LN1}$ (Pre-S <sub>2</sub> )	$M_{LN2}$	$M_{LN3}$ (Syn-S <sub>2</sub> )
Liberdade Nappe	Qz	—————	—————	—————
	Pl	—————	—————	—————
	Ms	—————	—————	—————
	Bt	—————	—————	—————
	Grt	—————	—————	- - - - -
	Ky	—————	————— ?	- - - - -
	Sil			—————
	St			—————
	Ilm		—————	—————
	Rt	- - - - -		
			$M_{AN1}$ (Pre-S <sub>2</sub> )	$M_{AN2}$ (Syn-S <sub>2</sub> )
Andrelândia Nappe	Qz	—————	—————	—————
	Pl	—————	—————	—————
	Ms	—————	—————	- - - - -
	Bt	—————	—————	—————
	Grt	—————	—————	—————
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	Sil			—————
	St			—————
	Ilm		—————	—————
	Rt	- - - - -		



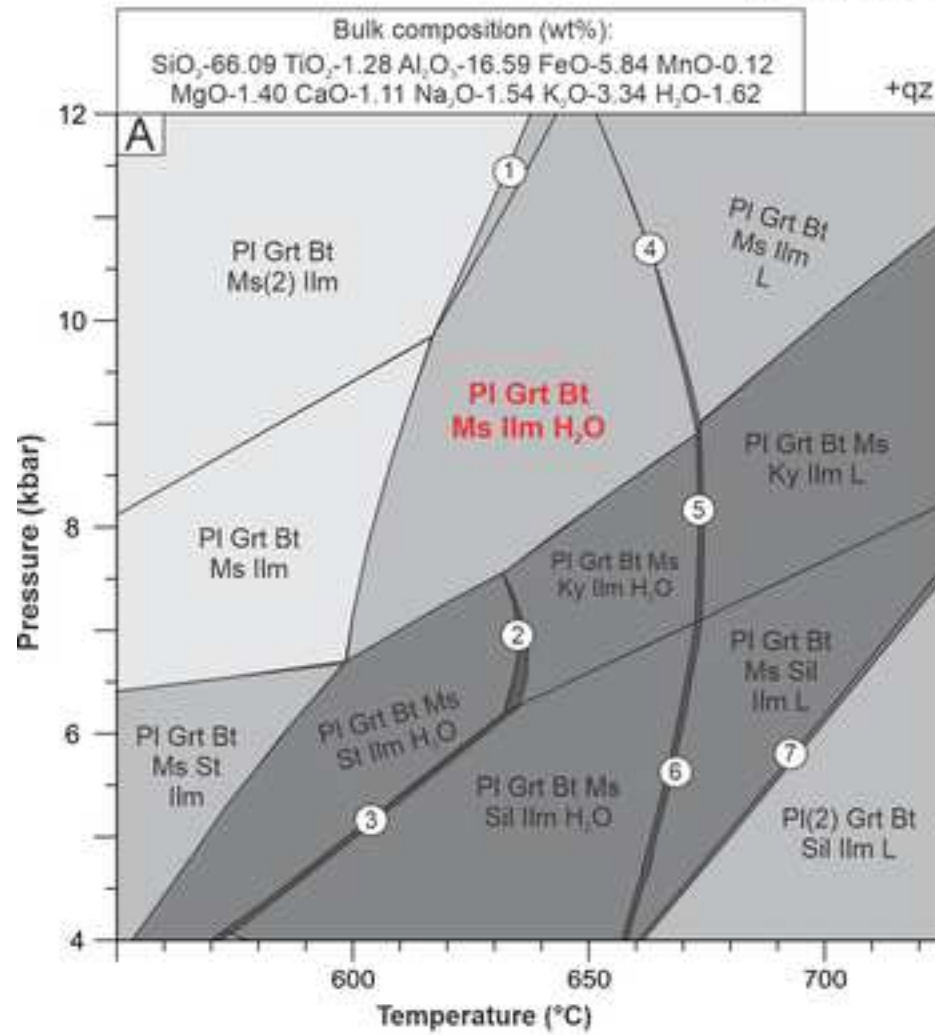
**Liberdade Nappe - NESG-388**



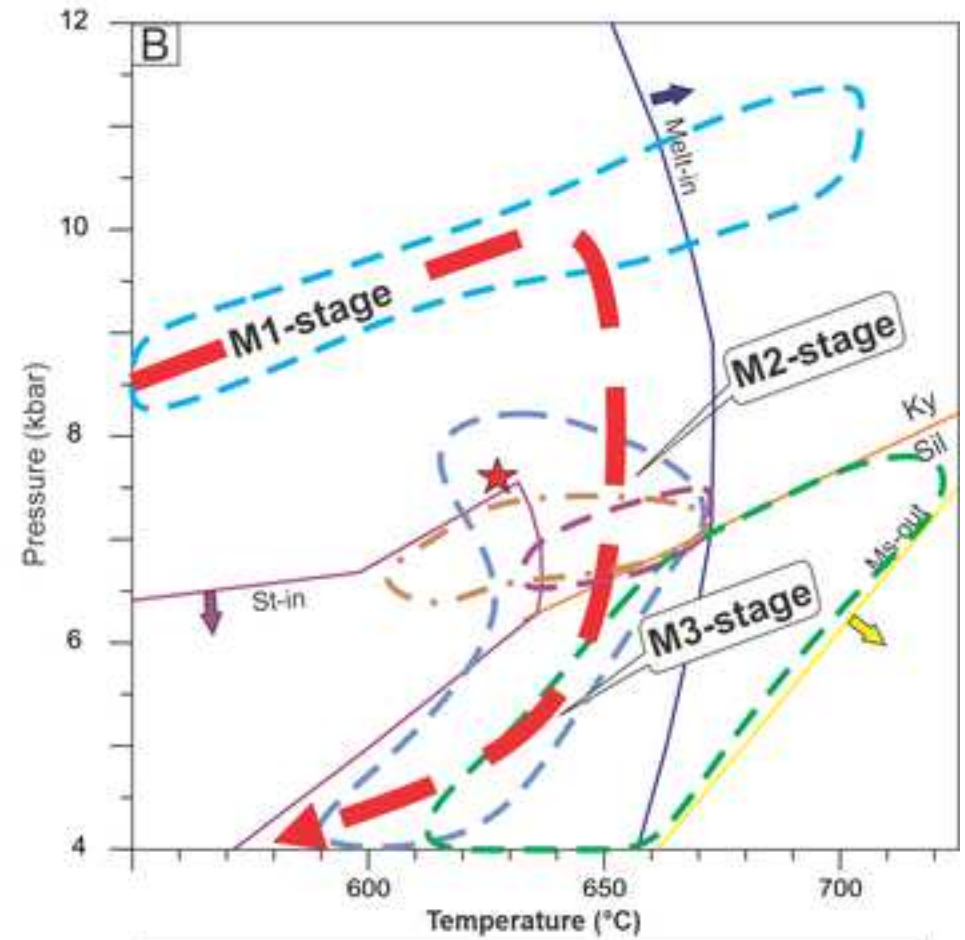
## Andrelândia Nappe - NESG-401



## Liberdade Nappe - NESG-388

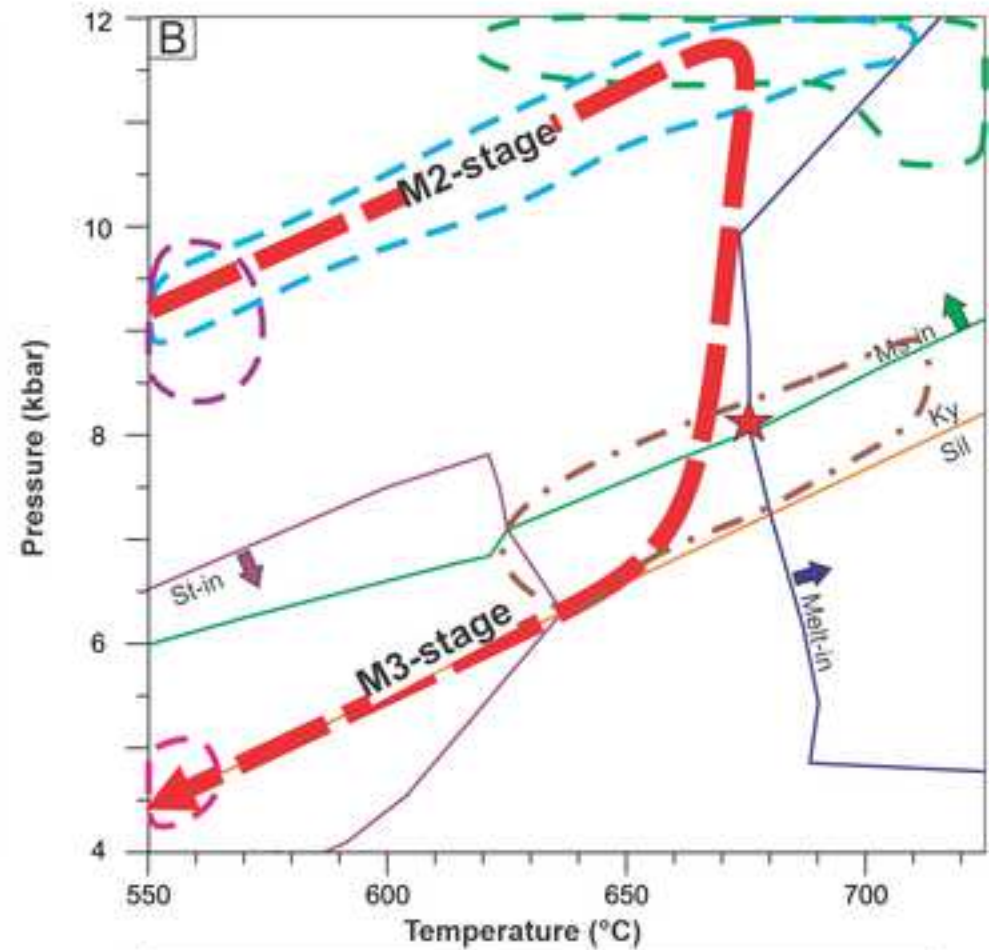
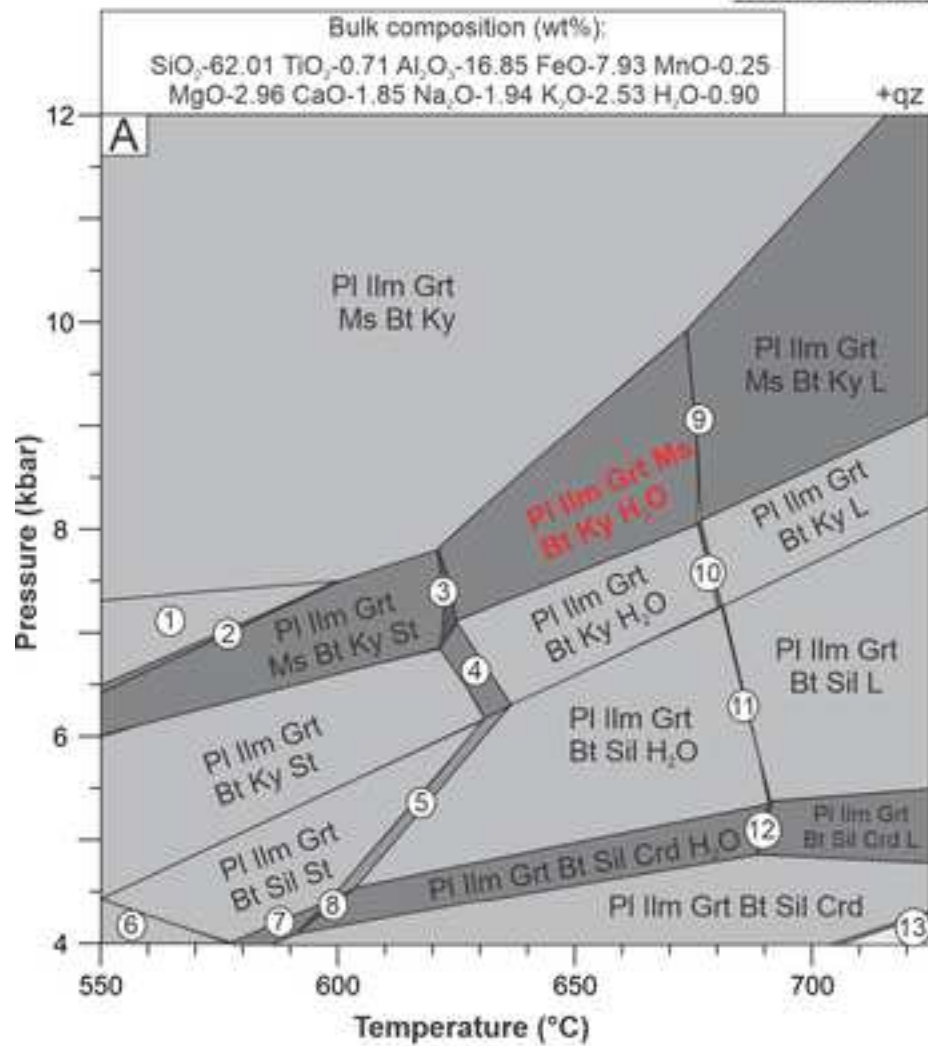


- |   |   |
|---|---|
| 1 PI Grt Bt Ms(2) Ilm H <sub>2</sub> O    | 4 PI Grt Bt Ms ilm H <sub>2</sub> O L     |
| 2 PI Grt Bt Ms Ky St Ilm H <sub>2</sub> O | 5 PI Grt Ms Bt Ky Ilm L                   |
| 3 PI Grt Bt Ms Sil St Ilm                 | 6 PI Grt Bt Ms Sil Ilm H <sub>2</sub> O L |
|   | 7 PI(2) Grt Bt Ms ilm H <sub>2</sub> O L  |

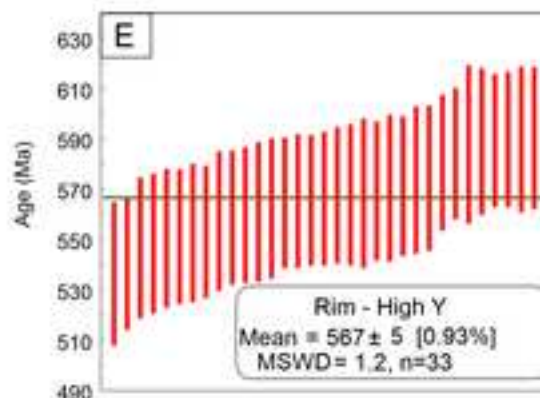
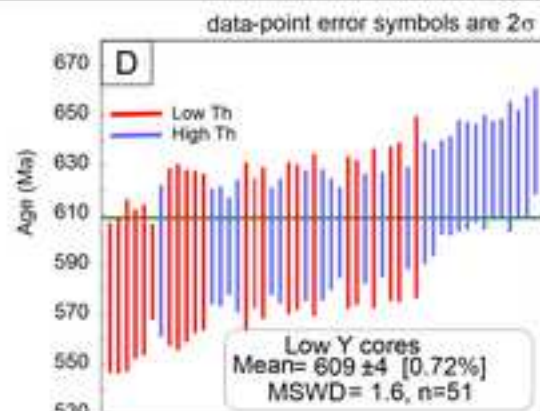
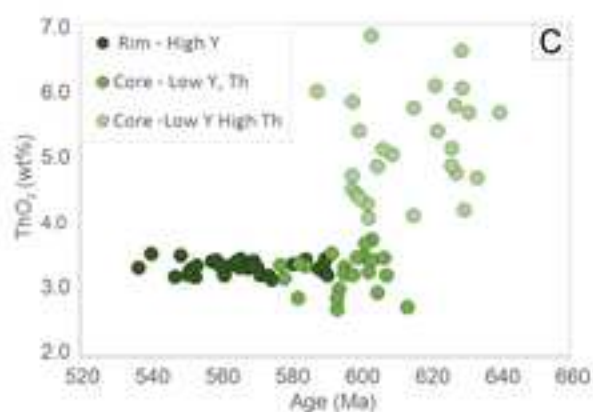
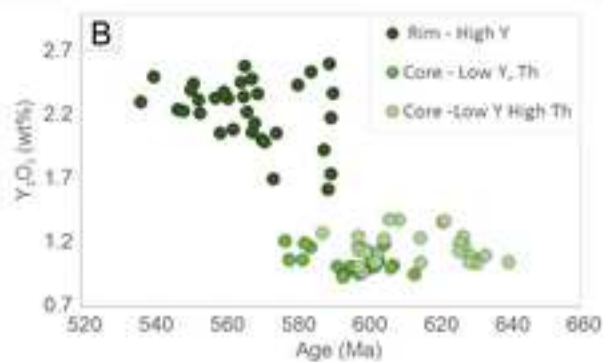
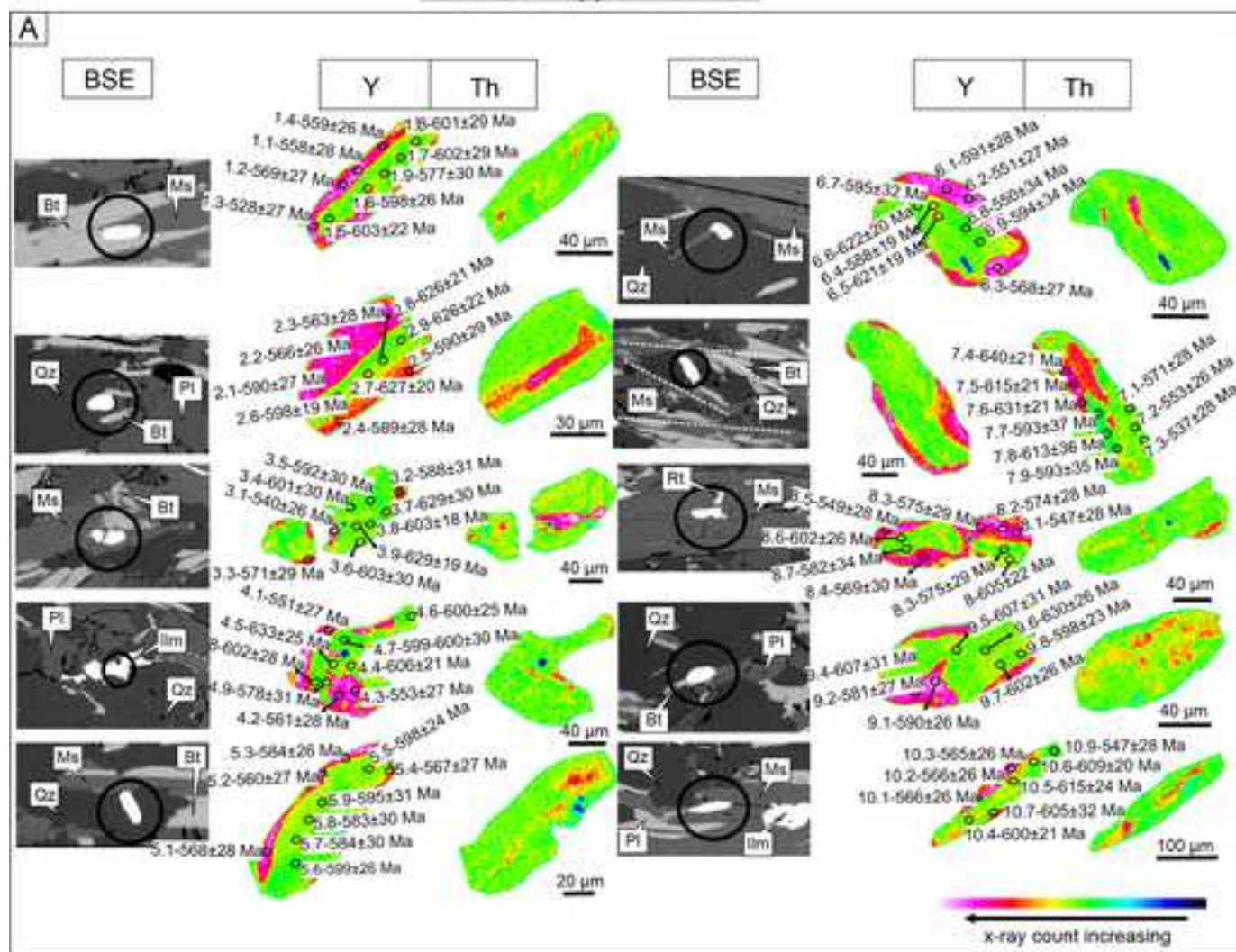


- ★ T- 628°C P- 7.5 kbar
- Quality factors
- $Q_{\text{reac}}$  : 100%
- $Q_{\text{mode}}$  : 92%
- $Q_{\text{cmp}}$  : 86
- $Q_{\text{out}}$  : 93%
- $Q_{\text{cmp}}$  factor
- PI Core (100%)
  - PI Rim (100%)
  - Ms (95%)
  - Grt (100-90%)
  - $Q_{\text{mode}}$  (100%)

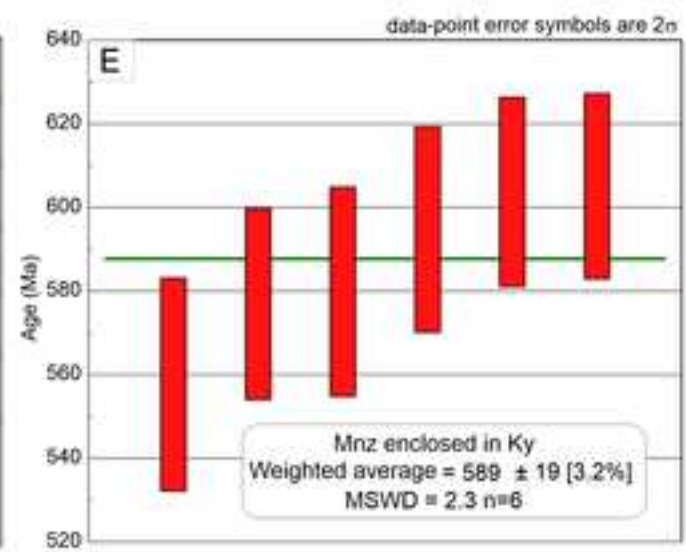
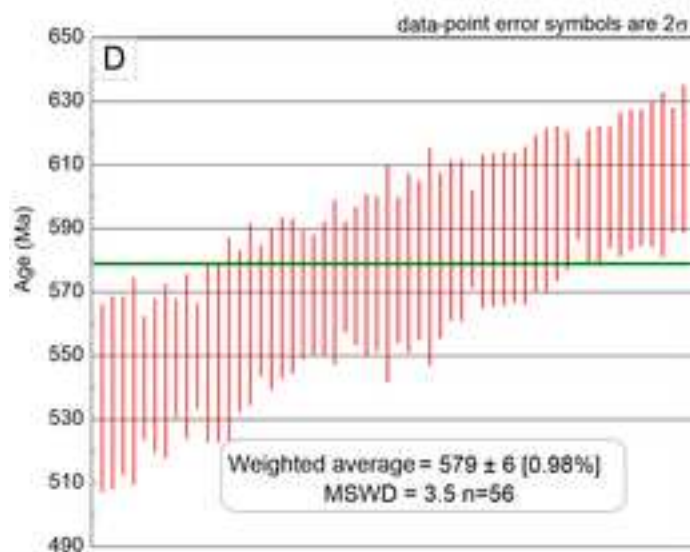
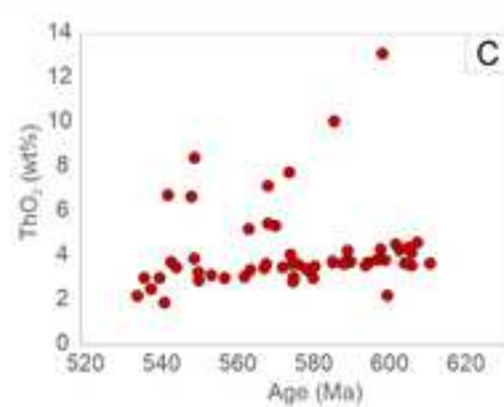
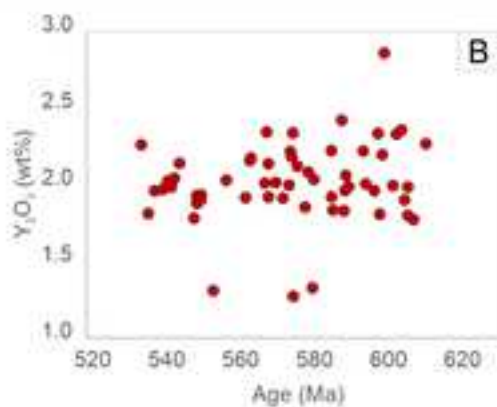
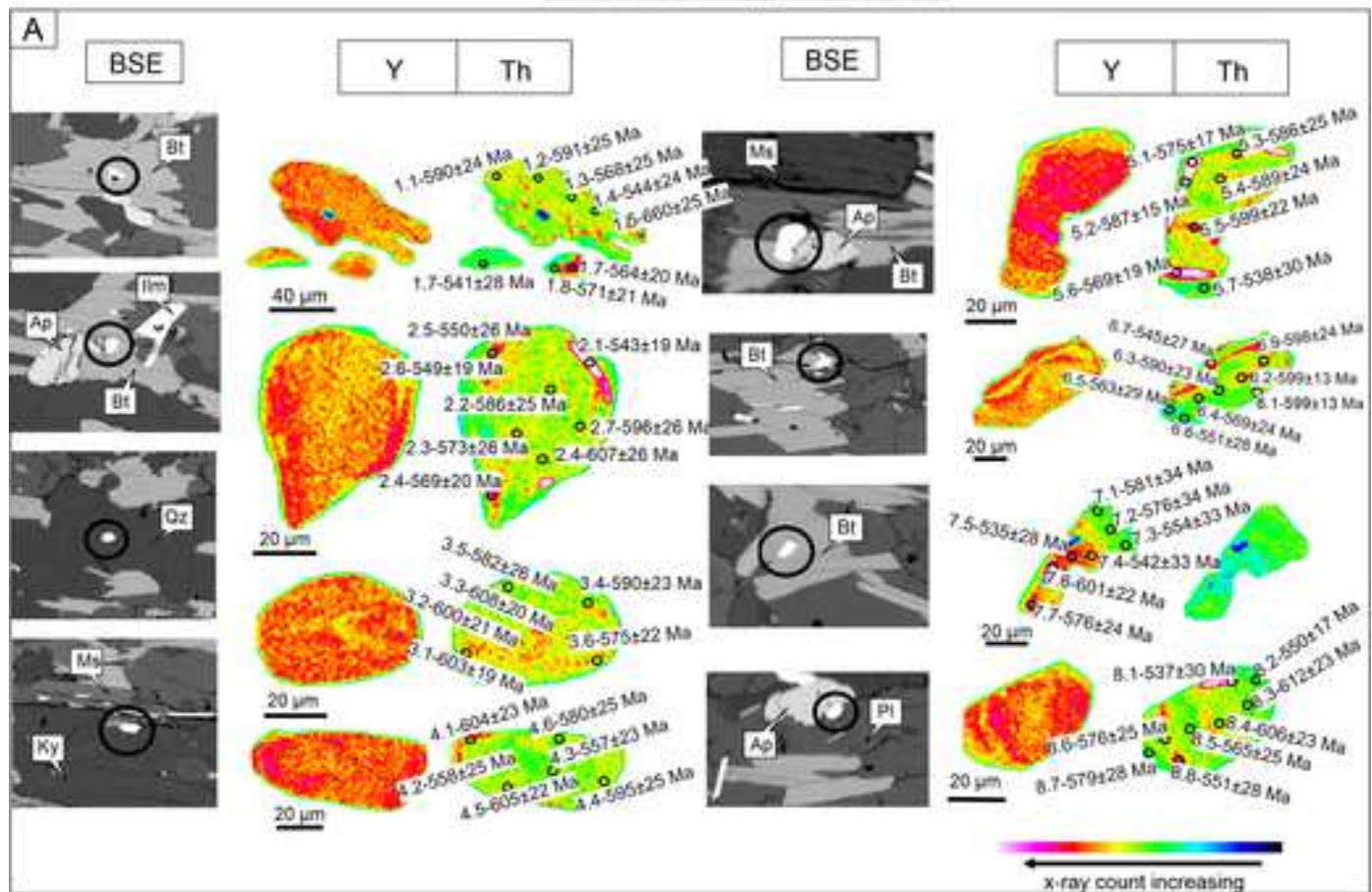
## Andrelândia Nappe - NESG-401

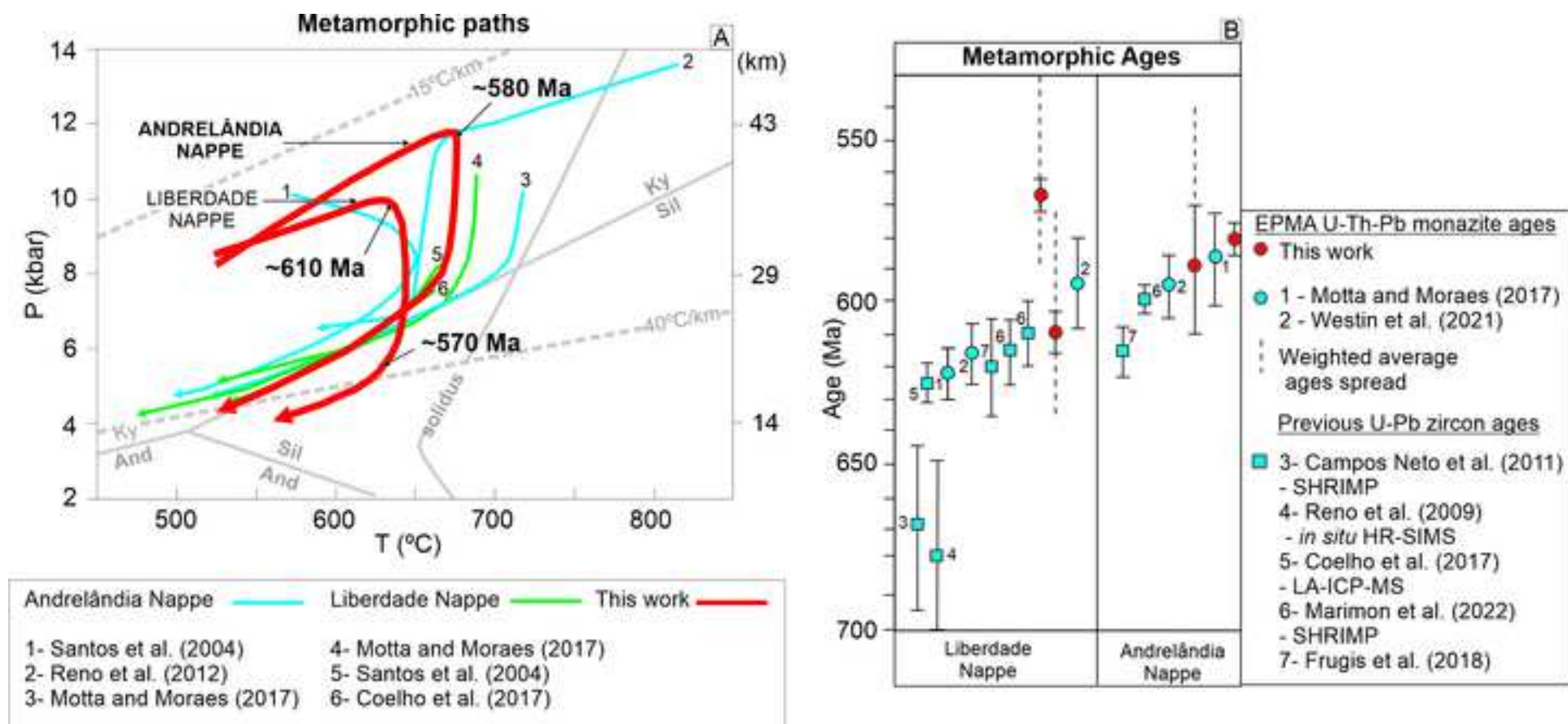


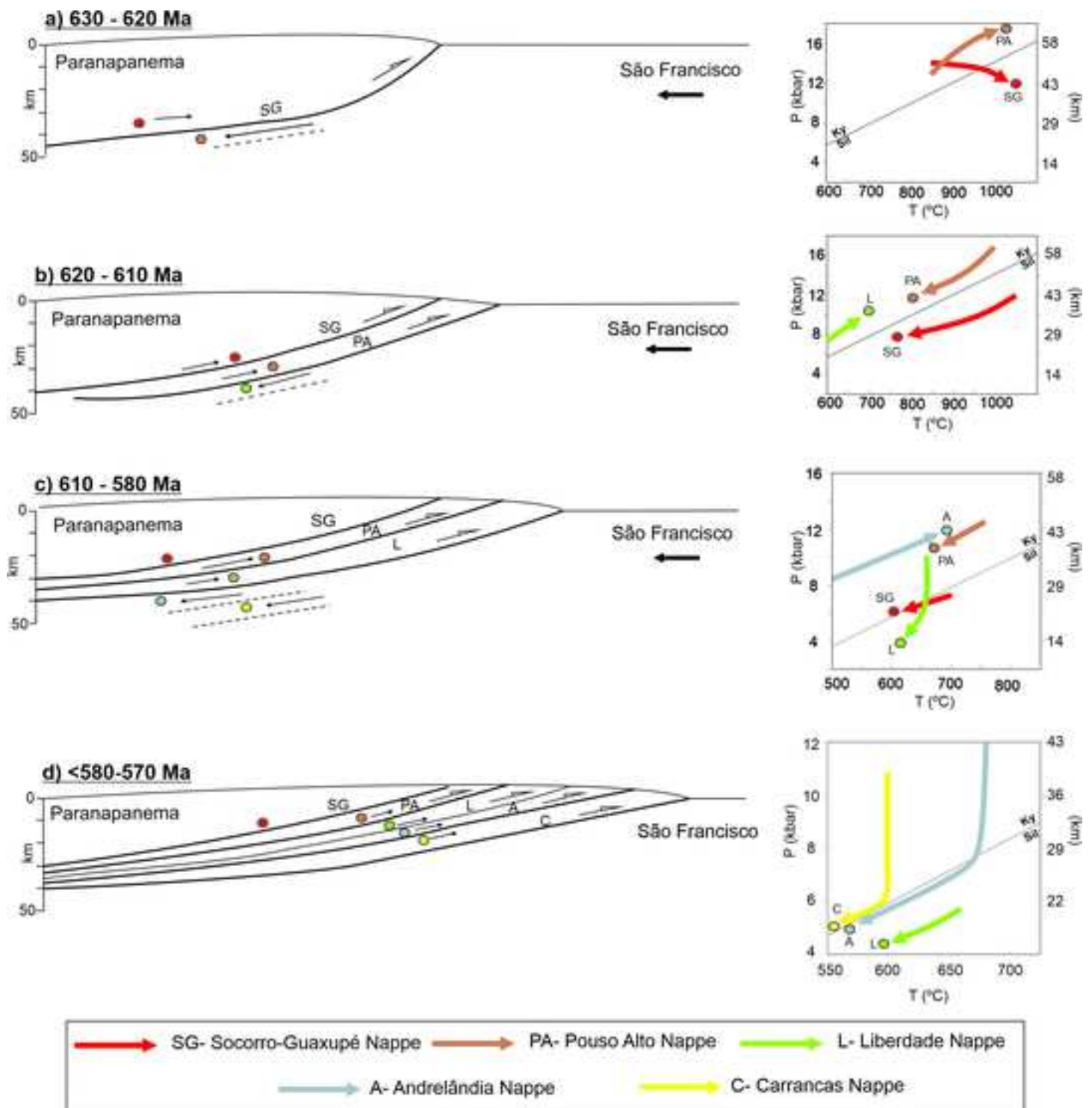
## Liberdade Nappe - NESG-388



## Andrelândia Nappe - NESG-401









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Supplementary Table File A.xls



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**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: