



Review Report

Musso Piantelli et al., From a Continental Margin to an Alpine Dome: 4D Geodynamic Evolution of the Aar Massif, TEKTONIKA, 2026.

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1st Round of Revisions

Decision Letter (11 July 2025)

Dear Ferdinando and Co-authors,

We have finally received the comments from two reviewers regarding your paper. First of all, we would like to apologize for the delay; it was quite challenging to find suitable reviewers for your manuscript, and subsequently, it took a considerable amount of time to receive their feedback.

That said, both reviewers agree that your paper represents a valuable scientific contribution, is suitable for the journal, and deserves to be published. However, they have requested some revisions.

We have carefully read both the reviews and the manuscript, and we concur with the reviewers' comments. We therefore invite you to revise your manuscript accordingly. In particular, we suggest paying close attention to the following points:

- Provide a clearer explanation of the nature of the faults and/or shear zones, including their relative kinematics. Sometimes it is not clear if you are dealing with faults or shear zones.
- Strengthen and elaborate on your interpretation of the transform faults located between the external massifs.
- Expand the literature review concerning previous studies in the area to help unfamiliar readers better understand the broader geological context.
- Address all requested figure modifications made by the reviewers, as well as the comments annotated directly in the manuscript text.

The reviews are appended below. Both reviewers have uploaded several files with their comments and suggestions. You will be able to get these files while connecting to your Tektonika space.

We look forward to receiving your revised manuscript. Together with the revised manuscript, please upload a rebuttal answering all points raised by the reviewers and editors, and also a manuscript version with changes marked. As reviewers have commented on the Tektonika review form and on the manuscript's PDF, please list their main points in your rebuttal letter and answer accordingly.

Given the relatively minor nature of these revisions, but also considering the coming summer break, we are giving you a deadline by the end of August.

Best regards

Chiara Montomoli, Tektonika associate editor

Robin Lacassin, Tektonika executive editor

Comments by Reviewer 1 (S. Iaccarino)

Dear Authors,

First of all, I would like to apologize for my delay in submitting my revision, but this is a busy period with the end of the spring semester and related field activities. I have attentively scrutinized the manuscript of Musso Piantelli et al., entitled "4D geodynamic evolution of the Aar Massif: from a passive margin to the core of the Central European Alps" submitted to the journal *Tektonika*.

The paper concerns the structural characterization of the Aar Massif, one of the External Crystalline Massifs of the European Alps (Central Alps). With the aid of geological mapping, 3D geological models, and cross-sections - integrated with published literature data (in particular data on metamorphic T and timing of deformation) - the Authors were able to clearly depict the present-day structural architecture of the Aar Massif, concerning both the deformation of basement and cover. Connecting their data and data from the literature, the authors were able to deconvolve the puzzling evolution of the Aar Massif during the Alpine collision, and to infer the possible original architecture of this portion of European proximal passive margin, before the onset of Alpine convergence. Interestingly (in parag. 5.5) Musso Piantelli et al., stressed also the importance of their reconstructions for the society, a point that in my opinion should be recalled also in the abstract.

Concerning the manuscript, the text is well organized, clear and well connected with figures. The figures and related captions are well done and clear. References are appropriate and pertinent. I would also like to point out how the supplementary material is really informative and well prepared.

In summary, I see a lot of potential in the Musso Piantelli et al. manuscript that could be of interest both to Alpine geologists and to a broader audience. The current shape of the manuscript (including the main text and figures) is really good, so I suggest Minor revisions.

Main comments

I have only one main points, which is more related to a nomenclature problem:

(i) in the whole manuscript, as well as in the figures, the authors use the term "faults" as a synonymous of ductile shear zones. Faults is "Generally used for brittle structures (structures dominated by brittle deformation mechanisms) [Fossen, 2010]" Indeed, you describe "stretching lineations" that are commonly part of mylonitic fabric in high strain zones. If you are describing brittle faults, maybe slickenlines would be better here – so, I suggest to clarify that you are referring to both brittle and ductile structures (namely brittle faults and narrow high-strain ductile shear zones).

Minor comments

I have listed several minor suggestions and comments directly on the annotated pdf files (main text and figures), that are attached.

Reviewer has also commented on the PDFs of the manuscript's text and figures. Please address all their comments and suggestions.

Comments by Reviewer 2 (P.H. Leloup)

Reviewer has used the TEKTONIKA review form. Please refer to their comments in the form. They have **also commented on the PDFs of the manuscript's text and figures.** Please address all their comments and suggestions.

Section A: Overview of manuscript

A1) Overall evaluation, general comments & summary

A1.1) Reviewer's comments

A1.1.1) General evaluation and publication suggestion – Required:

Please use this space to describe, in your own words, the core subject of the submission and your overall assessment of its suitability for publication.

The paper presents a 3D geological model of the Aar range, and a retro-deformation of that model. The authors then discuss the Alpine history of deformation of the range. The main implications are: 1) that the Aar range results from the inversion Mesozoic passive margin with basins localized on former Permian basins. 20% of the present structural relief is inherited from the passive margin. 2) Alpine uplift occurred since 20 Ma above 4 main faults activated in sequence from internal to external. 3) the central part of the range experienced more uplift than the two extremities.

Nice paper with an impressive amount of data that fit the scope of the journal but some details / interpretations are questionable.

A1.1.2) What does the submission need to be publishable? (select as needed; comment for all cases)

- No changes required
- Rewriting
- Reorganising
- More data/figures
- Condensing
- Reinterpretation
- Other

Comments:

The authors need to consider the numerous comments within the text to be more convincing. The absence of any kinematics analysis is quite surprising.

A1.1.3) Can the submission be improved by reducing/adding any of the following? (select as needed; comment for all cases)

- Text
- Table
- Figures
- Supplementary material

Comments:

An illustration of the faults kinematics is needed

A1.1.4) Please complete the following section if you recommend that the submission is NOT appropriate for publication (select as needed; comment if a box is selected)

- Quality is poor
- Research is not reproducible
- Other

Comments:

A1.2) Author(s) Responses:

A2) Summary of main merits and main points of improvement

A2.1) Reviewer's comments

Please describe below in a few sentences (100 to 300 words) the main merits of the submission and suggestions for improvements.

The main merits I have found are...

The paper is well written, well organized and with nice and clear figures. The methods are clearly presented. This is a large piece of work that deserve to be published.

The main points of improvement I have found are...

It should be made clearer that this is not exactly 3D.

The paper rests on a former long history of previous studies that are cited which is normal and necessary, but in some cases insufficient for the reader to really understand the details.

There is a lack of clear description of the kinematics that opens the way to slightly different interpretation.

A2.2) Author's responses:

Section B: Detailed evaluation of manuscript

B1) Title and abstract

B1.1) Reviewer's comments

*These statements are a **guide** to what good Titles and Abstracts include. Please select YES or NO to the statements below if you wish and detail in the free form box below your reasons for any box checked with NO, or to comment on any other matter.*

The *Title* describes the main topic of the manuscript **accurately** — [NO] Not sure to understand the second part.

The *Title* describes the main topic of the manuscript **succinctly** — [NO]

The *Title* includes **appropriate key terms** — [YES]

The *Abstract* includes a **clear aim and rationale** — [YES]

The *Abstract* supports the rationale with **sufficient background information** — [YES]

The *Abstract* includes a **well-balanced description of the methods** — [YES]

The *Abstract* describes the **main results sufficiently and adequately** — [YES]

The *Abstract* clearly describes the **importance/impact of the study** — [YES]

The *Abstract* clearly states the **conclusions of the study** — [YES] mostly

The *Abstract* is **clear and well structured** — [YES]

Comments:

B1.2) Author's responses

B2) Introduction

B2.1) Reviewer's comments

*These statements are a **guide** to what good Introductions include. Please select YES or NO to the statements below if you wish and detail in the free form box below your reasons for any box checked with NO, or to comment on any other matter.*

The *Introduction* provides **sufficient background and context** for the study — [YES]

The *Introduction* describes the **aim/hypothesis/rationale** clearly, providing **sufficient context** — [YES]

The *objective/hypothesis/rationale* **flows logically from the background** information — [YES]

The *Introduction* describes the study's **objective and approach** (last paragraph) — [YES]

The *Introduction* contains **relevant, suitable citations** — [YES]

The *Introduction* is **organized effectively** — [YES]

Comments:

B2.2) Author's responses

B3) Data and methods

B3.1) Reviewer's comments

*These statements are a **guide** to what good Method sections include and good practices for Dataset accessibility. Please select YES or NO to the statements below if you wish and detail in the free form box below your reasons for any box checked with NO, or to comment on any other matter.*

The *Methods* are described **concisely and with enough detail** for reproducibility — [YES]

Necessary information about **data sources/acquisition/processing** is included — [YES]

Data used are accessible via either supplementary files or links in the data availability statement — [YES] Mostly but not every structural measurement that has been used.

The *Dataset and/or Methods* are **organized effectively** — [YES]

Comments:

The method presented here is not formally a 3D reconstruction but the interpolation between 2D sections. In the case of the Aar, it works because the range is quite cylindrical. The same is true for the retro-deformation. This should made clearer as other methods exist that are closer to real 3D. These other methods should be cited.

I am also quite sceptical that shear zones can effectively mapped from the use of DEM without mixing with other structures such as joints.

B3.2) Author's responses

B4) Results

B4.1) Reviewer's comments

*These statements are a **guide** to what good Result sections include. Please select YES or NO to the statements below if you wish and detail in the free form box below your reasons for any box checked with NO, or to comment on any other matter.*

The *Results* findings are **supported by data** — [YES]

The *Results* findings are presented **clearly and succinctly** — [YES]

The text in the *Result* section **cites tables and figures appropriately** — [YES]

The *Results* directly **relate to the study objectives** — [YES]

The *Results* present **data for all the approaches** described in the *Methods* section — [YES]

The *Results* **text belongs to the Results section**, not to *Introduction, Methods, or Discussion*. — [YES]

The *Results* section is **organised effectively** — [YES]

Comments:

The range is described as a dome when it is in fact more a half dome. The basement / cover interface does not dip symmetrically on both sides. This is important because all the faults dipping in the same direction the shape mostly depends on the sense and amount of motion of the faults, and they are all described as dipping in the same direction and being all inverse.

The geometry of the structures is relatively well described, but there is a general lack of discussion on the kinematics of deformation. The “faults” generally show no offset. The word “shear criteria” does not appear. I am quite sceptical about the steep reverse faults that a) never show any offset, b) are supposed to precede the thrusts but in fact not, c) are supposed to be numerous when only three of them have a significant offset. I guess that a simpler interpretation with the steep shear zones being in pure shear, coevally with the shallower thrusts being in simple shear, might well explain the 4D reconstruction with the necessity of only 4 main thrusts activated from internal to external.

Note that the outward migration of deformation is appealing but is not constrained by the data (nor the geological setting).

There is some confusion about the “Aar basement high” or “central high”. It could give the impression that it is an NE-SW horst with lows on both sides, when it is a step with a deep on only one the SE side. Further, there is a NW-SE high between the Mesozoic basins in the South. In the discussion it is sometime confusing about which high the authors are talking about. I encourage to specify the directions and / or give different names.

It is surprising that the location of the normal faults inherited from Carboniferous / Permian guide the location of the Mesozoic basins but that these faults are not inversed. Further if they are not inversed they should have been preserved, but not one is described.

B4.2) Author's responses

B5) Discussion and conclusions

B5.1) Reviewer's comments

*These statements are a **guide** to what good Discussions and Conclusions include. Please select YES or NO to the statements below if you wish and detail in the free form box below your reasons for any box checked with NO, or to comment on any other matter.*

The *Discussion* is **focused on the objectives** of the study — [YES] mostly

The *Discussion* **addresses all major results** of this study, which are shown in *Results* — [YES]

The *Discussion* section makes **comparisons with other studies** that are relevant and informative — [NO] No comparison with other 3D model nor other External crystalline massif

The *Discussion* section properly identifies all **speculative statements** — [NO]

The *Discussion* section presents the **implications of the study** persuasively — [YES] / [NO]

The *Discussion* section **highlights novel contributions** appropriately — [YES] / [NO]

The *Discussion* section **addresses the limitations** of the study appropriately — [YES] / [NO]

The *Discussion* section is **organised effectively** — [YES] / [NO]

The *Conclusions* are **consistent** with and **summarise** the rest of the manuscript — [YES]

The *Conclusions* are **supported by the data** in *Results* and **follow logically** from the *Discussion* — [NO]

The *Conclusions* are **clear and concise** — [YES]

Comments:

The interpretation of transform faults in between the external massifs is not sustained by any data from this article.

The interpretation of larger amount of thrusting in the inner part of the range as due to buoyancy forces is taken from (Herwegh et al., 2017, 2020; Kissling and Schlunegger, 2018). However, the authors should give enough explanation that the reader can understand the hypothesis without reading the references.

B5.2) Author's responses

B6) Figures, tables and citations

B6.1) Reviewer's comments

*These statements are a **guide** to what good Figures and Tables include and how they are presented. Please select YES or NO to the statements below if you wish and detail in the free form box below your reasons for any box checked with NO, or to comment on any other matter.*

*Tables and Figures are **ordered logically** and **numbered sequentially** — [YES]*

*Tables and Figures have **captions that explain** all their major features — [YES]*

*Tables and Figures have **captions that complement** the information in the main text — [YES]*

*Tables and Figures present data that **relate** to the study objective — [YES]*

*Tables and Figures present data that are **consistent** with and support the description of results — [YES]*

*Tables and Figures have **succinct and informative titles** — [YES]*

*Figures are **accessible** (elements are clearly labelled, accessible colour palettes, colour contrasts, font size legible, etc....) — [YES]*

Please, check our [\[Figure guidelines\]](#)

Figures with maps or cross-sections contain all **elements to be understood** (north arrow orientation, scale, visible coordinates, sufficient coordinate grid intercepts) — [YES]
Unless Fig.4 and 6 missing coordinates

Figures with maps have **sufficient location information** (in the map or caption) — [YES]

Cross-sections have clear labels for **scale and coordinates** at ends and within-section kinks — [YES]

All georeferenced elements are provided in common format (.shp, .geotiff, .kml) [in an open-access repository] — [YES] / [NO]

Citations throughout are relevant, suitable, and comprehensive — [YES]

Comments:

B6.2) Author's responses

Section C: Additional comments

C1) Minor/line-numbered comments

C1.1) Reviewer's comments

See attached file

C1.2) Author's responses

C2) Other remarks

C2.1) Reviewer's comments

C2.2) Author's responses

Authors' Reply to Reviewer 1 and 2

General response to reviewer comments

This document contains our detailed replies to the comments from the two reviewers. Line numbers and chapter names refer to the originally submitted manuscript.

In this document:

- Reviewer comments appear in italic grey text.
 - Author responses are provided in regular font.
 - Revised manuscript excerpts are shown in bold.**
-

REPLY TO COMMENTS OF REVIEWER 1

Section A: Overview of manuscript

A1) Overall evaluation, general comments & summary

A1.1) Reviewer's comments

A1.1.1) General evaluation and publication suggestion – Required:

Dear Authors,

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Concerning the manuscript, the text is well organized, clear and well connected with figures. The figures and related captions are well done and clear. References are appropriate and

pertinent. I would also like to point out how the supplementary material is really informative and well prepared.

In summary, I see a lot of potential in the Musso Piantelli et al. manuscript that could be of interest both to Alpine geologists and to a broader audience. The current shape of the manuscript (including the main text and figures) is really good, so I suggest Minor revisions.

A1.2) Author(s) Responses:

We would like to thank the reviewer for the positive and constructive feedback. In response to the comments, we have made specific improvements in the manuscript. First, we refined the nomenclature used in the previous version, which may have caused some confusion regarding the specific types of structures encompassed by the general term “faults.” Second, we agree with the reviewer that the significance of large-scale 3D geological models should be emphasized. Accordingly, and in coordination with the comments from Reviewer 2, we have revised paragraph 5.5 and strengthened the corresponding emphasis in the abstract.

A detailed response to the reviewer’s specific comments is provided in the following paragraphs.

A2) Summary of main points of improvement

A2.1) Reviewer’s comments

The main points of improvement I have found are...

I have only one main points, which is more related to a nomenclature problem:

In the whole manuscript, as well as in the figures, the authors use the term "faults" as a synonymous of ductile shear zones. ‘Faults’ is "Generally used for brittle structures (structures dominated by brittle deformation mechanisms) [Fossen, 2010]" Indeed, you describe "stretching lineations" that are commonly part of mylonitic fabric in high strain zones. If you are describing brittle faults, maybe slickenlines would be better here – so, I suggest clarifying that you are referring to both brittle and ductile structures (namely brittle faults and narrow high-strain ductile shear zones).

A2.2) Author’s responses:

We thank the reviewer for the careful review. We agree that the nomenclature used in the previous version of the manuscript may have led to some confusion regarding the specific types of structures encompassed by the general term ‘faults’.

To address this, we have revised the text in the section **2. Geological Setting and Age Constraints** (lines 124–144) to clarify that, throughout the manuscript, the term ‘faults’ refers to both brittle faults and ductile shear zones. This confusion likely stems from the fact that high strain zones originate as (i) ductile shear zones at depth but are commonly overprinted with exhumation by younger lower-temperature brittle deformation and (ii) metamorphic conditions during deformation varied strongly between sub-

greenschist facies in the northern Aar Massif and upper greenschist facies conditions in the southern Aar Massif. The resulting deformation structures therefore often show characteristics of both brittle and ductile deformation. Additionally, we have checked the manuscript to make sure that the terms stretching lineation and slickenlines are consistently applied in the context of ductile or brittle structures, respectively. The revised paragraph now reads:

During the collisional stage, the Aar Massif experienced a protracted exhumation history from approximately 22 Ma to the present (Herwegh et al., 2020), accompanied by the development of a dense network of Alpine fault zones. Metamorphic conditions during deformation varied significantly across the massif. At its northern rim, Alpine metamorphic temperatures did not exceed ~250 °C (e.g., Bambauer et al., 2009; Berger et al., 2017a; Herwegh et al., 2017; Rosenberg et al., 2021). At the southern boundary, peak Alpine conditions reached approximately 450 °C and 600 MPa, corresponding to upper greenschist facies (Goncalves et al., 2012; Herwegh et al., 2020). Under these conditions, the basement units were primarily deformed in a ductile manner, as evidenced by the formation of mylonites and ultramylonites. However, brittle precursors and episodes of rapid embrittlement also contributed to strain localization (Wehrens et al., 2016; 2017). This deformation resulted in a dense network of subvertical to steeply inclined shear zones that dissect most of the Aar Massif (see Baumberger et al., 2022, and references therein).

With progressive deformation and exhumation, the basement rocks reached shallower crustal levels and lower temperatures. During this stage, brittle deformation often reactivated pre-existing ductile structures. This led to the formation of brittle fractures, cataclasites, fault gouges, and breccias. As a result, individual structural discontinuities often exhibit both ductile and brittle deformation characteristics, behaving as shear zones at depth and as fault zones at shallower levels, with a brittle–ductile transition in between.

To aid in clear and consistent communication, we refer to these structures collectively as "faults" throughout this contribution, following the nomenclature of Sibson (1977).

A similar clarification sentence was also added in the figure caption of Fig. 4. We trust this addition clarifies the intended usage of terminology and improves the manuscript's readability.

Section C: Additional comments

C1) Minor/line-numbered comments

C1.1) Reviewer's comments

I have listed several minor suggestions and comments directly on the annotated pdf files (main text and figures), that are attached.

Detailed comments:

1. Line 48

Which are such exhumation phenomena? It is not clear here

Text clarified into: **Such inversion-related exhumation processes**

2. Line 50

Which are such variations? It is not clear here, please specify

Text clarified into: **The full complexity of such geometric variations**

3. Line 61

structural,

structural added

4. Line 69

the External Crystalline Massifs

Text corrected into: **the External Crystalline Massifs**

5. Line 101

Please, give the types of rocks in a singular form. Check the remaining part of the manuscript

Corrected into singular form and the remaining part of the manuscript was also controlled.

6. Line 115

syn-rift

Corrected

7. Line 126

??? maybe Aar ?

Typo corrected

8. Line 141

;

Corrected

9. Line 147

;

Corrected

10. Line 153

what types of minerals?

We added in the text the specification: **The age of this transition is constrained by isotopic ages on syn- to post-kinematic minerals (white mica, biotite and monazite) from cross-cutting strike-slip faults and associated Alpine clefts (Challandes et al., 2008; Rolland et al., 2009; Bergemann et al., 2017; Ricchi et al., 2019)**

11. Line 168

do you mean faults and shear zones or only brittle faults?

This comment has already been addressed in the general response, where we clarified that the term "fault" is used broadly to encompass both brittle and ductile deformation features.

12. Line 170

;

Corrected

13. Line 188

please specify how these T are obtained

Obtained from Raman spectroscopy of carbonaceous material. This information was implemented in the text.

14. Line 195

The

Corrected

16. Line 250

so, actually they are ductile shear zones

To address the brittle component of the structures, we have also included the term **slickenlines**.

17. Line 250

,

Corrected

18. Line 288

;

Corrected

19. Line 337

(Fig. 7d)

Corrected

20. Line 355

;

Corrected

21. Line 438

give a references here for these nappes

Steck, 2008; Reference added

22. Line 458

Could you please specify a bit more what type of data/model(s) is/are presented in this long list of papers?

This study is based on the data reported by Nibourel et al. (2018), which already integrates all previously established concepts. This sentence was included in the text:

23. Line 472

could you specify a bit more here the implication of this re-equilibration?

We agree with the reviewer that assuming horizontal metamorphic isograds across the Aar Massif at peak temperature must be carefully justified. We have clarified that assuming horizontal isograds at peak metamorphic conditions allows us to constrain the z-component (depth) of our reconstruction. We have added the following statements to clarify that the vertical position of our retrodeformation is based on this assumption, and we justify this assumption more carefully:

Interpolation of the retrodeformed peak temperature data indicates in this portion of the margin an average geothermal gradient of 26 °C/km (Supporting Information). Peak metamorphism in the study area was reached by burial in the footwall to the basal Helvetic thrust, the main active tectonic boundary at the time, above which was situated the Alpine nappe stack of Helvetic, Penninic and Austroalpine nappes (Fig. 7a; Pfiffner, 2015). By assuming near-horizontal isograds during peak metamorphism, the peak-tempearature becomes a key constraint, defining the depth of our retrodeformed continental margin prior to the onset of Alpine contractional deformation. Note that in a setting with rapid tectonic movements, heat advection could result in oblique or locally even inverted thermal gradients (e.g., England & Molnar, Girault et al., 2020). However, numeric models (e.g., Shi & Wang, 1987) indicate that thermal perturbations across low-angle thrusts such as the basal Helvetic thrust, having slip rates lower than 5 mm/a re-equilibrate rapidly, (Nibourel et al., 2021b; Pfiffner, 2015). Although minor temperature perturbations cannot be excluded, this supports the assumption of an overall steady geothermal gradient of about 25°/km depth around peak metamorphic conditions.

24. Line 479

;

Corrected

25. Line 480

;

Corrected

26. Line 491

During

Corrected

27. Line 501

do you mean brittle and ductile or brittle-ductile structures?

Text simplified in **faults**, to be coherent set at the beginning of the manuscript. See reply to the general comment made by the reviewer.

28. Line 526

;

Corrected

29. Line 528

this could be difficult for a reader not expert of the area

To enhance clarity for readers who may not be familiar with the regional geology, the sentence was rephrased as follows:

The cumulative vertical uplift between 22 and 10 Ma led to a significant uplift of the Aar Massif. This uplift also caused passive bending of the overlying, already-emplaced Helvetic nappe stack, as demonstrated by the deformation of major basal thrusts such as the Glarus and Doldenhorn thrusts (e.g., Herwegh and Pfiffner, 2005; Pfiffner et al., 2011; Musso Piantelli et al., 2022).

30. Line 578

this is a rather important part - I think few words should be spent also in the abstract

We agree with the reviewer that the value of large-scale 3D geological models should be emphasised, the final sentence of the abstract was improved into:

The results of this study highlight the importance of integrating large-scale 3D geological modelling in the analysis of complex geological systems, such as orogens. By enabling a comprehensive understanding of their 4D evolution and geodynamic processes, this methodology opens the doors for a wide range of applications in tectonics, resource exploration, and hazard assessment.

31. Line 619

I would also stress that with your methods the amount of non-cylindricity is easier to imagine

The sentence was improved into: **This, as shown in our 4D reconstruction, resulted in a non-cylindrical deformation and exhumation of the massif, leading to a larger uplift component in the central regions of the massif and smaller uplift at the W and E-sides of the massif.**

32. Line 629

orogenic settings

Corrected

Figures minor comments

33. Figure 1

not informative - insert of what?

The sentence was improved into: **Regional overview map simplified after Schmid et al., 2004.**

is it possible to specify that the trace of the section is in (A)

What Reviewer 1 suggested was also considered by us already while designing the figure; however, this is not possible, as the trace extends well beyond the extent of the map shown in the figure. Nevertheless, the coordinates of the trace—as well as those of other profiles and field locations—are provided in Paragraph 1 of the SI file.

34. Figure 2

correct "fault sys." as above

Corrected

35. Figure 4

Actually, stretching lineation in case of faults is not a proper term, maybe slickenlines?

We thank the reviewer for noticing the inconsistency in nomenclature: in the legend of the figure and the figure caption it was added the term **slikenlines/stretching lineation** to include both brittle and ductile kinematic indicators.

poles of what? - poles to the main foliation???

For clarification, in the figure legend and caption we added the term: **fault planes poles and mean pole**.

please clarify if you are talking of faults, shear zones or both

The comment has been already addressed in the reply to the general comment of the Reviewer. Beside the improvements done in Section 2, we also added in the caption of Fig. 4 the following statement to clarify once more that the term fault includes both faults and shear zones: **As outlined in Section 2, the term 'faults' refers to both brittle faults and ductile shear zones.**

36. Figure 5

Modified

Corrected

Figure 7

Ma, the

Corrected

,

Corrected

2020, 2023;

Corrected

REPLY TO COMMENTS OF REVIEWER 2

Section A: Overview of manuscript

A1) Overall evaluation, general comments & summary

A1.1) Reviewer's comments

A1.1.1) General evaluation and publication suggestion – Required:

The paper presents a 3D geological model of the Aar range, and a retro-deformation of that model. The authors then discuss the Alpine history of deformation of the range. The main implications are: 1) that the Aar range results from the inversion Mesozoic passive margin with basins localized on former

Permian basins. 20% of the present structural relief is inherited from the passive margin. 2) Alpine uplift occurred since 20 Ma above 4 main faults activated in sequence from internal to external. 3) the central part of the range experienced more uplift than the two extremities.

Nice paper with an impressive amount of data that fit the scope of the journal but some details / interpretations are questionable.

A1.1.2) What does the submission need to be publishable? (select as needed; comment for all cases)

- No changes required
- Rewriting
- Reorganising
- More data/figures
- Condensing
- Reinterpretation
- Other

Comments:

The authors need to consider the numerous comments within the text to be more convincing. The absence of any kinematics analysis is quite surprising.

A1.1.3) Can the submission be improved by reducing/adding any of the following? (select as needed; comment for all cases)

- Text
- Table
- Figures
- Supplementary material

Comments:

An illustration of the faults kinematics is needed

A1.2) Author(s) Responses:

We thank the reviewer for the careful review and comments. We fully acknowledge that this work builds on a substantial body of research conducted over the past years by numerous authors. In the previous version, we kept the description of the kinematics brief in order to highlight the novel findings of our study, rather than repeating results already well documented in earlier work. The reviewer's comments prompted us to recognize that this description could benefit from additional detail, and we have accordingly expanded it. Rather than adding another figure, which would largely compile information

already presented in the cited studies, we have strengthened the text and emphasized references where readers can find the supporting field and microstructural evidence. We believe these revisions enhance clarity and provide a more complete context for the presented and discussed results.

A detailed response to the reviewer's comments is provided in the following paragraphs.

A2) Summary of main merits and main points of improvement

A2.1) Reviewer's comments

The main merits I have found are...

The paper is well written, well organized and with nice and clear figures. The methods are clearly presented. This is a large piece of work that deserve to be published.

The main points of improvement I have found are...

It should be made clearer that this is not exactly 3D.

The paper rests on a former long history of previous studies that are cited which is normal and necessary, but in some cases insufficient for the reader to really understand the details.

There is a lack of clear description of the kinematics that opens the way to slightly different interpretation.

A2.2) Author's responses:

Response to: It should be made clearer that this is not exactly 3D.

A detailed reply to this comment is provided under the [data and methods \(B3.2\)](#) section.

Response to: *The paper rests on a former long history of previous studies that are cited which is normal and necessary, but in some cases insufficient for the reader to really understand the details. There is a lack of clear description of the kinematics that opens the way to slightly different interpretation.*

We thank the reviewer for raising this point and for suggesting a more detailed discussion of the kinematics of the structures investigated in this study. The reviewer is correct that this work builds on a large amount of research conducted over the last fifty years by numerous authors.

In the manuscript we stated:

The kinematics and the age of these faults have been investigated and described in many scientific publications over the past decades (see Herwegh et al., 2017, 2020; Nibourel et al., 2021a, and references therein). In this study, we largely rely on such literature for the kinematics and age of the faults zones, hence a brief summary is provided below, but the reader is encouraged to consult the cited literature for more details.

Our reason for this approach was to keep the focus of the article on the new findings of our research, rather than repeating in detail results that have already been thoroughly documented in previous studies.

Furthermore, in the results section, the reviewer also provided a comment relevant to this topic: *The geometry of the structures is relatively well described, but there is a general lack of discussion on the kinematics of deformation. The “faults” generally show no offset. The word “shear criteria” does not appear. I am quite sceptical about the steep reverse faults that a) never show any offset, b) are supposed to precede the thrusts but in fact not, c) are supposed to be numerous when only three of them have a significant offset. I guess that a simpler interpretation with the steep shear zones being in pure shear, coevally with the shallower thrusts being in simple shear, might well explain the 4D reconstruction with the necessity of only 4 main thrusts activated from internal to external.*

We agree with the reviewer that what we refer to as “reverse faults” may have a strong pure shear component. However, a large number of independent observations indicate that these structures also have a significant simple shear component which appears to be dominated by S-block up movements. Here is a brief summary of our arguments:

- Outcrop-scale or thin section-scale kinematic indicators such as asymmetric porphyroblasts, shear bands or asymmetric folds often indicate S-up kinematics.
- Although individual shear planes record only relatively small displacements, their cumulative effect at a larger scale results in predominantly south-block up movements, which is particularly evident along the basement–cover contact (i.e. steep basement reverse faults steepen the basement-cover contact where they intersect).
- The exposed metamorphic pattern, increasing from sub-greenschist facies in the north to upper greenschist facies in the south, also suggests that the Handegg Phase structures, in the following summarised as reverse faults, contain a strong reverse component.

To make sure the reader is able to understand the kinematics, corresponding statements have been added to the kinematics section (lines 167 – 197, see below):

At 22 Ma the exhumation of the basement units was initiated with the formation of an early set of steep to sub-vertical NW-SE striking faults **and an associated heterogeneously developed foliation** (e.g., Handegg phase; Steck, 1968; Wehrens et al., 2017; Bergemann et al. 2017; Herwegh et al., 2017, 2020; Mair et al., 2018; Nibourel et al., 2021a). **Outcrop- and micro-scale kinematic indicators documented in these studies mostly point to S block up movement along these faults. Although individual shear planes record only relatively small displacements (less than a few tens of meters), their cumulative effect at a larger scale result in predominantly south-block up movements. This is particularly evident where steep basement reverse faults steepen the shallow-dipping basement-cover contact, see for example Fig. 3c. Such small offsets, distributed across a large number of reverse faults, cannot be represented at the map or cross-section scale (1:25,000). For this reason, in the map of Fig. 4 we display only the most prominent faults, while in the cross-sections and field images we highlight reverse faults using a patterned style that reflects their overall trend and orientation. The exposed metamorphic pattern, increasing from sub-greenschist facies in the north to upper greenschist facies in the south, also suggests that the Handegg Phase structures, in the following summarised as reverse faults, contain a reverse component (e.g. Herwegh et al., 2017).** These reverse faults were dated at 21–17 Ma based on isotopic ages on syn-kinematic micas (Challandes et al., 2008; Rolland et al., 2009;

Berger et al., 2017a).

In the northern domain, where the Handegg-phase structures are less developed, discrete thrusts dominate the structural appearance (e.g., Burkhard, 1988; Herwegh et al., 2020; Nibourel et al., 2021a). Offsets along the basement-cover contact or slickenfibres on the thrust surfaces consistently indicate top-to-the-NNW kinematics. Some of the thrusts are overprinted by subsequent steeper reverse faults and must, therefore, predate the Handegg reverse faults (e.g., Windgällen phase D2; Nibourel et al., 2021a, and reference therein). In the southern domain (subregions R1 to R3 in Fig. 4), these early thrusts are mostly obliterated by subsequent deformation. A second set of thrusts, having the same kinematics and characteristics, clearly post-dates the Handegg reverse faults (i.e., Pfaffenchof faults; Mock, 2014; Wehrens et al., 2017; Herwegh et al., 2020; Nibourel et al., 2021a, b). This dichotomy of exhumation of the basement units including reverse faulting and thrusting lasted until 12-10 Ma and led to the formation of the structural relief of the massif as well as the passive “up-doming” of the overlying nappe stack (Fig. 2; e.g., Handegg and Pfaffenchof faults; Mock, 2014; Wehrens et al., 2017; Herwegh et al., 2020; Nibourel et al., 2021a, b). According to recently published thermochronology studies (e.g. Nibourel et al. 2021b; Glotzbach et al. 2010), the exposed Aar Massif internal thrusts and reverse faults have not accommodated significant vertical displacements between 10 Ma and present.

A major kinematic switch occurred at 14-10 Ma whereby: (a) large-scale NNW-vergent thrust structures developed at the northern front of the massif, causing an ‘en bloc’ exhumation of the massif (Herwegh et al., 2020, 2024; Nibourel et al., 2021a,b). **These frontal thrusts are situated at a greater depth and their presence is inferred from seismic profiles (Pfiffner et al., 1997).** (b) In the southwestern units of the massif, strike-slip to oblique faults **developed, often reactivating** the precursor reverse faults (Fig. 1; Oberaar phase, Wehrens et al., 2017; Herwegh et al., 2020, 2024). **According to Wehrens et al. (2016), SSW-NNE to NW-SE striking mostly subvertical faults, for which shear criteria indicate a dextral sense of shear, are most abundant. A subordinate set of SW-NE to NNW-SSE striking steep shear zones is also documented (Wehrens et al., 2016, Nibourel et al. 2021a).** The age of this transition is constrained by isotopic ages on syn- to post-kinematic minerals from cross-cutting strike-slip faults and associated Alpine clefts (Challandes et al., 2008; Rolland et al., 2009; Bergemann et al., 2017; Ricchi et al., 2019). (c) Transtensional movements along the Rhone-Simplon fault system affected the southern margin of the western massif and adjacent units (Fig. 2; e.g., Grosjean et al., 2004; Campani et al., 2014).

Related to this comment the reviewer made also a comment to the figures: *The red ones on figures 3, 4 and 5? If yes none of these does not show any offset. Are they really faults or shear zones or simply of foliation? Could the authors show one example of thin section to be sure of what we are talking about.*

The Aar Massif is dissected by thousands of faults (see e.g., Wehrens et al., 2017). At the map scale (1:25,000), only the most prominent faults could be displayed. In the cross-sections and field images, we highlighted them with a patterned style that reflects their overall trend and orientation. Including all faults would have obscured the figures entirely, as they would appear almost uniformly red. To clarify this for the reader, we have revised the captions of Figures 2, 3, 5, and 7 to state: **Reverse faults are shown using a patterned style due to their high frequency and dense distribution.**

Each of these faults makes a vertical displacement. Wehrens et al., 2017, Berger et al., 2017 and Nibourel et al., 2021, are all publications where such structures have been already largely discussed both in the field and microstructurally. When cross-cutting the basement-cover contact or prominent

markers (e.g. dikes) estimates on the actual displacements can be made (see Wehrens et al., 2017; Nibourel et al., 2021). These studies demonstrate that individual shear zones typically show offsets of less than a few tens of meters, which cannot be resolved at map or cross section scale (see also Figs. 12 and 13 in Nibourel et al., 2012). Nevertheless, the cumulative displacement accommodated by the large number of shear zones is significant and is clearly expressed in the pronounced north–south metamorphic gradient. To clarify this for the reader, we added the following sentence (Lines 185 - 190): **This is particularly evident where steep basement reverse faults steepen the shallow-dipping basement-cover contact, see for example Fig. 3c. Such small offsets, distributed across a large number of reverse faults, cannot be represented at the map or cross-section scale (1:25,000). For this reason, in the map of Fig. 4 we display only the most prominent faults, while in the cross-sections and field images we highlight reverse faults using a patterned style that reflects their overall trend and orientation. The exposed metamorphic pattern, increasing from sub-greenschist facies in the north to upper greenschist facies in the south, also suggests that the Handegg Phase structures, in the following summarised as reverse faults, contain a reverse component (e.g. Herwegh et al., 2017).** These reverse faults were dated at 21–17 Ma based on isotopic ages on syn-kinematic micas (Challandes et al., 2008; Rolland et al., 2009; Berger et al., 2017a).

The reviewer brings up another important point: *Note that the outward migration of deformation is appealing but is not constrained by the data (nor the geological setting).*

Indeed, we assume an in-sequence evolution of deformation affecting first the S and later the N domain of the Aar Massif. In the revised version of our manuscript, we specify (1) that this is an assumption (line 291), and (2) we justify this assumption using the arguments listed below in lines 293 – 307:

The results of the cross-section restoration are presented in a 4D stepwise evolution, **assuming an in-sequence deformation** of the basement units of the massif from 22 Ma to the present day (Fig. 7). **This assumption is supported by the following observations and arguments: (i) Given the N-directed movement of the Helvetic nappes and higher tectonic units, the proposed in-sequence deformation in the Aar Massif basement from S to N appears to be a reasonable assumption. (ii) the fan-shaped arrangement of reverse faults (in section view, see Fig. 1c), with progressively steeper dips toward the hinterland. Such an arrangement commonly reflects an in-sequence evolution of the fault system in which older faults were passively rotated within the hanging wall of younger, frontal faults. (iii) The Windgällen thrust and recumbent anticline structure is passively folded and rotated by later steep reverse faults emerging from the footwall to this early thrust (Fig. 2). This indicates that deformation overall migrated from S to N. (iv) Recently published thermochronology studies (e.g. Nibourel et al. 2021b; Glotzbach et al. 2010) demonstrate that the exposed Aar Massif-internal thrusts and reverse faults have not accommodated significant vertical displacements between 10 Ma and present (e.g., see Fig. 5 in Herwegh et al., 2020). However rapid cooling between 10 Ma and present at the larger scale point to continued thrusting along frontal thrusts at depth north of the Aar Massif (Fig. 1c, Nibourel et al., 2021b). This also suggests an overall in-sequence evolution.**

Section B: Detailed evaluation of manuscript

B1) Title and abstract

B1.1) Reviewer's comments

The *Title* describes the main topic of the manuscript **accurately** — [NO] Not sure to understand the second part.

The *Title* describes the main topic of the manuscript **succinctly** — [NO]

The *Title* includes **appropriate key terms** — [YES]

The *Abstract* includes a **clear aim and rationale** — [YES]

The *Abstract* supports the rationale with **sufficient background information** — [YES]

The *Abstract* includes a **well-balanced description of the methods** — [YES]

The *Abstract* describes the **main results sufficiently and adequately** — [YES]]

The *Abstract* clearly describes the **importance/impact of the study** — [YES]

The *Abstract* clearly states the **conclusions of the study** — [YES] mostly

The *Abstract* is **clear and well structured** — [YES]

B1.2) Author's responses

Response to: *(Title) Not sure to understand the second part*

A new title more descriptive of the article and engaging has been suggested:

From a Continental Margin to an Alpine Dome: 4D Geodynamic Evolution of the Aar Massif

Response to: *(abstract states clearly the conclusion of the study) mostly.*

As in response to Reviewer 1's main comment, we have revised the abstract to highlight the key outcomes of our work more clearly. We also emphasize the value of integrating 3D geological models to better understand the evolution of complex geological systems, such as orogens.

B2) Introduction

B2.1) Reviewer's comments

The *Introduction* provides **sufficient background and context** for the study — [YES]

The *Introduction* describes the **aim/hypothesis/rationale** clearly, providing **sufficient context** — [YES]

The *objective/hypothesis/rationale* **flows logically from the background** information — [YES]

The *Introduction* describes the study's **objective and approach** (last paragraph) — [YES]

The *Introduction* contains **relevant, suitable citations** — [YES]

The *Introduction* is **organized effectively** — [YES]

B3) Data and methods

B3.1) Reviewer's comments

The *Methods* are described **concisely and with enough detail** for reproducibility — [YES]

Necessary information about **data sources/acquisition/processing** is included — [YES]

Data used are accessible via either supplementary files or links in the data availability statement — [YES] Mostly but not every structural measurement that has been used.

The *Dataset and/or Methods* are **organized effectively** — [YES]

Comments:

The method presented here is not formally a 3D reconstruction but the interpolation between 2D sections. In the case of the Aar, it works because the range is quite cylindrical. The same is true for the retro-deformation. This should made clearer as other methods exist that are closer to real 3D. These other methods should be cited.

I am also quite sceptical that shear zones can effectively mapped from the use of DEM without mixing with other structures such as joints.

B3.2) Author's responses

Response to: *The method presented here is not formally a 3D reconstruction but the interpolation between 2D sections. In the case of the Aar, it works because the range is quite cylindrical. The same is true for the retro-deformation. This should made clearer as other methods exist that are closer to real 3D. These other methods should be cited.*

The Reviewer on line 180 requests discussion of the 3D modelling technique used to build the 3D model of the manuscript:

If I understand well this is not really 3D bur rather 2.5D: the 3D comes from the interpolation of data in

2 D (along the cross sections). This is not exactly the same than doing a real 3D interpolation. Some methods / softwares allow to do such real 3D interpolations directly from the measurements, not their projection on 2D sections. This point should be discussed.

See for example:

Campani, M., Mancktelow, N., & Courrioux, G. (2014). The 3D interplay between folding and faulting in a syn-orogenic extensional system: the Simplon Fault Zone in the Central Alps (Switzerland and Italy). *Swiss Journal of Geosciences*, 107, 251-271.

Mercier, A., Leloup, P. H., Courrioux, G., Caritz, S., Lopez, S., Grandjean, P., ... & Kalifi, A. (2023). Large thrusting and late faulting shape the Aiguilles Rouges crystalline massif (Western Alps), structural implications. *Tectonophysics*, 847, 229691.

Mercier, A. (2023). *4D reconstruction of alpine deformations in the western Alps: implications on the orogenic wedge evolution (Doctoral dissertation, Université Claude Bernard-Lyon I)*.

We thank the Reviewer for raising this point and requesting clarification. However, we respectfully disagree with the assertion that the results presented in this manuscript are ‘not really 3D but rather 2.5D.’ Both the Aar Massif model and the 4D reconstruction meet the widely accepted definition of 3D geological models. Specifically, they are “digital representations of the Earth’s subsurface that use data models and computer techniques to represent geo-objects (for example, strata, structures, non-stratified geological bodies, and rock type) in 3D and depict, in a volumetric sense, information that geologic maps portray at the Earth’s surface (Turner, 2005; Apel, 2006)”, as defined, for example, in the U.S. Geological Survey Inventory of three geologic models (2004–2022, <https://doi.org/10.3133/dr1183>).

In our case, the models contain explicit three-dimensional geometries that can be queried, sliced, and visualized from any orientation. This is fundamentally different from 2.5D approaches, in which variation in one dimension is merely represented as an attribute draped over a 2D surface. Our reconstructions incorporate not only 2D constructional cross sections, but also continuous 3D spatial information derived from: (i) 3D lithostratigraphic and structural contacts of model units exposed at the surface (from 4’200 to 400 m a.s.l.); (ii) borehole and railway tunnel logs from the Lötschberg–Gotthard transect; and (iii) all available seismic data.

We agree with the reviewer that we did not employ implicit 3D modelling techniques or software (the ‘real 3D interpolation’ intended by the reviewer) to construct our models but instead used an explicit 3D modelling approach. In implicit modelling, geological surfaces are typically derived from isosurfaces in a three-dimensional scalar field interpolated from all the available input data, in the form of interface points, orientation data, and potentially additional off-surface constraints (e.g., Wellmann and Caumon, 2018). With the explicit modelling approach the same input dataset is used but it is also supplemented by multiple cross sections that define the geological rules and form of the resulting interpolated meshes.

We also agree with the Reviewer that the implicit approach is generally preferable, as more mathematically driven, less subjective, and more reproducible than the explicit approach (although even these approaches require a considerable number of user-defined rules, which introduces subjectivity similar to that in explicit models). In fact, we even tested implicit modelling software during our workflow to generate the surfaces. However, the large size of our model (surface area ~5’300 km²), the number of geological units (22), and the highly complex structural setting exceeded the

computational capabilities of the implicit softwares we evaluated. The results did not achieve the spatial resolution required to address the scientific questions central to this project.

For this reason, for this project, we decided to follow an explicit modelling strategy. In the manuscript, as well as in the SI file this was already stated:

Line 182: **Following this approach, the 3D tectonic architecture of the Aar Massif was explicitly modelled incorporating all available field observations, structural analyses at the outcrop scale, tunnel and literature data, as well as large-scale seismic profiles from the NFP20 atlas and 3D tomographic imaging (Pfiffner et al., 1997, Diehl et al., 2021).**

Chapter 4 of SI: **Due to the complex geometries of the units, an explicit modelling approach was used to generate the 3D geological model.**

To address the comment made by the Reviewer we improved the Paragraph 3.2 where we:

- changed the title form '3D Geological modelling' to **3D Explicit Geological modelling**
- clarified that we did not use only cross sections for the interpolation but also the continuous 3D spatial information derived from: **3D lithostratigraphic and structural contacts of model units exposed at the surface (from 4'200 to 400 m a.s.l.); (ii) borehole and railway tunnel logs from the Lötschberg–Gotthard transect; and (iii) all available seismic data.**

Furthermore, in the Paragraph 4 of the SI file we added a section that explains why we decided to work with an explicit approach and not an implicit one due to the very large scale of the model, the high number of geological units modelled and the highly complex alpine geological/structural setting we aimed to model.

Lastly, we have gladly included the citations to the publications suggested by the reviewer. We would, however, like to note that the scale and, importantly, the number of units modelled in these studies is significantly smaller than in our work. This is relevant because, when applying the same methodologies at the scale of our study, most implicit modelling software reach their computational limits and are not yet capable of interpolating regions of this size and complexity while producing results of sufficiently accurate quality.

Response to: I am also quite sceptical that shear zones can effectively mapped from the use of DEM without mixing with other structures such as joints.

In our remote sensing strategy, we did not rely only on a DEM. As described in Section 3.1, faults were identified remotely using high-resolution orthophotos (SwissImage, raster resolution 0.25 × 0.25 m; swisstopo), a high-resolution Digital Elevation Model (swissALTI3D, downsampled raster resolution 2 × 2 m, version 2013; swisstopo), and derived hillshade maps.

We acknowledge the reviewer's point that faults can be difficult to detect remotely without mistaking them for joints or foliation. To address this challenge, our methodology was based on a previous study by Baumberger et al. (2022) in a valley of the Aar Massif, which demonstrated a strong match between remotely detected structures (the same one discussed in our manuscript) and field observations.

In addition, in 2023 we conducted our own study (Musso Piantelli et al., 2023; <https://doi.org/10.1111/ter.12666>) along the Aletsch Glacier valley in the centre of the Aar Massif. In that work, faults were first detected at a large scale (using orthophotos, DEM, and hillshades)

and then at much higher resolution using UAV orthomosaics (millimetre resolution) at multiple field locations (Fig. A1). Then we performed at the same sites field verification along scan-line surveys, during which we collected rock hardness measurements (Schmidt hammer, Classic 'N' type), lithological descriptions, and records of fault plane occurrence at 1 m intervals on exposed rock surfaces (Fig. 1a; Appendix B). The sites were selected in close proximity to the glacier and within the Little Ice Age limit to minimise the effects of weathering on the outcrops. Across all field locations, we found a strong correspondence between remotely detected faults and field observations (Fig. A1; Musso Piantelli et al. 2023).

Several factors make the faults discussed in this manuscript particularly well-suited for remote detection: (i) most structures are nearly vertical, minimising topographic intersection effects; (ii) the massif has limited vegetation and extensive rock exposure; and (iii) the faults themselves are relatively limited in width (decimetres to a few metres) yet laterally very persistent, often traceable for several kilometres, making them easily distinguishable from much shorter joints.

To address the comment made by the Reviewer we improved the **Paragraph 3.1** where we clarified that this methodology has been testified with correlation across several scales and provided the references: **Baumberger et al., 2022 and Musso Piantelli et al. 2023.**

B4) Results

B4.1) Reviewer's comments

The *Results* findings are **supported by data** — [YES]

The *Results* findings are presented **clearly and succinctly** — [YES]

The text in the *Result* section **cites tables and figures appropriately** — [YES]

The *Results* directly **relate to the study objectives** — [YES]

The *Results* present **data for all the approaches** described in the *Methods* section — [YES]

The *Results* **text belongs to the Results section**, not to *Introduction*, *Methods*, or *Discussion*. — [YES]

The *Results* section is **organised effectively** — [YES]

Comments:

The range is described as a dome when it is in fact more a half dome. The basement / cover interface does not dip symmetrically on both sides. This is important because all the faults dipping in the same direction the shape mostly depends on the sense and amount of motion of the faults, and they are all described as dipping in the same direction and being all inverse.

The geometry of the structures is relatively well described, but there is a general lack of discussion on

the kinematics of deformation. The “faults” generally show no offset. The word “shear criteria” does not appear. I am quite sceptical about the steep reverse faults that a) never show any offset, b) are supposed to precede the thrusts but in fact not, c) are supposed to be numerous when only three of them have a significant offset. I guess that a simpler interpretation with the steep shear zones being in pure shear, coevally with the shallower thrusts being in simple shear, might well explain the 4D reconstruction with the necessity of only 4 main thrusts activated from internal to external.

Note that the outward migration of deformation is appealing but is not constrained by the data (nor the geological setting).

There is some confusion about the “Aar basement high” or “central high”. It could give the impression that it is an NE-SW horst with lows on both sides, when it is a step with a deep on only one the SE side. Further, there is a NW-SE high between the Mesozoic basins in the South. In the discussion it is sometime confusing about which high the authors are talking about. I encourage to specify the directions and / or give different names.

It is surprising that the location of the normal faults inherited from Carboniferous / Permian guide the location of the Mesozoic basins but that these faults are not inverted. Further if they are not inverted, they should have been preserved, but not one is described.

B4.2) Author’s responses

Response to: *The range is described as a dome when it is in fact more a half dome. The basement / cover interface does not dip symmetrically on both sides. This is important because all the faults dipping in the same direction the shape mostly depends on the sense and amount of motion of the faults, and they are all described as dipping in the same direction and being all inverse.*

We acknowledge the comment made by the reviewer and we changed in the term ‘dome’ in the whole the manuscript into **half dome**.

Response to: *The geometry of the structures is relatively well described, but there is a general lack of discussion on the kinematics of deformation. The “faults” generally show no offset. The word “shear criteria” does not appear. I am quite sceptical about the steep reverse faults that a) never show any offset, b) are supposed to precede the thrusts but in fact not, c) are supposed to be numerous when only three of them have a significant offset. I guess that a simpler interpretation with the steep shear zones being in pure shear, coevally with the shallower thrusts being in simple shear, might well explain the 4D reconstruction with the necessity of only 4 main thrusts activated from internal to external.*

Note that the outward migration of deformation is appealing but is not constrained by the data (nor the geological setting).

A detailed reply to this comment is provided under the summary of main merits and main points of improvement (A2.2) section.

Response to: *There is some confusion about the “Aar basement high” or “central high”. It could give the impression that it is an NE-SW horst with lows on both sides, when it is a step with a deep on only one the SE side. Further, there is a NW-SE high between the Mesozoic basins in the South. In the discussion*

it is sometime confusing about which high the authors are talking about. I encourage to specify the directions and / or give different names.

We thank the reviewer for the comment and agree that the lack of clear directions could be misleading for readers. To address this, we have:

- Corrected the nomenclature by removing inconsistencies between Aar basement high and central high, standardising all text and figures to **Aar basement high**.
- Revised **Figure 9** to reduce potential confusion: in both **Fig. 9b** and **Fig. 9c**, we added a contour line clearly delimiting and highlighting the area reconstructed as the **Aar basement high**.
- Improved the text at lines 396–399 as follows:

The reconstructed passive margin shown in Figure 9 displays a prominent topographic high, highlighted by the black contour line, and flanked by three asymmetric half-grabens: Doldenhorn, Susten–Windgällen, and Tödi. This basement high, here named the ‘Aar topographic high’, coincides with a southern promontory of the Alemannic Land (see Fig. 9b and c; Trümpy, 1952).

Response to: *It is surprising that the location of the normal faults inherited from Carboniferous / Permian guide the location of the Mesozoic basins but that these faults are not inverted. Further if they are not inverted they should have been preserved, but not one is described.*

Jurassic normal faults are indeed well preserved in some locations within the Aar Massif and have been documented in previous work (e.g., Nibourel et al., 2021 but also already Rohr in 1926). Prominent examples include the Färnigen (Susten) normal fault (illustrated in Fig. 3c of our manuscript) and the Tödi normal fault. These occurrences provide robust field evidence for the preservation and not (or only weak reactivation) during the alpine collision of Jurassic extensional structures in the region.

Regarding the Färnigen normal fault Nibourel et al., 2021 wrote:

‘The Färnigen normal fault is marked by an up to metre thick non-cohesive fault breccia (Fig. 11b). The directly adjacent gneisses are dissected by cataclasites, which indicate S-block down normal fault kinematics. A few metres away from the normal fault, gneisses preserve their pre-Variscan foliation and are largely unaffected by Alpine deformation (Fig. 11b). The normal fault strikes 060° ENE and dips 70° – 80° SSE. Stretching lineations on the fault surface are down-dip (Fig. 11b). The Färnigen normal fault was weakly reactivated as a steep reverse fault during Alpine inversion, as indicated by an increasingly sharp angle between the Mesozoic strata and the fault plane with decreasing distance to the normal fault (Fig. 11a).’

Regarding the Tödi normal fault Nibourel et al., 2021 wrote:

‘The SSE-vergent Tödi normal fault is a major structure, which was not reactivated during Alpine Structural and thermal evolution eastern Aar Massif Page 25 of 43 9 collisional deformation (Fig. 13a). It can be subdivided into two segments, separated by an up to 50 m wide fault block Fig. 13a). Each of these segments accommodated approximately 250 m of displacement during normal faulting, which amount to an estimated SSE-down displacement of 500 m (when dip-slip kinematics are assumed, see Fig. 13a). Triassic pre-rift strata are still attached to the footwall, the intermediate fault block and to the hanging wall to the normal fault, while they were eliminated along the fault surface (Figs. 12 and 13a). This is consistent with the larger thickness of the Middle Jurassic strata in the Tödi “syncline” (i.e., the

inverted half-graben, Fig. 13a), thus attesting to active rifting during the Middle Jurassic (cf. Günzler-Seiffert 1941). Note that thickness-variations could partly be due to layer thickening during folding (Ramsay and Huber 1987). The Tödi normal fault intersects the basal Mesozoic strata at an angle of approximately 60° (Fig. 13a). Basement and cover units adjacent to the northern tectonic normal fault contact were not significantly affected by Alpine deformation as highlighted by (i) preserved pre-Alpine fabrics in the basement or (ii) by primary sedimentary structures in the cover strata. In the basement close to the normal fault, we observed monomictic breccias with internally weakly deformed clasts, which are presumably related to the normal faulting (Fig. 13a).'

Regarding the reactivation or not of such faults, we interpret from what has been observed in the field by the over abovementioned authors that the temperature and tectonic burial at which the localisation of the faults occurs is very important. Indeed, as we wrote in Paragraph 5.4: **The pre-existing normal faults were not, or only weakly reactivated as described with field data by Nibourel et al., 2021a. A primary reason for this was their unfavourable orientation at the onset of reverse faulting (22 Ma), when the top of the basement dipped 10–15° southward, causing the normal faults to be in a subvertical position. In addition, the thermal and burial conditions strongly influenced fault behaviour reactivation of inherited crustal structures. High metamorphic temperatures and significant tectonic burial tend to inhibit the reactivation of inherited crustal structures, as supported by numerical models (Lafosse et al., 2016). At temperatures exceeding 300 °C, such as those prevailing during the formation of the reverse faults, deformation is accommodated through the pervasive localisation of new structures, without significant reactivation of older ones. In contrast, at lower temperatures (<300 °C), either reactivation of pre-existing faults or the localisation of newly formed ones is more likely, as for the case of the Permo-Carboniferous troughs (Lafosse et al., 2016).**

To address the comment made by the Reviewer we:

- Reinforced the link to the publications Nibourel et al., 2021 and Rohr, 1926.
- We improved the figure caption of Fig. 3c where the Färnigen normal fault is represented: **(C) Färnigen zone (modified after Nibourel et al., 2021a). The zone comprises two synformal sediment wedges, bounded by two early Jurassic normal faults (purple), and associated Permo-Carboniferous sediments. The original half-graben geometry, as well as the inherited normal fault, is still recognizable and preserved in the field. Field data from Nibourel et al. (2021) indicate that the normal fault was only weakly reactivated during Alpine inversion.**
- We stated both in the results sections as well as in the discussion that: **Along the strike, the basement units have been dissected by normal faults, still nowadays visible in the field (as described with field data by, Nibourel et al., 2021a), often associated with former Permo-Carboniferous half grabens.**

B5) Discussion and conclusions

B5.1) Reviewer's comments

The *Discussion* is focused on the objectives of the study — [YES] mostly

- The *Discussion* addresses all major results of this study, which are shown in *Results* — [YES]
- The *Discussion* section makes **comparisons with other studies** that are relevant and informative — [NO] No comparison with other 3D model nor other External crystalline massif
- The *Discussion* section properly identifies all **speculative statements** — [NO]
- The *Discussion* section presents the **implications of the study** persuasively — [YES] / [NO]
- The *Discussion* section **highlights novel contributions** appropriately — [YES] / [NO]
- The *Discussion* section **addresses the limitations** of the study appropriately — [YES] / [NO]
- The *Discussion* section is **organised effectively** — [YES] / [NO]
- The *Conclusions* are **consistent** with and **summarise** the rest of the manuscript — [YES]
- The *Conclusions* are **supported by the data** in *Results* and **follow logically** from the *Discussion* — [NO]
- The *Conclusions* are **clear and concise** — [YES]

Comments:

The interpretation of transform faults in between the external massifs is not sustained by any data from this article.

The interpretation of larger amount of thrusting in the inner part of the range as due to buoyancy forces is taken from (Herwegh et al., 2017, 2020; Kissling and Schlunegger, 2018). However, the authors should give enough explanation that the reader can understand the hypothesis without reading the references.

B5.2) Author’s responses

Response to: *The interpretation of transform faults in between the external massifs is not sustained by any data from this article.*

The reviewer in the detailed comments also wrote: *Maybe it is compatible, but I do not see what in your data allow to reach such a conclusion. All the saddle between the MCE are right-lateral NW-SE Mesozoic transform faults? Where do you see that in your data?*

We agree with the reviewer that such interpretation and upscale goes beyond the dataset and reconstruction that we presented in this study. A major limitation in discussing this issue at a larger scale is that the transfer zones between the External Crystalline Massifs are buried not only beneath autochthonous sediments but also beneath the entire Austroalpine, Penninic, and Helvetic nappe stack. This makes direct observations of these zones currently impossible and thus very difficult to

substantiate with solid data in any publication. The only robust evidence we can rely on is the en echelon arrangement of the External Crystalline Massifs, which has been documented in earlier works (e.g., Herwegh et al., 2023, and references therein).

Evidence/Interpretation for lateral offsets in transfer zone manner was already pointed out by Burkhard (1988) or by top basement isohypse and thrust lines maps of Pfiffner, 2014 (Fig. A2, below) (derived by the deep seismic project see Pfiffner et al., 1997) showing a dextral offset between the Aar Massif and the Aiguilles Rouges/Mont Blanc massifs. Furthermore the sketch represented in Fig. 9a is modified after Handy et al. 2010.

To assess the fair comment posed by the reviewer we improved the paragraph where we stated that our interpretation is based on Burkhard (1988) and Pfiffner et al., 2011 and that the one we suggested should be regarded as a conceptual model: **These features (1–3) have already been recognized by Burkhard (1988) and Pfiffner et al. (2011), who inferred a dextral transfer fault between the Aar Massif and the Aiguilles Rouges/Mont Blanc massifs. As a possible interpretative model, we suggest that such a geometry may be explained by an initial stage of oblique rifting between Europe and Adria (Herwegh et al., 2024, and references therein), with sequential pull-apart basins developing between basement highs (Fig. 9a). This scenario is consistent with patterns observed in oblique rift systems reproduced in analogue modelling experiments (e.g., McClay and White, 1995; Mart and Dauteuil, 2000; Corti et al., 2007). We emphasize, however, that this should be regarded as a conceptual model since such transfer zones are largely buried beneath thick sedimentary successions and thus cannot be directly observed.**

Response to: *The interpretation of larger amount of thrusting in the inner part of the range as due to buoyancy forces is taken from (Herwegh et al., 2017, 2020; Kissling and Schlunegger, 2018). However, the authors should give enough explanation that the reader can understand the hypothesis without reading the references.*

We thank the reviewer for the good point. In line with the reply given in the general comment in [main points of improvements](#) we expanded and refined the explanation of the interpretation in the paragraph 5.4: **On one hand, as suggested by the buoyancy-driven model of Herwegh et al. (2017) and lithospheric mantle rollback (Schlunegger and Kissling, 2018), the Aar Massif at 22 Ma underwent delamination, interpreted as a mechanical decoupling of the light continental upper and middle crust from the denser lower crust and lithospheric mantle (Nelson, 1992; Herwegh et al., 2017). As a result of this delamination, the gravitational slab-pull and negatively buoyant forces exerted by the European lithospheric mantle, which counterbalance the positively buoyant forces of the less dense upper and middle crust and the overlying rocks of the accretionary complex, were reduced (Herwegh et al., 2017). This reduction in restraining forces allowed positive buoyancy to**

On one hand, deep-seated decoupling between the middle and the lower European crust triggered the formation of steep to sub-vertical reverse faults with a strong rock uplift component (Herwegh et al., 2017, 2024). These reverse faults formed pervasively within the basement and mostly did not reactivate inherited crustal extensional structures.

B6) Figures, tables and citations

B6.1) Reviewer's comments

Tables and Figures are ordered logically and numbered sequentially — [YES]

Tables and Figures have captions that explain all their major features — [YES]

Tables and Figures have captions that complement the information in the main text — [YES]

Tables and Figures present data that relate to the study objective — [YES]

Tables and Figures present data that are consistent with and support the description of results — [YES]

Tables and Figures have succinct and informative titles — [YES]

Figures are accessible (elements are clearly labelled, accessible colour palettes, colour contrasts, font size legible, etc....) — [YES]

Please, check our [\[Figure guidelines\]](#)

Figures with maps or cross-sections contain all elements to be understood (north arrow orientation, scale, visible coordinates, sufficient coordinate grid intercepts) — [YES] Unless Fig.4 and 6 missing coordinates

Figures with maps have sufficient location information (in the map or caption) — [YES]

Cross-sections have clear labels for scale and coordinates at ends and within-section kinks — [YES]

All georeferenced elements are provided in common format (.shp, .geotiff, .kml) [in an open-access repository] — [YES] / [NO]

Citations throughout are relevant, suitable, and comprehensive — [YES]

B6.2) Author's responses

Response to: [YES] Unless Fig.4 and 6 missing coordinates.

We respectfully note that the coordinates are already provided in the manuscript. In Fig. 4, the coordinates are shown directly, and in Fig. 6a and 6b they are also indicated. For Fig. 6c-e, as stated in the figure caption, the coordinates of the field locations are listed in the Supplementary Information file and are also shown on the map in Fig. 4.

Section C: Additional comments

C1) Minor/line-numbered comments

C1.1) Reviewer's comments

Detailed comments:

1. Title

In what sense ?

This point has already been addressed in our response to the general comments on the Title section.

2. Line 15

If I understand well these data are compared at posteriri. Not used to build the model. Are they?

It is correct that the peak-temperature metamorphic data were not collected in this study but obtained from previous work by other authors. However, we retro-deformed this dataset together with our cross sections. This approach allowed us to reconstruct the shape of the passive margin segment along the isograds corresponding to peak-temperature conditions. Thus, the dataset was not used simply a posteriori, but actively retro-deformed alongside the cross sections to produce a robust reconstruction.

Accordingly, we have improved the sentence in the manuscript to read: **Cross-section restoration of such units and of metamorphic peak temperature data, allowed us to reconstruct the 4D geodynamic evolution of the massif during the late-stage Alpine orogeny.**

3. Line 58

Missing Grandes Rousses and Grand Chatelard. And Gotthard?

Grandes Rousses Grand Chatelard and Gotthard added

4. Line 66

Missing for example, and Mercier et al., 2023 (that is in 3D)

Reference **Leloup et al., 2005** added. The reference to Mercier et al. 2023 was added on line 68.

5. Line 68

Not in the case of Mercier et al. (2023)

Text improved into: **These previous approaches have documented and studied deformation structures in structural maps and/or on cross-sections, while the three-dimensional and non-cylindrical architecture and evolution of these complexes remains largely unexplored, with only limited studies addressing these aspects (Campani et al., 2014; Musso Piantelli et al., 2022; Mercier et al., 2023).**

6. Line 81

This is more a conclusion / abstract than an introduction

Sentence deleted.

7. Line 89

Why using this term and not range ? Do you imply that its is a fold ? If yes what exactly is folded ?

This point has already been addressed in our response to the general comments on the Results section.

8. Line 101

What is this meaning ? What is that cover ? Is it displaced with respect to the basement?

The following explanatory sentence was added into the manuscript: **The overlying succession of**

limestone, marl, shale, and sandstone, that compose the para/autochthonous sedimentary units, were deposited during the Mesozoic. Part of the autochthonous sedimentary cover of the Aar Massif was tectonically detached from its substrate. These detached units, referred to as the parautochthonous cover, form a series of nappes or tectonic slices. They contain incomplete successions of the same stratigraphic units preserved in the autochthonous cover (see Berger et al., 2017b) and are therefore described and discussed together in this contribution.

9. Line 103

I am not sure exactly what are these thickness variations and how they are measured especially given the high level of deformation.

We thank the reviewer for this valuable comment. Thickness variations of the studied units have indeed been measured and synthesised by several authors at multiple locations within the Aar Massif, commonly presented in the form of stratigraphic columns (Krebs, 1925; Rohr, 1926; Collet, 1947; Masson et al., 1980; Dolivo, 1982; Gisler et al., 2007; Krayenbuhl and Steck, 2009; Spillmann et al., 2011; Ziegler and Isler, 2013; Mair et al., 2018). We agree that the high deformation of these units may have caused some volume loss. Nevertheless, stratigraphic columns provide, even under such conditions, a minimum estimate the thickness of these units. Importantly, these columns consistently document greater thicknesses to the west and east of the massif, where sedimentary basins were present, and more limited thicknesses in its central part, where basins were absent (see as an example Musso Piantelli et al., 2022).

To address the comment we added the following sentence to the text and related literature citations: **These thicknesses variations have been documented by several authors at multiple locations within the Aar Massif, commonly presented in the form of stratigraphic columns (Krebs, 1925; Rohr, 1926; Collet, 1947; Masson et al., 1980; Dolivo, 1982; Gisler et al., 2007; Krayenbuhl and Steck, 2009; Ziegler and Isler, 2013; Mair et al., 2018). Importantly, these columns consistently document greater thicknesses to the western and easter regions of the massif, and more limited thicknesses in its central part (see e.g., Musso Piantelli et al., 2022).**

10. Line 110

What are these zones ? thrust ? Synforms ?

Term changed into **gneiss boundaries**.

11. Line 115

Mesozoic?

Sentence deleted.

12. Line 119

No pressure estimate ?

We have added a pressure estimate from the literature (line 137): while at the southern boundary, peak Alpine conditions reached approximately 450 °C and 600 MPa, corresponding to upper greenschist facies (Goncalves et al., 2012; Herwegh et al., 2020).

13. Line 138

The red ones on figures 3, 4 and 5? If yes none of these does not show any offset. Are they really faults or shear zones or simply of foliation? Could the authors show one example of thin section to be sure of what we are talking about.

The red lines represented in figures 3,4 and 5 but also.

This point has already been addressed in our response to the general comments on the main points of improvement (A2.2) section.

14. Line 141

Rb/Sr, 40Ar/39Ar?

On isotopic Rb/Sr and Ar/Ar ages on micas

15. Line 142

The blue ones on figures 3, 4 and 5? Some of them appear to have a significant amount of motion. So the two structures are coeval ? This is exactly the geometry one would expect for a single shearing event with steep S planes (Red) and shallow C planes (blue).

As outlined in our response to the general comments (section A2.2), we have rephrased the entire paragraph to provide a clearer discussion of this point. The revised text now in this section explicitly incorporates multiple references to field evidence previously documented by authors working in the region, which supports our interpretation of the relationship between the two structures.

16. Line 143

I am not sure to understand

We thank the reviewer for pointing this out. In our response to the general comments (section A2.2), we have rephrased the entire paragraph to improve its structure and clarity. We hope that the revised version now communicates our points more clearly.

17. Line 145

What are the data to constrain the end of that deformation?

We thank the reviewer to point out this unprecise statement. The end of massif-internal thrusting and reverse-faulting is constrained by recent thermochronology studies. These show that the exposed thrusts and faults have not accommodated significant vertical displacement between 10 Ma and present. Corresponding statements have been added (see below, line 190-197):

Within the massif, this dichotomy of exhumation of the basement units characterized by differential

uplift induced by reverse faulting and thrusting lasted until 12-10 Ma as indicated by zircon fission track ages (Herweg et al., 2022). This differential uplift led to the formation of the structural relief of the massif and caused the passive “up-doming” of the overlying sedimentary cover of the massif and Helvetic and Penninic nappe stack. (Fig. 2; e.g., Handegg and Pfaffenchof faults; Mock, 2014; Wehrens et al., 2017; Herwegh et al., 2020; Nibourel et al., 2021a, b). According to recently published thermochronology studies (e.g. Nibourel et al. 2021b; Glotzbach et al. 2010), the exposed Aar Massif internal thrusts and reverse faults have not accommodated significant vertical displacements between 10 Ma and present.

18. Line 145

Not sure to understand how you make a dome with parallel faults that have all the same sense. I understand below that it is due to outward propagation of the active faults.

As described in the Results section, the reverse faults are not all parallel; they are organized into two main fault systems that bound undeformed to weakly deformed rhomboidal basement blocks. Differential uplift of these blocks, greater in the central regions of the massif and smaller toward the margins, produces the characteristic half-dome shape of the massif, which passively bends the overlying sediments. We note that this interpretation is a direct result of our study and therefore we prefer to present it within the Results and Discussion sections, as in the original manuscript.

To address this comment, we rephrased the sentence into: **Within the massif, this dichotomy of exhumation of the basement units characterized by differential uplift induced by reverse faulting and thrusting lasted until 12-10 Ma as indicated by zircon fission track ages (Herwegh et al., 2020, 2024). This differential uplift led to the formation of the structural relief of the massif and caused the passive “up-doming” of the overlying sedimentary cover of the massif and Helvetic and Penninic nappe stack.**

19. Line 146

So the para autochtoneous sediments are a nappe stack ?

Sentence rephrased into: **sedimentary cover of the massif and Helvetic and Penninic nappe stack.**

20. Line 148

How is that constrained?

Clarification added: **As indicated by zircon fission track ages, (see Herwegh et al., 2020) major kinematic switch occurred at 14-10 Ma**

21. Line 148

Thus all the shallow faults were not active at the same time? In the reconstruction the thrust motion on the frontal fault (the only one that has a significant offset) occurs between 10 and 0 Ma.

This point has already been addressed in our response to the general comments on the main points of improvement section.

22. Line 151

Right-lateral or left-lateral? Green on Figs 2, 4 and 5. I guess it is right-lateral but again there is not a single offset along these faults.

Dextral strike slip added to the text. This is also indicated in Fig. 5.

23. Line 153

What kind ?

See reply n°10 to Reviewer 1.

24. Line 153

So this constrains the strike -slip not the frontal thrust.

Correct the isotopic ages constrain the strike slip movement.

25. Line 155

What do you mean ? Normal and right-lateral ? What direction?

Correct, normal and dextral strike slip. The sentence was completed in: **Transtensional movements (resulting from a combination of normal and dextral strike slip components) along the Rhone-Simplon fault system affected the southern margin of the western massif and adjacent units.**

26. Line 162

I am quite sceptical of this: in the basement even if the main structures (e.g. mylonitic foliation) can be seen in the landscape, there are many other joints that have also a strong inprint in the landscape. So it is difficult to know what is it exactly. By the way the result is a network of "fault zone" but that do not offset each other even when they cross.

This point has already been addressed in our response to the general comments on the [data and methods](#) section.

27. Line 167

This is the geometry not the kinematics

Text corrected into **geometry**.

28. Line 177

virtual ? Not sure what would be the best term

We thank the reviewer for this suggestion. While we understand that alternative terms such as virtual

cross-sections could be considered, we have chosen to retain the term **constructional cross-sections** in order to maintain consistency with Musso Piantelli (2022).

29. Line 180

*If I understand well this is not really 3D bur rather 2.5D: the 3D comes from the interpolation of data in 2 D (along the cross sections). This is not exactly the same than doing a real 3D interpolation. Some methods / softwares allow to do such real 3D interpolations directly from the measurements , not their projection on 2D sections. This point should be discussed. See for example Campani, M., Mancktelow, N., & Courrioux, G. (2014). The 3D interplay between folding and faulting in a syn-orogenic extensional system: the Simplon Fault Zone in the Central Alps (Switzerland and Italy). *Swiss Journal of Geosciences* , 107 , 251-271. Mercier, A., Leloup, P. H., Courrioux, G., Caritg, S., Lopez, S., Grandjean, P., ... & Kalifi, A. (2023). Large thrusting and late faulting shape the Aiguilles Rouges crystalline massif (Western Alps), structural implications. *Tectonophysics* , 847 , 229691. Mercier, A. (2023). 4D reconstruction of alpine deformations in the western Alps: implications on the orogenic wedge evolution (Doctoral dissertation, Université Claude Bernard-Lyon I).*

This point has already been addressed in our response to the general comments on the [data and methods](#) section.

30. Line 185

*Again, this is 2D not 3D. The method for 3D balancing are very rare but some have tried. Affolter, T., Faure, J. L., Gratier, J. P., & Colletta, B. (2008). Kinematic models of deformation at the front of the Alps: new data from map-view restoration. *Swiss Journal of Geosciences* , 101 , 289-303. Affolter, T., & Gratier, J. P. (2004). Map view retrodeformation of an arcuate fold-and-thrust belt: The Jura case. *Journal of Geophysical Research: Solid Earth* , 109 (B3).*

This point has already been addressed in our response to the general comments on the [data and methods](#) section.

31. Line 194 and 196

Common asumption that make the retrodeformation 2.5 D. All rest on the choice of the direction of the cross-sections that should be better justified.

Reply to this comment given in the following comment.

32. Line 196

quite strong - assumption. has to be more clearly justified.

We thank the reviewer for highlighting the weak argumentation regarding the assumptions underlying the cross-section restoration. In response, we have substantially revised this section by providing clearer justifications and stronger links to the relevant literature. The revised paragraph now reads as follows:

The paragraph now reads: **The cross-section restoration involved five assumptions: (i) constant length of top basement and constant area of the crustal basement in cross-section view; (ii) the pre-collisional geometry of the proximal part of the European passive continental margin were bent by ~10° below the tectonically active boundary of the overriding Helvetic nappes (see), based on the**

study of Nibourel et al., 2018, 2021b. These studies indicate that the intersection angle between inferred isograds and the top basement, as well as the basal Helvetic thrust, ranged from 10° to 15°, implying that both marker horizons at peak temperature conditions dipped southward at this angle; (iii) no significant Alpine deformation in the basement units of the Aar Massif prior to the thermal peak. This assumption is supported by the data and thermo-kinematic models of Nibourel et al. (2018, 2021a), which build upon and integrate the earlier findings of Burkhard (1988), Rahn & Grasemann (1999), and Glotzbach et al. (2010); (iv) constant mean topographic elevation throughout the restored sections, as stated by Campani et al. (2012) and Schlunegger and Kissling (2015); (v) the location of Permo-Carboniferous and sedimentary wedges (Figs. 1, 3, and 4) served as markers for the locations of syn-rift faults. This assumption is supported by field observations of Jurassic extensional structures in multiple Permo-Carboniferous and sedimentary wedges across the massif (e.g., Susten, Windgälle, Tödi, and Gastern, see e.g., Rohr in 1926; Nibourel et al., 2021b). The throws of the normal faults were reconstructed using as a minimum estimate the vertical extent of the multiple sedimentary wedges and Permo-Carboniferous troughs (for details see Musso Piantelli et al., 2022).

33. Line 207

I understand that individual offsets are difficult to quantify but is there a global estimate ? 1m as stated below seems very small.

We thank the reviewer for the comment. However, the statement is not accurate: in the manuscript we indicated a displacement of a few meters, not 1 m as suggested by the reviewer. As discussed in the manuscript, **the displacement is difficult to quantify in the field as it has been partitioned into a large number of shear zones and at the contact between the sedimentary cover and the basement in the western Aar Massif, the displacement is limited to a few meters.** Unfortunately, in this study we have not been able to observe more in the field, therefore we would prefer such conservative estimation, as any other value would not be supported by field data.

34. Line 210

So you mean outside of your "box"?

The sentence indicates the major Rhone-Simplon related strike-slip displacements occurred in the Rhone valley and did not significantly dissect the crystalline basement units of the Aar Massif. We improve the sentence into: **However, at the contact between the sedimentary cover and the basement in the western Aar Massif, the displacement is limited to a few meters (Fig. 1; note that the major Rhone-Simplon related strike-slip displacements occurred in the Rhone valley and therefore largely not affecting the Aar Massif basement units; see 3D model of Campani et al., 2014).**

35. Line 233

Again if I clearly see geometrical arguments, not much about kinematics.

We thank the reviewer for the comment, term changed in: **structural style.**

36. Line 234

I do not understand the logic of that splitting. To what corresponds the limit between the outer (R4 and R5) and inner (R1, R2, R3) regions? . Within their domain why is the R2 zone across the bend described above ?

We thank the reviewer for the comment. We have clarified the reasoning behind the subdivision into inner (R1, R2, R3) and outer (R4, R5) regions. The distinction reflects differences in structural style: the inner regions are dominated by reverse faults and dextral strike-slip structures, whereas the outer regions are mainly characterised by thrust and reverse faults.

The further subdivision of the inner domain into R1, R2, and R3 is justified as follows:

- **R1 and R3:** These regions are bounded by two principal fault systems that enclose un- to weakly-deformed rhomboid basement blocks (Fig. 5a, b). In R1, the dominant fault sets strike SW–NE and SSW–NNE, while in R3 they strike WSW–ENE and E–W (stereoplots in Fig. 4).
- **R2:** This central area represents a structural transition zone between R1 and R3, characterised by the coexistence of all three reverse fault orientations.

37. Line 242

In both cases the rose pattern rather show a maxima in between the two orientations described here. Only R5 shows a clear bimodal population.

We appreciate the observation made by the reviewer. We agree that the bending of the thrust planes induced by the exhumation of the M. and N. blocks is slight. To clarify this point we rephrased in the text: **Exposed thrust planes in the southern areas of the regions (R4-R5) exhibit a gentle curvature, dipping moderately SW before progressively flattening in the central areas and even gently tilting to the NW towards the northern rim of the massif (e.g., the thrust plane at Jungfrau, Fig. 3a; see also Fig. 4).**

38. Line 247

± ?

Sentence corrected into: **This observation is also supported by the rotation of the average dip/dip direction of the reverse fault planes in the three regions from 146/60(R1) to 153/57 (R3, Fig. 4).**

39. Line 247

± ?

Sentence corrected into: **This observation is also supported by the rotation of the average dip/dip direction of the reverse fault planes in the three regions from 146/60(R1) to 153/57 (R3, Fig. 4).**

40. Line 147

Is SR5 similar to R3, and R4 similar to R1 ? Would it be logical to draw the cross-section with an azimuth of N146° and N153°?

We agree with the reviewer's observation. R5 is indeed comparable to R3, with average dip direction/dip values of 154/66 and 153/57, respectively. Similarly, R4 corresponds well with R1, with values of 142/48 and 146/60. The cross-sections were intentionally constructed perpendicular to the main structural planes of the massif; for example, section AA' (region R1) strikes 147°, and section LL' (region R5) 156°. The difference of few degrees arises because we also considered the principal orientations of the lithostratigraphic boundaries (gneiss and plutonic intrusions), which needed to be integrated into the model.

41. Line 250

Make the symbols bigger, they are difficult to see.

The symbols in Fig. 3 have been enlarged.

42. Line 257

I guess you use thrust for shallow reverse fault. What dip is the boundary ? You should define this somewhere.

The sentence was corrected into: **Both regions are dominated by NW-vergent thrusts (formed at angle <35°) and reverse faults (Fig. 5e).**

43. Line 264

So suggesting they are folded. Note that if the thrust are folded most of reverse fault should also and in the same way than the cover/basement interface.

We thank the reviewer for this observation. As discussed in the Geological Setting and Age Constraints and Results/Discussion sections of the manuscript, the thrusts exposed at the surface of the Aar Massif belong to the southern (S) block of the massif (Fig. 10) and formed between 22 and 18 Ma. During subsequent in-sequence deformation, the central (M) and northern (N) blocks were also exhumed, and this exhumation passively overprinted the thrust planes of the S block, bending them, as observed in the field by Nibourel et al. (2021; e.g., Windgällen phase D2). This overprint affected only the regions of the massif where the S block was thrust over the M and N blocks, and therefore only the thrust areas, not the reverse faults located in the southern regions of the massif.

44. Line 329

General comment for that section. In the reconstruction the inner steep faults are active first (before 18 Ma), thus rising the inner part of the range (Fig. 7b). But in fact only some of those faults are active (the more external ones), as the basement / cover interface stays horizontal in all the inner part. Then steep faults in the center of the range activate prior to 15 Ma (Fig. 7c). But again, only the frontal ones should be active as part of the cover /basement stays horizontal. Then, prior to 10 Ma the frontal steep faults are activated (Fig.7d). During these three stages the relationship between steep and shallow faults is unclear. At last between 10 Ma and now the frontal shallow thrust is activated. I do not think that there is any geochronological data that constrain that migration. Is it ?. At least it is not clearly exposed here. Further one could propose a slightly different scenario: instead of having the steep planes activated,

three relatively shallow thrusts (blue lines) could have been activated in sequence with the red planes being only the foliation. This would give the same retro-deformation. This is somehow how it is depicted in figure 10.

We appreciate the comment of the reviewer that in part we already addressed in our response to the general comments on the main point of improvements section.

We agree that between 22 and 18Ma reverse faults (ant thrust faults) are active. However, it would not be accurate to state that only the more external faults were active during this time. As described in **paragraph 4.1**, numerous reverse faults developed in the southern block, generating a series of rhomboidal blocks (Fig. 5a,b; schematic representation in Fig. 10).

In the 2D section DD' (but also in all the other sections), the cover–basement interface rotates from a ~10° southward dip to an almost horizontal orientation, already indicating that the southern (internal) reverse faults accommodated a greater exhumation component than the northern (external) ones. Furthermore, in 3D (Fig. 10b), each rhomboidal block displays a distinct uplift component, with larger displacements concentrated in the central part of the southern basement block and smaller ones toward the western and eastern margins of the massif. These observations indicate that within the southern block a large number of reverse faults were active, ranging from the most internal to the most external parts of the block. The same process can also be recognized in both the M and N blocks (Fig. 10c,d).

Regarding the part of the comment relative to the thrusts faults and geochronological data we addressed in our response to the general comments on the main point of improvements section.

45. Line 355

So at the same time thrust towards the NW in the outer part of the massif, ENE-WSW trending right-lateral faults in the inner part of the range, and normal faulting on the Simplon (connected to right-lateral motion on E-W faults)? I thought that the Simplon fault was older (18 Ma).

In the text as well as in the figures the Rhone Simplon fault system we stated is active from ca. 15 Ma in accordance to literature (Grosjean et al., 2004; Campani et al., 2014; Cardello et al., 2024).

46. Line 358

Is this the width of the deformed zone?

2.5 km is the vertical offset. Sentence improved into: **as was the Rhone Simplon transtensional system, which dissected the south-western edge of the massif by ca. 2.5 km of vertical offset (Purple line in Fig. 7d,e; Grosjean et al., 2004; Campani et al., 2014; Cardello et al., 2024).**

47. Line 396

This is more a step than really a high. All the normal faults dip to the south and it is not an horst between two basins. So its not in "center" as there is not another basin on the other side (north).

This point has already been addressed in our response to the general comments on the results section.

48. Line 399

Not sure to see that on the figure. In fact there are two different things here. 1) A basement high step along the trend of the range whose geometry appears in part inherited from the Permian basins (same orientation). 2 a high basement zone in between the Doldenhorn and susten basin , which is perpendicular but do not appears controled by another set of faults but simply by less throw on the main Mesozoic fault system, somehow similarly to the Permian fault system. In the following discusion it is not always clear for me to what the authors refer to.

This point has already been addressed in our response to the general comments on the results section.

49. Line 420

The evidence of this rather that all three Mesozoic basins are located on top and parallel to Permo-Carboniferous troughs . Not the 3D reconstruction.

We thank the reviewer for the comment and agree with their observation. In the original sentence:

Besides this large-scale 3D margin architecture, the reconstruction reveals also a direct link between Mesozoic margin topography/basin asymmetries to the pre-existing crustal structures of the basement units imposed by the multiple Permo-Carboniferous troughs.

we intended to convey that our reconstruction allows this link to be clearly visualized (“reveals”), which is difficult to express without a reconstruction. To clarify this point, we have improved the paragraph as follows:

Besides this large-scale 3D margin architecture, the reconstruction highlights also the direct link between Mesozoic margin topography/basin asymmetries to the pre-existing crustal structures of the basement units imposed by the multiple Permo-Carboniferous troughs (e.g., Santantonio and Carminati, 2011; Lafosse et al., 2016; Balázs et al., 2017). The large number of wedges with Mesozoic sediments associated with the occurrence of the pre-existing Permo-Carboniferous troughs (e.g., Fig. 3c) indicates a strong correlation between Mesozoic normal faulting and inherited crustal structures (Berger et al., 2017b).

50. Line 444

Unclear

Sentence improved into: **The Aar Massif transitions basins at the western and eastern side, whereby both depth and width diminish gradually towards the Aar basement high.**

51. Line 447

Maybe it is compatible but I do not see what in your data allow to reach such a conclusion. All the saddle between the MCE are right-lateral NW-SE Mesozoic transform faults ? Where do you see that in your data?

This point has already been addressed in our response to the general comments on the Discussion and conclusion section.

52. Line 465

How much thickness for the Penninic and Helvetic nappes?

The sentence has been improved into: **Peak metamorphism in the study area was reached by burial in the footwall to the basal Helvetic thrust, the main active tectonic boundary at the time, above which was situated the ca. 15km thick Alpine nappe stack of Helvetic, Penninic and Austroalpine nappes (Fig. 7a; Pfiffner, 2015).**

53. *Line 475*

You mean were larger?

We meant that the peak-temperature at maximum burial conditions of the reconstructed sedimentary–basement contact along the margin shows a pronounced north-to-south increase.

Sentence improved into: **The peak-temperature at maximum burial conditions of the reconstructed sedimentary–basement contact along the margin shows a pronounced north-to-south increase, rising from ~240°C in the north to ~380–460°C in the south (Fig. 7 extended).**

54. *Line 479*

What do you mean exactly?

Sentence improved into: **Such reconstruction is in good agreement with the thermochronometric and structural data of Nibourel et al. 2021b; Berger et al. 2020; Herwegh et al. 2017, 2020; and the pressure estimate of 6.5 kbar from Goncalves et al., (2012).**

55. *Line 480*

Why?

As discussed in the assumptions for the cross-section restoration, the pressure estimate of Goncalves et al. (2012) is consistent with the depth of the margin reconstructed in our study. This comment has already been addressed through the improvements made to the assumptions underlying the cross-section restoration.

56. *Line 495*

Not sure to understand precisely what you are referring to

This point has already been addressed in our response to the general comments on the Discussion and conclusion section.

57. *Line 509*

with respect to what ?

Sentence improved into: **Consequently, a combination of enhanced horizontal shortening and vertical exhumation rates (Fig. 8c) in the central region of the block, induced a +4 km uplift of the basement-cover contact relative to its depth at maximum burial (see Fig. 10a).**

58. Line 517

in this case sides means East and west. Right ?

Correct. The sentence was improved into: **At these locations, thrust structures were generated and, together with reverse faulting, they induced a further exhumation of basement units, which was greater in the central regions (+4 km) compared to the western and eastern sides (+2 km).**

59. Line 519

sorry but not sure to see steep faults offsetting the shallow one on that figure

We thank the reviewer for finding a wrong figure referencing. The sentence was deleted.

60. Line 539

Not sure to understand what you mean. How to stop buoyancy forces ?

We thank the reviewer for requesting clarification. We have revised the text to provide a clearer and more detailed explanation: **During this phase, exhumation, which had previously been influenced by the interplay between isostasy and the orogenic stress field, became increasingly controlled by far-field compressional forces. In other words, thrusting ('horizontal tectonics') overtook the previously observed 'vertical tectonics' as the role of isostatic forces diminished (Herwegh et al., 2017, 2020; Schlunegger and Kissling, 2020).**

61. Line 549

What are you talking about?

We agree with the reviewer that the sentence was overly intricate and could confuse the reader. To improve clarity, we have removed this statement from the manuscript.

62. Line 561

sorry I am not sure to understand how the decoupling induces the formation of steep thrusts.

This point has already been addressed in our response to the general comments on the Discussion and conclusion section.

63. Line 571

So the normal faults control the location of the thrusts but are not reactivated. If they are then preserved is there any direct observation of such fault ?

This point has already been addressed in our response to the general comments on the results section.

64. Line 583

not that much.

The term considerable was deleted.

65. Line 587

I basically do agree but the point is whether what brings your 3D model.

We thank the reviewer for the comment. We reinforced the paragraph introducing the example of the Aletsch Glacier (central Aar Massif), where with our 3D model we have been able to prove that the 3D pattern of faults initiated at deep crustal level, nowadays exposed on the surface, strongly dominate the valley morphology and distribution of natural hazards in present-day Alpine landscapes (Musso Piantelli et al., 2023).

66. Line 606

with half grabens in the south separated by a high.

Correct. We improved the sentence into: **The Aar Massif is the result of the inversion of former ~6000 km² of passive European continental margin. Reconstruction of the proximal margin has revealed an asymmetric architecture with local half-graben basins, on the western and eastern sides of the massif and a the Aar Massif basement high in the central regions of the massif.**

67. Line 607

half dome

This point has already been addressed in our response to the general comments on the [results](#) section.

68. Line 608

basement / cover interface

Sentence corrected into: **The resulting structural relief developed in this stage formed 20% of the present-day half dome-shape of the basement-cover contact of the massif.**

Figures minor comments

69. Figure 2

= Para-/autochthonous cover ?

Correct the indication of: **the overlying upper Helvetic nappes.**

Of the Para-/autochthonous cover / basement interface ?

Sentence improved into: **The sections highlight the half dome-shape of the crystalline units of the massif.**

70. Figure 3

none of these "faults" has a significant offset.

As replied in the general comments section, we chose to represent the reverse faults in the figures using a patterned style that reflects their general trend and orientation. To clarify this for the reader, we have added the following sentence to the captions of Figures 2, 3, 5, and 7: **Reverse faults are shown using a patterned style due to their high frequency and dense distribution.**

In the North there is no Permian associated. Is the Southern normal fault hidden? Because of a quite different orientation? Why two Permian synforms in the south? Only one thrust appears to have a significant offset bringing the basement on top of the Mesozoic that goes through the top of the Griessenhorn, but it barely appears on the drawing.

The comment was partly addressed already in our general response to the results section. The Färnigen Zone was described in detail by Nibourel et al. (2021) based on field observations. The southern normal fault was also documented by Nibourel et al. (2021), who wrote:

'A second SSE-vergent inherited normal fault appears to be located in the north of the southern wedge. This second normal fault is poorly exposed but can be inferred from (i) the presence of Permo-Carboniferous clastic and volcanoclastic sediments only in its hanging wall, (ii) the elimination of the Middle Jurassic strata in its footwall (Kammer 1985) and (iii) cataclasites in the adjacent crystalline basement (Kammer 1985). It dips approximately 70° towards SSE. The sediments of the southern wedge represent the fill of a second half-graben'.

Regarding the two Permian synforms in the south, we interpret these as the result of an inherited extensional paleogeographic feature that was subsequently inverted by multiple reverse faults with varying exhumation components. Note indeed that the Permo-Carboniferous sediments are present also on both the 'limbs' of the synform.

To directly address the reviewer's comment, we have revised the figure caption to strengthen the explicit link to Nibourel et al. (2021) and to clarify that the southern normal fault is only poorly exposed.

71. Figure 4

Why not code the colors as for the other figures? Blue (two different blues if you like) for thrust, red for reverse fault and green for strike-slip (whilst it would be good to differentiate right-lateral from left-lateral).

We thank the reviewer for the comment. The stereoplots are already color-coded as suggested; however, we agree that the color scheme may not have been sufficiently clear, as it was not explained in the figure caption or in the main text. To address this, we have now explicitly clarified in both the caption and the main text that the colors correspond to the different structural types.

72. Figure 6

Why not show the location of the original data? Why not the two maps at the same scale so a direct correspondance could be made?

We thank the reviewer for their comments on Fig. 6. We intentionally made insert A smaller than B because the map in insert A is not new, it was previously published by Nibourel et al. (2021b). By keeping it smaller, we aimed to direct the reader's focus toward the main outcome of the study, namely the 3D

model and its DEM presented in the 2D top view.

Regarding the display of the original peak-temperature data, we found that adding the points and labels directly on the map made it difficult to read. Therefore, we opted to show the interpolated isogrades from Nibourel et al., which interpolated the data used in this study, while providing the full dataset locations in Table S2 of the Supporting Information. Additionally, the locations are illustrated in both map and section views in the reconstructions shown in Fig. S12. This approach ensures that the figure remains clear and readable while keeping all the necessary information of the underlying available.

2nd Round of Revisions

Decision Letter (18 Nov. 2025)

Dear Ferdinando and Co-authors,

We have finally received the comments from two reviewers regarding your revised manuscript.

Both reviewers agree that now your manuscript has been significantly improved and represents a valuable scientific contribution and deserves to be published pending minor revisions. We invite you to revise your manuscript accordingly. In particular, we suggest paying close attention to the second reviewer's comment regarding the reconstruction of the tectonic evolution and consequently the 4D model. Since the sequences of different tectonic phases strongly affects the 4D model, as noted by the reviewer, you should consider and discuss that also other interpretations than the one you are proposing are also possible.

Please also amend all the minor errors highlighted by both reviewers.

The reviews are appended below.

We look forward to receiving your revised manuscript in less than a month. Together with the revised manuscript, please upload a rebuttal answering all points raised by the reviewers and editors, and also a manuscript version with changed marked.

Best regards

Chiara Montomoli, Tektonika associate editor
Robin Lacassin, Tektonika executive editor

Comments by Reviewer 1 (S. Iaccarino)

Dear Editor, Dear Authors

I have evaluated the revision version of the manuscript of Musso Piantelli et al., submitted to the journal Tektonika.

The authors have duly considered our previous suggestions. I have identified only a few minor errors, listed below, which do not compromise the overall quality of the manuscript. After these minor issues are addressed, I recommend the manuscript for acceptance.

Minor comments:

Line 271 - faults(Fig. 1

please add a space between "faults" and "("

Line 273 - Rolland et al., 2009),) and

please remove the extra ")"

Line 408 - correct "Nibouel" it is misspelled

Line 427 - faults(blue in Fig. 4)

please add a space between "faults" and "("

Line 445 - 146/60(R1)

please add a space between "60" and "("

Line 521 - field data by, Nibourel

I think the "," is not need here

line 655 - correct "hypothethised" in hypothethised

line 666 - ", " and "." are flipped after e.g.

Line 674-675 - please correct in Pfiffner et al. (2011)

Line 701 - move the head of parag. 5.2 to the next line

Line 709 - I think "Rahn & Grasemann (1999)", should be Rahn and Grasemann (1999)

Line 733 - temperature is misspelled here

Line 740 - add a space between "conditions." and "The"

Line 747 - ad a space between "data" and "of Nibourel"

Line 806 - one "by" is superfluous

Line 1059 - I think here "and" and "()" are not needed here

Line 994 - references: I have noticed that some journals are cited with their full names, while others are abbreviated. Please check the Tektonika guidelines for references and ensure consistency.

Comments by Reviewer 2 (P.H. Leloup)

For author and editor

- The authors have meticulously answered to the questions of my 1st review, and I think that the paper is now clearer on several points, and I would recommend publication with only minor revisions.
- However, I still have a main concern that was not really taken into account. This concerns the succession of tectonic phases and the way it is implemented in the 4D reconstruction, and the interpretation. In my first review I raised that point both in the geological setting and in the results section.

- In the geological setting (now lines 147-201) the authors have increased de details of the structural evolution resting on many published papers. This improves the understanding of the context, but it does not really clarify a key point. If I understand well the Windgällen phase (D2 of Nibourel et al., 2021a) with top to the NNW thrusts, is followed by the Handegg phase (D3 of Nibourel et al., 2021a) with heterogeneous deformation and steep NW-SE foliation with predominantly south-block up movements, and then by the Pfaffenchoepf phase with again top to the NNW thrusts similar to D2 (D4 of Nibourel et al., 2021a). These three phases are presented as occurring one after the other. However, only the timing of D2 is actually constrained by geochronology (syn-kinematic micas at 21–17 Ma; Challandes et al., 2008; Rolland et al., 2009; Berger et al., 2017a), and none of the cited papers clearly demonstrate that succession in time. It would then appear much simpler that these 3 “phases” are in fact all coeval, with the D3 structure being S planes and the D2 and D4 structures being C planes of a single progressive deformation phase of thrusting toward the NW. Large pure shear on the D3 structures (Choukroune and Gapais, 1983; Marquer and Gapais, 1985) could have a small component of simple shear (also top to the NW). For example, the Fig.6b & c in Herwegh et al. (2020) can simply interpreted as a classical S/C structure where both structures are synchronous, rather than the crosscutting and passive folding of Sh planes by latter SP shear planes.

Some detailed comments on that geological setting are found below:

Line 198: why initiated? It appears below that a first phase of thrusting toward the NW already occurred.

Line 202: I did not find any of these shear indicators in any of the referred publications. From other publications (e.g., Choukroune and Gapais, 1983; Marquer and Gapais, 1985), it appears that while there is simple shear on many of individual shear zone, the bulk deformation is mostly pure shear. A small component of simple shear top to the NW is however given by the isograds geometry as mentioned on line 279-280.

Lines 235-244: It is not so clear to start by the D3 structures then describe the D1 and then the D4 that looks like the D1. But this stresses out that all these different “phases” have the same kinematics.

Lines 266-278: these three deformation phases (a, b, c) are clearly younger than the one discussed above. Are they all coeval or do they occur in sequence: a), then b), then c) ?

Note also that Nibourel et al. (2021) describe significant back-thrusting (top to the South) at the southern boundary of the massif (see their Fig. 15). To what phase should be related that deformation? Is it taken into account?

- In the result section I pointed out that different interpretations on the structure could have led to slightly different 4D reconstruction. For example, considering that the steep foliation/shear planes (Handegg) are in fact coeval with the shallow shear planes (Windgällen and Pfaffenchopf) would lead to a slightly different 4D reconstruction with the necessity of only four main thrusts activated from internal to external. The point here is not to dismiss the actual work but to show to the reader that other interpretations are possible, and that the transition from « vertical-isostatic tectonics » to « horizontal tectonics » (lines 333-337 and 864-878) stays an hypothesis, i.e. the 4D reconstruction depends on the structural model and do not by itself brings a demonstration of that model.

- The paper as still several typos, and I recommend a careful reading. Some of them are listed below:

Line 44-49 the sentence is very long and the « crustal structures » are repeated two times.

Line 116 : Along the strike of the massif, Permo-Carboniferous to Cenozoic sediments are also locally ...

Line : 123-125 “besides the Permo-Carboniferous graben infills, also syn-rift sedimentation occurred (e.g., Rohr, 1926; Nibourel et al., 2021a).” I do not really understand what this sentence is doing here. Should it not rather be on line 115?

Line 702. Missing a paragraph mark

Authors' Reply to Reviewer 1 and 2

Revised Manuscript for *Tektonika*

Dear Prof. Chiara Montomoli and Prof. Robin Lacassin,

Please find enclosed our revised manuscript entitled '**From a Continental Margin to an Alpine Dome: 4D Geodynamic Evolution of the Aar Massif**'.

We appreciate the opportunity to revise the manuscript and submit an improved version. We are also thankful for the reviewers' suggestions and comments, which we have carefully addressed, resulting in improvements to the manuscript. In detail, their feedback motivated us to:

- **Restructure the geological setting chapter:** We realised that in the previous version of the manuscript we have not sufficiently differentiated between the classification of the structures, their timing and influence on the exhumation history of the massif. For this reason, we decided to clarify this aspect and introduce three sub paragraphs dedicated to the three main groups of structures. In each of the sub paragraph the kinematics, timing and cross cutting relationships are discussed for each structure and linked to the respective literature.
- **Explicitly state the uncertainties and limitations** of our 4D reconstruction and structural model.
- **Improved the text** by reviewing the manuscript and correcting typos and minor imperfections.

We thank you for considering the manuscript for publication in *Tektonika*. Please do not hesitate to contact me at any time if further questions, comments or remarks arise.

Yours sincerely,

Ferdinando Musso Piantelli

On behalf of all authors

General response to reviewer comments

The following pages provide a detailed response to all comments from the two reviewers.

All line numbers, as well as chapter names and numbers, refer to the first reviewed version of

the manuscript. Reviewer comments are shown in *italic grey font*, while the authors' responses appear in regular font. Extracts from the revised manuscript that include changes are highlighted in **bold**.

Reply to comments of Reviewer 1

Detailed comments:

1. *Line 271 – faults (Fig. 1 please add a space between "faults" and "(".*

Space was added.

2. *Line 273 - Rolland et al., 2009),) and please remove the extra ")".*

The extra parenthesis was removed

3. *Line 408 - correct "Nibouel" it is misspelled.*

Reference was corrected.

4. *Line 427 – faults (blue in Fig. 4).*

Space was added.

5. *Line 445 - 146/60(R1) please add a space between "60" and "(".*

Space was added.

6. *Line 521 - field data by, Nibourel I think the "," is not need here.*

Comma was removed.

7. *line 655 - correct "hypothethised" in hypothethised.*

The term was corrected.

8. *line 666 - "," and "." are flipped after e.g.*

Corrected.

9. *Line 674-675 - please correct in Pfiffner et al. (2011)*

Citation corrected.

10. *Line 701 - move the head of parag. 5.2 to the next line.*

Head of paragraph was corrected.

11. *Line 709 - I think "Rahn & Grasemann (1999)", should be Rahn and Grasemann (1999).*

Citation corrected.

12. *Line 733 - temperature is misspelled here.*

Term corrected.

13. Line 740 - add a space between "conditions." and "The".

Space added.

14. Line 747 - ad a space between "data" and "of Nibourel".

Space added.

15. Line 806 - one "by" is superfluous.

Removed.

16. Line 1059 - I think here "and" and "()" are not needed here.

List of references was improved.

17. Line 994 - references: I have noticed that some journals are cited with their full names, while others are abbreviated. Please check the Tektonika guidelines for references and ensure consistency.

The list of reference was improved and corrected.

Reply to comments of Reviewer 2

Major concerns:

However, I still have a main concern that was not really taken into account. This concerns the succession of tectonic phases and the way it is implemented in the 4D reconstruction, and the interpretation. In my first review I raised that point both in the geological setting and in the results section.

1 In the geological setting (now lines 147-201) the authors have increased de details of the structural evolution resting on many published papers. This improves the understanding of the context, but it does not really clarify a key point. If I understand well the Windgällen phase (D2 of Nibourel et al., 2021a) with top to the NNW thrusts, is followed by the Handegg phase (D3 of Nibourel et al., 2021a) with heterogeneous deformation and steep NW-SE foliation with predominantly south-block up movements, and then by the Pfaffenchofp phase with again top to the NNW thrusts similar to D2 (D4 of Nibourel et al., 2021a). These three phases are presented as occurring one after the other. However, only the timing of D2 is actually constrained by geochronology (syn-kinematic micas at 21–17 Ma; Challandes et al., 2008; Rolland et al., 2009; Berger et al., 2017a), and none of the cited papers clearly demonstrate that succession in time. It would then appear much simpler that these 3 “phases” are in fact all coeval, with the D3 structure being S planes and the D2 and D4 structures being C planes of a single progressive deformation phase of thrusting toward the NW. Large pure shear on the D3 structures (Choukroune and Gapais, 1983; Marquer and Gapais, 1985) could have a small component of simple shear (also top to the NW). For example, the Fig.6b & c in Herwegh et al.

(2020) can simply interpreted as a classical S/C structure where both structures are synchronous, rather than the crosscutting and passive folding of Sh planes by latter SP shear planes.

We thank the reviewer for raising this point and for making us improve the Geological Setting section. The reviewer's comment made us realise that the previous version was poorly structured, which could indeed lead to confusion regarding the structural evolution of the Aar Massif.

We indeed made an unclear mix between highlighting the typology of faults structures and the timing/evolution and exhumation of the massif. For this reason, we decided to clarify this aspect and introduce three sub paragraphs dedicated to the three main groups of structures: (i) **Reverse faults**; (ii) **Thrust faults**; (iii) **Dextral strike slip and back thrust faults**. In each of the sub paragraph the kinematics, timing evolution, cross cutting relationships are discussed for each structure and linked to the respective literature.

We agree with the reviewer that the relative temporal succession of reverse and thrust faulting has not yet been conclusively demonstrated. Accordingly, we now state explicitly in the manuscript that the proposed in-sequence, south-to-north, stepwise evolution should be regarded as an assumption. Nevertheless, we consider this assumption to be robust, based on the observations and arguments presented in **Section 4**:

The results of the cross-section restorations are presented as a 4D, stepwise evolutionary sequence, assuming an in-sequence, south-to-north propagation of deformation affecting the basement units of the massif from 22 Ma to the present (Fig. 7). This assumption is supported by the following observations and arguments: (i) Nibourel et al. (2021a, and references therein) documented that the thrusts currently exposed at the highest elevations (intersecting the top of the basement between ~4000 and ~3000 m a.s.l.; Fig. 6b) formed during the early stages of exhumation of the massif are overprinted and rotated by subsequent steep to subvertical reverse faults formed in the central regions of the massif (D3; Nibourel et al., 2021a). (ii) Mock (2014), Wehrens et al. (2017), Herwegh et al. (2020), and Musso Piantelli et al. (2023) showed that the thrusts currently exposed at intermediate elevations in the massif (intersecting the top of the basement between ~3000 and 0 m a.s.l.; Fig. 6b) cut and post-date the northernmost exposed reverse faults, recording a younger phase of deformation (e.g., 5e). (iii) The lowest thrusts (intersecting the top of the basement between 0 and -5000 m a.s.l.; Fig. 6b), have been active since ca. 14–10 Ma, as inferred by recent thermochronological studies (cite). These structures, imaged in seismic profiles (NFP20; Piffner et al., 1997) and 3D tomographic models (Diehl et al., 2021), cut and offset an already steepened and partially exhumed northern front of the massif.

Finally, published P-T evolution further support this temporal framework (see e.g., Herwegh et al. 2020, Fig. 15 and references therein for P and T constrains): between 22 and ca. 12 Ma, exhumation was dominated by a major vertical component (differential uplift), with the top of the crystalline basement exhuming from ~18 km depth to shallow crustal levels at high exhumation rates and low shortening. After ~10 Ma, this pattern reverses, with exhumation rates decreasing and horizontal shortening becoming dominant ('en bloc' exhumation stage), reflecting the transition to a tectonic regime dominated by low-angle thrusts.

We believe that this reorganisation resolves the ambiguity highlighted by the reviewer and results in a clearer and more coherent description of the geological evolution of the Aar Massif.

Some detailed comments on that geological setting are found below:

Line 198: why initiated? It appears below that a first phase of thrusting toward the NW already occurred.

The entire paragraph was restructured and that term was corrected into **‘sub-vertical NW-SE striking reverse faults formed within the massif’**.

Line 202: I did not find any of these shear indicators in any of the referred publications. From other publications (e.g., Choukroune and Gapais, 1983; Marquer and Gapais, 1985), it appears that while there is simple shear on many of individual shear zone, the bulk deformation is mostly pure shear. A small component of simple shear top to the NW is however given by the isograds geometry as mentioned on line 279-280.

Lines 235-244: It is not so clear to start by the D3 structures then describe the D1 and then the D4 that looks like the D1. But this stresses out that all these different “phases” have the same kinematics.

The entire paragraph has been reorganized to provide a clearer description of the thrust structures and their evolution, along with the corresponding literature references.

Lines 266-278: these three deformation phases (a, b, c) are clearly younger than the one discussed above. Are they all coeval or do they occur in sequence: a), then b), then c)?

The paragraph has been restructured clarifying that these structures occurred coevally to the ‘en bloc’ exhumation stage of the Aar massif.

Note also that Nibourel et al. (2021) describe significant back-thrusting (top to the South) at the southern boundary of the massif (see their Fig. 15). To what phase should be related that deformation? Is it taken into account?

We thank the reviewer for pointing this out. It is correct that back-thrusting occurs locally along the southern boundary of the Aar Massif. The geometry represented in our 3D meshes of the model reflects the present-day structural configuration of the massif and therefore includes the north-westward dip of the southern boundary in some areas (see section BB’ and, in the SI, sections γγ’, and δδ’), which results from this back-thrusting event. Following the reviewer’s comment, we have added two statements to the manuscript explicitly acknowledging that local back-thrusting, along the southern boundary of the Aar Massif has been omitted from our retrodeformation model.

Chapter 2.3: In the south-eastern Aar Massif, widely spaced south-vergent back-thrust faults, ranging from a few tens to a few hundred meters in length, developed (Nibourel et al., 2021a,b). Because of their limited size, these back-thrusts cannot be displayed or resolved in the regional-scale 3D model of the Aar Massif. Their occurrence becomes increasingly rare toward the central part of the massif.

Chapter 3.3: We note also that local back-thrusting also occurred along parts of the southern

boundary of the Aar Massif (see D4 in Nibourel et al., 2021a). This deformation is responsible for the north-westward dip of the southern boundary in some areas (see section BB' and in the SI sections γγ', and δδ' in the SI). Because this local back-thrusting involved only minor displacements, these deformation structures were not included in our retrodeformation model.

2 In the result section I pointed out that different interpretations on the structure could have led to slightly different 4D reconstruction. For example, considering that the steep foliation/shear planes (Handegg) are in fact coeval with the shallow shear planes (Windgällen and Pfaffenchoepf) would lead to a slightly different 4D reconstruction with the necessity of only four main thrusts activated from internal to external.

The point here is not to dismiss the actual work but to show to the reader that other interpretations are possible, and that the transition from « vertical-isostatic tectonics » to « horizontal tectonics » (lines 333-337 and 864-878) stays an hypothesis, i.e. the 4D reconstruction depends on the structural model and do not by itself brings a demonstration of that model.

We thank the reviewer for raising this point, but we respectfully disagree with the interpretation that 'only four main thrusts active' could be responsible for the exhumation of the massif. Considering both the horizontal and (limited) vertical displacement accommodated by these shallow dipping thrust faults, such a configuration would not be sufficient to exhume the top of the crystalline units from ~18 km depth to the surface in less than 20 Ma. Moreover, all published P–T evolution data for the Aar Massif consistently show two distinct trends: (i) high uplift rates between 22 and ~12 Ma, which we interpret as reflecting predominantly vertical-isostatic tectonics; followed by (ii) lower uplift rates but high shortening rates from 14–10 Ma to the present, visible also in the foreland, which we interpret as dominated by horizontal tectonics.

We agree with the comment raised from the reviewer that the presented 4D reconstruction depends on the underlying structural model and, by itself, does not constitute proof of the model's correctness. Furthermore, we are also aware that key deformation structures that are the thrusts at the front of the massif are buried at several km depth and this adds large uncertainties to our reconstruction. For this reason, we stated in the manuscript:

Chapter 4.3: **Most of the structures which formed during and after this interval remain buried at depth are not exposed at the surface today (see Fig. 2). For this reason, no field information can be provided, and the thrusts and reverse faults are inferred from large-scale seismic profiles (NFP20; Pfiffner et al., 1997) and 3D tomographic imaging (Diehl et al., 2021).**

Chapter 5.3: **However, this hypothesis cannot be confirmed since the trough is currently buried at an elevation of -7/8 km. Interpretations of the available seismic data in the area are difficult and associated with high uncertainties (Pfiffner et al., 1997; Diehl et al., 2021). Additionally, as also stated in the result sections, the structures formed during and after this time interval, remain inaccessible to surface observations (see Fig. 2). Consequently, the thrusts and reverse faults can be inferred primarily from large-scale seismic profiles (NFP20; Pfiffner et al., 1997) and 3D tomographic imaging (Diehl et al., 2021). This inevitably**

introduces some uncertainty into the proposed 4D reconstruction and structural model. In this context, alternative structural solutions remain possible, given the limited resolution of the deep geophysical datasets.

With this regard, to valorise the reconstruction done we would like to highlight that the 6 cross sections (including the paleo peak temperature data) used as input for generating the 4D model were retrodeformed independently and they all aligned in all the four evolutionary steps in a consistent shape of the reconstructed passive margin and exhuming massif, as well as disposition of the paleo peak temperature data. While this does not constitute a validation and is therefore not stated explicitly in the manuscript, it gave us however confidence that the structural model is internally consistent; any significant incompleteness or lateral variation in the structural architecture would have resulted in clear misalignments among the independently retrodeformed sections.

Detailed comments:

The paper as still several typos, and I recommend a careful reading. Some of them are listed below:

We thank the reviewer for drawing our attention to typos and imperfections in the text. We have carefully reviewed the manuscript and corrected the identified typos.

1. *Line 44-49 the sentence is very long and the « crustal structures » are repeated two times.*

The sentence was improved.

2. *Line 116 : Along the strike of the massif, Permo-Carboniferous to Cenozoic sediments are also locally ...*

The sentence was improved.

3. *123-125 “besides the Permo-Carboniferous graben infills, also syn-rift sedimentation occurred (e.g., Rohr, 1926; Nibourel et al., 2021a).” I do not really understand what this sentence is doing here. Should it not rather be on line 115?*

The sentence was deleted.

4. *Line 702. Missing a paragraph mark*

Paragraph mark was added.

Acceptance Letter (15 Dec. 2025)

Dear Fernandino, dear authors,

Thanks for resubmitting the revised version of your manuscript.

We appreciated all the work you did on the manuscript according to the reviewers' comments. Your manuscript has been significantly improved and will represent a valuable scientific contribution for Alpine Geologists.

We are happy to tell you that the manuscript is now accepted for publication on TEKTONIKA.

You will be contacted by our copy editing team in the coming weeks.

Thanks for submitting to Tektonika !

Chiara Montomoli, Tektonika Associate Editor
Robin Lacassin, Tektonika Executive Editor