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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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Abstract:	The metamorphic and kinematic evolution of medium-high grade rocks of the Andrelândia Nappe System (ANS), the orogenic wedge of the Southern Brasilia 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 thrusted nappes. This mechanism is consistent with the ANS in-sequence fold-and-thrust architecture.
Suggested Reviewers:	Alice Westin, PhD University of São Paulo alice.teixeira@usp.br Dr. Westin has worked in the Southern Brasilia Belt, with several papers published in the area. 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. Regiane Fumes, PhD regiane.fumes@unesp.br Dra. Fumes has developed her work using monazite petrochonology and metamorphic modeling techiniques in the Southern Brasília Belt.

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

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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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 Brasilia 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 Brasilia 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, Corresponding author: Beatriz Benetti, PhD (on behalf of all authors) Dipartimento Scienze della Terra, Università degli Studi di Torino Email: beatrizyuri.benettisilva@unito.it

Yours sincerely, Corresponding author: Beatriz Benetti, PhD (on behalf of all authors) Dipartimento Scienze della Terra, Università degli Studi di Torino Email: beatrizyuri.benettisilva@unito.it 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 importat 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 Brasilia 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 insequence 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).

1.23. 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).

1.27 be consistent when using \sim or ca. for temperature.

Done (see Line 25).

1. 29-30. myr instead of Ma if you are referring to an interval of time.

Done (see Line 31).

1.30-31. "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).

1. 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 Andrelândia Nappe (see Line 34-38).

If you are interpreting both prograde and retrograde metamorphism occuring during thrust stacking, what changes in you 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 Andrelândia 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-andthrust 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 petrocrhonology.

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 obsersarvations" 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. "Allochtonous 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 you 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_{cmp}; see sup. Fig. file A4, A5, and A6). The Q_{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_{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 ($Q_{cmp}=100\%$) 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_{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_{LN1} 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 S₂ foliation with decompression, and in opposite the AN S₂ 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

ABSTRACT

The metamorphic and kinematic evolution of medium-high grade rocks of the Andrelândia Nappe System (ANS), the orogenic wedge of the Southern Brasilia 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 thrusted nappes. This mechanism is consistent with the ANS insequence 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.

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
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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 whose ages progressively decreased toward the bottom of the nappe stack. We attribute this 29 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 thrusted nappes. 33 This mechanism is consistent with the ANS in-sequence fold-and-thrust architecture.

34 **KEYWORDS**:

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

37 **1. INTRODUCTION**

The growth of a mountain belt is controlled by the balance among accretion of crustal material, such as sediments and magma addition as well as thrust stacking, and removal by erosion, delamination, and post-orogenic extension (Beaumont et al., 2001; Davies et al., 1983; Jamieson and Beaumont, 2013; Vanderhaeghe, 2012; Whipple, 2009; Willett, 1999). An orogenic wedge is constituted by crustal material mainly detached from 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., 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 <i>ca</i> . 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, indicate a thrust propagation from WSW to ENE toward the São Francisco Craton southern 76 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

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

95

2. GEOLOGICAL SETTING

96 The Brazilian-Pan African event is the name given to a series of diachronic collisions in the São Francisco-Congo Craton side of the West Gondwana paleocontinent 97 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., 2013, 2000). 103

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 Auiruoca, 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 <i>P</i> - <i>T</i> 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 <i>P-T</i> 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

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

163The 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

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

182 The Andrelândia Nappe crops out in the north of the study area (Fig. 4a and b). It is 183 made of gravish metawackes, and at its lithostratigraphic boundaries metapelites 184 associations prevail. The main lithology described is a garnet+kyanite(±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 weight percentage maps applying internal standards (Andrade et al., 2006) in the software
XMapTools 3.4 (Lanari et al., 2014, 2019). Such areas were the basis for estimating the
Local Bulk Composition (LBC) needed for petrological modeling (see section 5). The
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 (S₂, 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 S₂ 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 (XAn -0.20-0.32) (Fig. 7b). Garnet end-members vary slightly from core
238	to rim: almandine (XAlm)=0.81-0.79, pyrope (XPrp)=0.11-0.07, spessartine (XSps) =0.05-
239	0.06 and grossular (XGrs)=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	$quartz+plagio clase+biotite+white\ mica+garnet+kyanite+ilmenite(\pm sillimanite\pm staurolite)$

 $247 \qquad \text{and tourmaline+apatite+monazite+zircon+rutile as accessories. The AN has a S_2 foliation}$

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 ($post-S_2$). 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 (≤2 cm in size) (Fig. 8b). Discontinuous 257 inclusion trails of opaque minerals within garnet, with respect to the S_2 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 S₂ foliation (Fig. 8b). Twinning in kyanite is observed. Late fibrolite 262 growth (post-S₂) along shear bands and replacing biotite crystals are observed (Fig. 8c and d). Two generations of staurolite were observed, the first is characterized by tiny crystals 263 264 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-S₂ 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 ($M_{\rm AN1}$), 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 (XAn -0.22) and Ca-rich rims (XAn -0.32).
283	The highest Ca-content (XAn -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- XAlm-0.6, XPrp-0.06,
288	XSps -0.1, XGrs-0.22; Rim- XAlm-0.72, XPrp-0.13, XSps-0.03, XGrs-0.08) (Fig. 9c, d, e,
289	and f). Spessartine displays a sharp increase in the outermost rim (XSps-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 XMg- 0.54-0.52 and Ti(a.p.f.u)- 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 and b). The Si⁴⁺ content in white mica is
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 ₂ O-CaO-K ₂ O-FeO-MgO-
319	Al ₂ O ₃ -TiO ₂ -SiO ₂ -H ₂ O. The water amount was chosen using recipe 14 of the antidote, a
320	statistical routine that asses 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_2O , at fixed <i>P</i> - <i>T</i> conditions. The
322	diagrams were calculated for the <i>P</i> - <i>T</i> 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

6.5-12 kbar and $600-670^{\circ}$ C. Assuming the mineral phase equilibrium, the optimal *P-T*

condition is expected to be achieved at 628°C and 7.5 kbar. At this condition, the quality

factors for the mode (Q_{mode}) is 92%, and the system mineral chemistry (Q_{cmp}) is 86% (Fig.

336 10b).

337	The mineral <i>P</i> - <i>T</i> 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 ($Q_{cmp}=100\%$) 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	antidote, peak conditions are better constrained by plagioclase rim composition (Q_{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 ($Q_{cmp} = 100\%$), and garnet ($Q_{cmp} = 90-100\%$) mineral chemistry
349	compositions in addition with the mineral modes ($Q_{mode} = 100\%$) 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 <i>P</i> - <i>T</i> path. Lastly, the <i>P</i> - <i>T</i> path later stage is recorded by the
354	compositional match between the plagioclase rim and muscovite (Pl- $Q_{cmp} = 100\%$; Ms-
355	$Q_{cmp} = 95\%$) 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

applied (supplementary figure A2c). It displays values from 650 to 580°C consistent with
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_{cmp}) are provided in the supplementary figure A5. 371 Therefore, the M_{AN1} 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+H₂O, was constrained 374 in the quadri-variant field delimitated 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 $Q_{cmp} = 92\%$ and $Q_{mode} = 95\%$ 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 ($Q_{cmp} = 100\%$), 380 which records early stages of amphibolite facies around 550-570°C and 8-9 kbar, 381 plagioclase core ($Q_{cmp} = 100\%$), and white mica ($Q_{cmp} = 85-80\%$). 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 <i>ca</i> .
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

To constrain the timing of the metamorphic and deformation events, *in-situ* U-(Th)-Pb monazite chemical dating was carried out by EMPA (e.g., Dumond et al., 2015;

Williams and Jercinovic, 2002, 2012). The analytical procedures are described in appendixA.

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 μ 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 Y₂O₃ content (wt%) 413 varies from 1.02 to 1.39, and the ThO₂ (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_2O_3 (wt%) and 415 ThO₂ (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_2O_3 (wt%) amounts are spread in a broad range from 1.62 up to 2.61, and ThO₂ (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 $613 \text{ Ma} \pm 36 \text{ Ma}$ to $550 \pm 33 \text{ Ma}$. 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 μ m up to 100 μ 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 Y_2O_3 contents varying from 1.3 to 2.9 wt% and variable Th amounts,
436	varying the 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 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±23 Ma to 535±28 Ma. The dates are plotted in the weighted
441	average diagram (Fig. 13d), and they yield a mean age of 579±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 ± 22 Ma to
445	558±25 Ma and yield a mean age of 589±19 Ma (MSWD=2.3; Fig. 13e).

446 **4. DISCUSSION**

447 *4.1 Monazite chemical dating interpretation*

The in-situ monazite dating combined with the X-ray maps (e.g., Y and Th) allows
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

releases Y and HREE in the system, and the monazite precipitating from this reaction willdisplay 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±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±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 S₂ 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 the development of the S_2 fabric related with the SE tectonic transport. 487

The monazites grains from the sample NESG-401 of the Andrelândia Nappe are homogenous with intermediate Y and Th-depleted. They are interpreted as growing coeval with the garnet during the prograde metamorphism ($M_{AN}2$ stage), at a minimum age of 579±6 Ma. The Mnz 4 is enclosed in kyanite and parallel to the AN S₂ fabric, providing time constraint for the foliation-forming deformation coeval with kyanite growth during the *P-T* path. This single crystal yields mean age of 589±19 (n=6), consequently interpreted as corresponding to the time of the S₂ deformation, and taking into account the age standard

deviation, is considered contemporary to the prograde metamorphism ($M_{AN}2$ stage). Rims
highly enriched in Th (Mnz 2, 5, and 8) are attributable to exchange reactions between
apatite and monazite and have no signatures that can associate them with any significant
tectono-metamorphic event.
4.2 Tectono-metamorphic evolution of the Andrelândia Nappe System (ANS)
The microstructural descriptions, <i>P</i> - <i>T</i> path traced through thermodynamic
metamorphic modeling, and monazite petrochronological data presented here help elucidate
the complex ANS framework in the southern sector of the SBO. The Liberdade and
Andrelândia Nappes evolved from a clockwise sub-solidus <i>P</i> - <i>T</i> path characterized by burial
and heating, followed by nearly isothermal decompression, and lastly, cooling and
decompression. The Liberdade Nappe (NESG-388) M_{LN1} stage assemblage (Qz-Pl-Grt-Bt-
Ms-Ilm) records peak conditions at ca. 650°C and 9.5-10 kbar and has a minimum age of
609±4 Ma (Fig. 14a). The peak conditions indicate that the LN rocks were buried by 36
km, corresponding to the middle and lower depth of a thickened crust with an apparent
geothermal gradient of 18°C/km (Fig. 14a). The further stages, MLN2 (Qz-Pl-Grt-Bt-Ms-
Ilm-Ky(?)) and the M_{LN3} (Qz-Pl-Grt-Bt-Ms-Ilm-Sil-St), represent respectively the
isothermal decompression and decompression/cooling episodes related to the LN migration
toward SE, whose the minimum age is constrained at 567±5 Ma (Fig. 14a).
The Andrelândia Nappe sample (NESG-401) records a burial and heating episode in
the kyanite stability field during the prograde metamorphism, from ~550°C and 9.0-9.5
kbar up to ~680 °C and 11-12 kbar (M _{AN2} stage; Fig. 14a). The <i>P</i> - <i>T</i> data suggest an
apparent geothermal gradient of 16°C/km and burial into crustal depths of 43 km (Fig. 14a).
The minimum age for the prograde metamorphism was estimated at 579±6 Ma, and within

the uncertainties is considered coeval with the S₂ deformation event underwent by this rock. It was followed by an almost isothermal decompression, in which the pressure conditions decreased from 12 kbar down to 8.0-7.0 kbar (Fig.14a). Lastly, the M_{AN3} stage related to staurolite and sillimanite appearance in the system was constrained in the *P*-*T* range of 670-520 550°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.

Fig. 14b is a summary of the available metamorphic ages for the Andrelândia and Liberdade Nappes using monazite and zircon U-Pb geochronology techniques. The oldest ages of the Liberdade Nappe, at *ca*. 680-670 Ma, reported by Campos Neto et al. (2011) 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 micaschits 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 \sim 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	μ 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 (S₂)
- 990 defined by biotite and white mica shape preferential orientation (SPO). Quartz displays
- moderately irregular contacts (UTM 521535/7560145); b) Skeletal garnet and decussate
- 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
- 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 (XGrs), pyrope (XPrp) and spessartine (XSps) zoning in garnet. The red circles
1000	indicate the area used to perform the Q_{cmp} 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 ₂), and
1005	kyanite aligned according to the external S ₂ 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 ₂) 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 (XGrs), pyrope (XPrp) and spessartine (XSps) zoning in garnet. The red circles
- 1014 indicate the area used to perform the Q_{cmp} 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_{cmp}) and mode (Q_{mode}) 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_{cmp}) and mode (Q_{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 Y₂O₃ (wt%) vs. age plot; c) ThO₂ (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 Y₂O₃ (wt%) vs. age plot; c) ThO₂ (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⁺⁴ content in white mica (a.p.f.u).

1056 Red circle indicates the area used to perform the Q_{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^{+4} content in white mica (a.p.f.u).
- 1060 Red circle indicates the area used to perform the Q_{cmp} maps.
- 1061 Figure A4- Maps of quality factors by Antidote for Liberdade Nappe. a) Q_{asm}; b)Q_{mode}; c)
- 1062 Q_{cmp} for the LBC bulk composition; d)Q_{cmp} for garnet composition; e) Q_{cmp} for plagioclase

1063 core composition; f) Q_{cmp} for plagioclase rim composition; g) Q_{cmp} for white mica

- 1064 composition; h) Q_{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_{cmp} by Antidote for AN garnet core composition.
- 1068 Figure A6 Maps of quality factors by Antidote for Andrelândia Nappe. a) Q_{asm}; b) Q_{mode};
- 1069 c) Q_{cmp} for the LBC bulk composition; d) Q_{cmp} for garnet mantle composition; e) Q_{cmp} for
- 1070 garnet rim composition; f) Q_{cmp} for white mica composition; g) Q_{cmp} for plagioclase core
- 1071 composition; h) Q_{cmp} for plagioclase rim composition; i) Q_{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 offorming 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. Tthe 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 $-ca$. 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 eachthe nappe of the Andrelândia System recordrecords a
30	single metamorphic cycle of burial and decompression, although it took place at different
31	ages over a period of <i>ca</i> . 60 Mamyr, 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 thrusted nappes external parts of the
39	wedge. This mechanism is consistent with the ANSwould 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, tThe 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 Brasilia 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., 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 separate tectono-metamorphic events from different orogenic cycles. The first event is was 78 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

al., 2021). In this hypothesis, the sillimanite and staurolite presence documented by the
ANS rocks would result from the decompression/exhumation of the nappe pile rather than
testify a second tectono-thermal event. The available metamorphic ages, from 630 to 580
Ma, indicate a thrust propagation from WSW to ENE toward the São Francisco Craton
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 modelingmodern 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 Auiruoca, 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 <i>ca</i> . 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 <i>P</i> - <i>T</i> range of 642-715°C and 6-10 kbar (Coelho et al.,
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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 <i>P-T</i> 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	Ffrom 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+biotiebiotite+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 <i>ca</i> . 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 <i>S</i> - <i>C</i> 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	$(\pm sillimanite \pm rutile \pm kyanite \pm staurolite)$ -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 Complex203 (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 gravish metawackes, and at its lithostratigraphic boundaries metapelites 206 associations prevail. The main lithology described is a garnet+kyanite(±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 (XAn -0.20-0.32) (Fig. 7b). Garnet end-members vary slightly from core
260	to rim: almandine (XAlm)=0.81-0.79, pyrope (XPrp)=0.11-0.07, spessartine (XSps) =0.05-
261	0.06 and grossular (XGrs)=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)

 $269 \qquad \text{and tourmaline+apatite+monazite+zircon+rutile as accessories. The AN has a S_2 foliation}$

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 ($post-S_2$). 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 contactsboundaries, typical of the GBM recrystallization 277 mechanism (Law, 2014).

278 Garnet is present as porphyroblast (≤2 cm in size) (Fig. 8b). Discontinuous 279 inclusion trails of opaque minerals within garnet, with respect to the S_2 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 S₂ foliation (Fig. 8b). Twinning in kyanite is observed. Late fibrolite 284 growth (post-S₂) 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_2 289 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+Rtgarnet(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 pathassemblage,
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+ilmeniteQz+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 (XAn -0.22) and
306	Ca-rich rims (XAn -0.32). The highest Ca-content (XAn -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- XAlm-0.6, XPrp-0.06, XSps -0.1, XGrs-0.22; Rim- XAlm-0.72, XPrp-0.13,
312	XSps-0.03, XGrs-0.08) (Fig. 9c, d, e, and f). Spessartine displays a sharp increase in the
313	outermost rim (XSps-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

and b). The Si^{4+} 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 ₂ O-CaO-K ₂ O-FeO-MgO-
343	Al ₂ O ₃ -TiO ₂ -SiO ₂ -H ₂ O. The water amount was chosen using recipe 14 of the antidote, a
344	statistical routine that asses 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 <i>P</i> - <i>T</i> conditions.
346	The diagrams were calculated for the <i>P</i> - <i>T</i> 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

The calculated isochemical diagram for the Liberdade Nappe LBC is presented in Fig. 10a. The observed peak mineral assemblage, quartz+plagioclase+white mica+biotite+ilmenite, is stable in the penta-variant field constrained in the *P-T* range of 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

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

361	The mineral <i>P</i> - <i>T</i> 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 ($Q_{cmp}=100\%$) 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	antidote, peak conditions are better constrained by plagioclase rim composition (Q_{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 ($Q_{cmp} = 100\%$), and garnet ($Q_{cmp} = 90-100\%$) mineral chemistry
373	compositions in addition with the mineral modes ($Q_{mode} = 100\%$) intersect at the hexa-
374	variant field in which Qz+Pl+Bt+Grt+Ms+Ky+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 (Pl- Q_{cmp} =100%; Ms-
379	Q _{cmp} =95%) in the hexa-variant field where Qz+Pl+Grt+Bt+Ms+Ilm+Sil+H ₂ 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_{LN1} , M_{LN2} , and M_{LN3} metamorphic stages described in

section 4.1. The quantitative map of the Ti-in-biotite thermometer (Henry et al., 2005) was
applied (supplementary figure A2c). It displays values from 650 to 580°C consistent with
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_{cmp}) are provided in the supplementary figure A5. 395 Therefore, the M_{AN1} 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, Qz+Pl+Bt+Grt+Ky+Ms+Ilm+H₂O, was constrained 398 in the quadri-variant field delimitated 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 $Q_{cmp} = 92\%$ and $Q_{mode} = 95\%$ 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 ($Q_{cmp} = 100\%$), 404 which records early stages of amphibolite facies around 550-570°C and 8-9 kbar,

405	plagioclase core ($Q_{cmp} = 100\%$), and white mica ($Q_{cmp} = 85-80\%$). 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 <i>ca</i> .
408	660°C-670°C and 11.5-12 kbar, at these conditions, Qz+Pl+Bt+Grt+Ky+Ms+Ilm are the
409	stable phases (M_{AN2} stage). An almost isothermal decompression is suggested based on the
410	mineral modes (Q_{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 °C. At last, garnet rim chemical
412	composition (Q_{cmp} =80%) provided information about the AN cooling stage. It is
413	equilibrated at 550°C and 4.5 kbar in the stability field of Qz+Pl+Grt+Bt+Ilm+St+Sil
414	$(M_{AN3} \text{ stage}; \text{Fig. 11b})$. The Ti-in-biotite thermometer map (supplementary figure A3c)
415	displays temperatures ranging from 630 to 560 $^\circ$ 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 µm, except the Mnz 4, associated with ilmenite which shows an irregular lobate

shape. In some crystals, small quartz (e.g., Mnz 4, Mnz 5, and Mnz 6) inclusions were
observed, but most of the monazites are inclusions free. The monazites display a sectorial
core-rim internal zoning (e.g., Mnz 1, 2, 6 and 7). A remarkable feature that might be
highlighted is the core and rim zonation pattern that is well-aligned (e.g., Mnz1, 2, 6, 8, and
10) with the main foliation, suggesting a pre-to syn-mylonitic growth related to the rock
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_2O_3 content (wt%) 437 varies from 1.02 to 1.39, and the ThO₂ (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_2O_3 (wt%) and 439 ThO₂ (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 Y₂O₃ (wt%) amounts are spread in a broad range from 1.62 up to 2.61, and ThO₂ (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 ± 21 Ma 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 μ m up to 100 μ 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 Y_2O_3 contents varying from 1.3 to 2.9 wt% and variable Th amounts,
460	varying the 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 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±23 Ma to 535±28 Ma. The dates are plotted in
465	the weighted average diagram (Fig. 13d), and they yield a mean age of 579±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±22 Ma
- to 558±25 Ma and yield a mean age of 589±19 Ma (MSWD=2.3; Fig. 13e).

470 **4. DISCUSSION**

471 *4.1 Monazite chemical dating interpretation*

The in-situ monazite dating combined with the X-ray trace elements maps (e.g., Y
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 in-situ dating allows us to relate the monazite chemical zonation with its microstructural 482 483 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_{LN1} 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 metamorphismpath
508	(early M_{LN1} 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_{LN2} and M_{LN3}). Furthermore, the growth orientation of some
512	high-Y rims aligned with the S_2 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_2 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 ($M_{AN}2$ stage), at a minimum age of

- 518 579 \pm 6 Ma. The Mnz 4 is enclosed in kyanite and parallel to the AN S₂ 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 ± 19 (n=6), consequently interpreted as 521 corresponding to the time of the S₂ deformation, and taking into account the age standard 522 deviation, is considered contemporary to the prograde metamorphism (M_{AN}2 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±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, MLN2 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±5 Ma (Fig. 540 14a).

541The Andrelândia Nappe sample (NESG-401) records a burial and heating episode in542the 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 <i>P</i> - <i>T</i> 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±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 <i>P</i> - <i>T</i> range of 670-
550	550°C and 8.0-4.5 kbar (Fig. 14a).
551	A compilation of literature <i>P</i> - <i>T</i> 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 decompressionexhumation,
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 micaschits 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*

581Our present findings shed new light on some critical points regarding the tectono-582metamorphic events experienced by the ANS. The first point is related to the Andrelândia583and Liberdade Nappes P-T paths. Microstructural observations and thermodynamic584modeling show that the staurolite and sillimanite in the matrix are related to decompression585and cooling stages. Furthermore, the suggested metamorphic paths to the LN and AN586pointed out that the baric and thermic peaks occur almost simultaneously. These587information in conjunction with monazite petrochronology indicate that likely each one of

the nappes those rocks underwent a single metamorphic eyele loop of burial and
decompression.

590 The second critical point concerns the timetiming 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 thrustexternal parts of the wedge.

653

APPENDIX A – ANALYTICAL METHODS

The equipment employed in the trace elements, quantitative mineral analyses, and compositional maps is a JEOL JXA-8230 Electron Probe Micro Analyzer (EPMA) equipped with five wavelengths dispersive spectrometry (WDS) detectors hosted at the 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	μ 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.

- Figure 4 a) Geological map of Pouso Alto county; b) Geological cross-section of the area
 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 (S₂)
- 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-S₂), and
- 1043 kyanite aligned according to the external S₂ 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-S₂) made by sillimanite, quartz, and biotite. Staurolite

- with internal foliation continuous with the external one. Note the fibrolite replacing biotitecrystals (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_{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_{cmp}) and mode (Q_{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_{cmp}) and mode (Q_{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) ThO₂ (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 Y₂O₃ (wt%) vs. age plot; c) ThO₂ (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 Si^{+4} content in white mica (a.p.f.u).
- 1094 Red circle indicates the area used to perform the Q_{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 Si^{+4} content in white mica (a.p.f.u).
- 1098 Red circle indicates the area used to perform the Q_{cmp} maps.
- 1099 Figure A4- Maps of quality factors by Antidote for Liberdade Nappe. a) Q_{asm}; b)Q_{mode}; c)
- 1100 Q_{cmp} for the LBC bulk composition; d)Q_{cmp} for garnet composition; e) Q_{cmp} for plagioclase
- 1101 core composition; f) Q_{cmp} for plagioclase rim composition; g) Q_{cmp} for white mica
- 1102 composition; h) Q_{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_{cmp} by Antidote for AN garnet core composition.
- 1106 Figure A6 Maps of quality factors by Antidote for Andrelândia Nappe. a) Q_{asm}; b) Q_{mode};
- 1107 c) Q_{cmp} for the LBC bulk composition; d) Q_{cmp} for garnet mantle composition; e) Q_{cmp} for
- 1108 garnet rim composition; f) Q_{cmp} for white mica composition; g) Q_{cmp} for plagioclase core
- 1109 composition; h) Q_{cmp} for plagioclase rim composition; i) Q_{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).









Figure

	Phase	M _{LN} 1 (Pre-S ₂)	M _{LN} 2	M _{LN} 3 (Syn-S ₂)
Liberdade Nappe	Qz Pl Ms Bt Grt Ky Sil St Ilm Rt			
		M _{AN} 1 (Pre-S ₂)	M _{AN} 2 (Syn-S ₂)	M _{AN} 3 (Post-S ₂)
Andrelândia Nappe	Qz Pl Ms Bt Grt Ky Sil St Ilm Rt			





Liberdade Nappe - NESG-388





Grt

0.09

80.0

0.07

0.06

1mm

Grt

0.06

0.05

0.04

0.03

1mm

Andrelândia Nappe - NESG-401

А



Liberdade Nappe - NESG-388







Andrelândia Nappe - NESG-401





Supplementary material/Appendix (Files for online publication only)

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