

Solid Earth

Editorial Office

Zagreb, 29th May 2026

Dear editor,

we are submitting the revised manuscript “***Middle Triassic ignimbrites as markers of Eoalpine high-pressure metamorphism and large-scale lateral extrusion of Adria derived units at the edge of the European Alps***”.

Please accept our sincere thanks for the opportunity to have our paper considered for publication in your journal. We further extend our gratitude to the reviewers, Prof. Franz Neubauer and Prof. Emilio Saccani, for high quality reviews they provided and for useful comments and suggestions that significantly improved our manuscript.

After consideration, we accepted almost all of reviewer’s suggestions and corrections. Changes we made to the manuscript are visible in Word document with “track changes” option turned on. We also uploaded the “clean” version of the manuscript. Below in this letter you will find our responses to each of the reviewer’s comments. We refer to the line numbering in the original version of the manuscript.

We also made additional changes to the figures proposed by reviewers.

We hope you will find that the corrections we made to the manuscript improved its quality and can now be published in your journal.

Thank you for your kind consideration.

Sincerely,

Matija Vukovski, corresponding author

Response to the comments by Emilio Saccani

Specific comments and suggestions

- 1) **Title:** “Mid-Triassic rhyolitic lavas and ignimbrites as markers of Eoalpine high-pressure metamorphism and large-scale lateral extrusion of Adria derived units at the edge of the European Alps”

This title can be definitely improved.

- “Mid-Triassic“ (descriptive) is used only here, while “Middle Triassic” (formal) is used throughout the text. While the descriptive form is fine in titles, I suggest using the formal term for consistency with the manuscript.
- “rhyolitic lavas and ignimbrites as markers of Eoalpine high-pressure metamorphism...” strictly speaking, only the ignimbrites record HP–LT metamorphism. Therefore, this wording may be misleading and should be revised.
- “...at the edge of the European Alps”. The whole alpine belt is “European”. I think the authors mean to say “at the edge between Adria-derived and Europe-derived units (or domains?).

Answer: **Partly adopted.** For line references see below.

Line 1: **Corrected.** In the manuscript title, “Mid-Triassic” has been replaced with “Middle Triassic,” and “rhyolitic lavas” has been removed since only the ignimbrites indicate metamorphism.

Line 3: **Suggestion was not accepted.** The term “European Alps” in the title is used to immediately remove any ambiguity for non-European readers. The term is used in geographic not tectonic sense.

2) **Introduction and Geological framework.**

While the other sections are generally well written, these two sections read somewhat heavily. These sections would benefit from improved readability. I have suggested several changes in the attached annotated version. In general, I recommend splitting long sentences.

Finally, the first three lines of the “Geological Framework” section form a single-sentence paragraph. Single-sentence paragraphs are generally discouraged in academic English.

Answer: **Corrected.** Reviewer’s suggestions have been adopted, the readability of both paragraphs has been improved and long sentences are splitted. For line references see below.

Lines 30, 32, 35, 47, 55, 56, 57, 67 and 69: **Corrected.**

Line 70: Suggestion was not accepted. We used the term “Southern Alps” as a widely accepted tectono-stratigraphic designation for the area south of the Periadriatic Lineament, composed of Adria-derived units and characterized by Neogene south-vergent thrusting. Therefore we did not accept to use term “Southern Alpine domain” instead.

Lines 72, 76, 78, 80, 81, 83, 91, 92, 93, 98, 99, 100, 101, 102, 105, 106, 107 and 110: Corrected.

- 3) In several parts of the manuscript (lines 246, 333, 409, and 483), the authors, based on Figure 5b, describe their rocks as showing a “calc-alkaline to shoshonitic affinity.” However, in this figure, only one sample plots across the boundary between the calc-alkaline and shoshonitic compositional fields. In my opinion, a single sample, which does not even clearly plot in the shoshonite field is insufficient to support the conclusion that these rocks exhibit a “calc-alkaline to shoshonitic affinity.” I suggest cautiously using the clear evidence for a calc-alkaline affinity only.

Answer: Corrected. For line references see below.

Lines 246, 333, 409 and 483: Corrected.

4) Lines 313-314 and 355 versus lines 485-489:

In lines 313–314: “Rhyolitic eruptions are characteristic of continental settings and are commonly associated with partial melting of the continental crust, accompanied by magma differentiation, fractional crystallization, and crustal assimilation (Wilson, 1989; Halder et al., 2021).” A similar statement is made in line 355.

As currently phrased, this suggests that rhyolites are generated primarily (or exclusively) by anatectic processes (i.e., melting of continental crust), which is not entirely correct. In fact, a more appropriate interpretation is provided later in the manuscript (lines 485–489): “The formation of these felsic volcanic rocks involved partial melting of a compositionally heterogeneous subcontinental lithospheric mantle, accompanied by subordinate melting of the continental crust and concurrent fractional crystallization of feldspar. The emplacement of rhyolitic lavas and ignimbrites occurred during passive continental rifting along the northern margin of Adria...”

It is clear that partial melting of the continental crust may occur in addition to mantle melting. Therefore, I suggest revising the earlier statements accordingly. For example:

“Rhyolitic eruptions are characteristic of continental settings and are commonly associated with partial melting of subduction-influenced mantle sources, potentially accompanied by partial melting of the continental crust, as well as magma differentiation and crustal assimilation.”

Please note that I deleted “fractional crystallization”, as it is one of the main processes of magma differentiation and should not be listed separately.

Answer: Corrected. All of the reviewer's suggestions have been adopted, for line references see below.

Lines: 314, 315 and 355: Corrected.

- 5) **Lines 141-145:** This section should be improved. Please specify if XRF measures were made on pressed powder pellets or on fused beads. Describe how powders were digested before ICP-MS analyses. The last sentence is unclear. Give details about detection limits.

Answer: Corrected. This section has been revised for clarity and completeness. We now explicitly state that XRF analyses were performed on fused glass beads. The ICP-MS methodology has been expanded to include sample preparation details, specifying that trace element concentrations were determined following a near-total four-acid digestion (HF–HNO₃–HClO₄) with subsequent dissolution in aqua regia, as performed at Actlabs. In addition, we clarified the description of detection limits and now report that they are typically in the range of 0.01–0.1 ppm, depending on the element, and are defined as three times the standard deviation (3σ) of the blank. The previously unclear sentence has been rewritten accordingly.

Comment: Describe in Table which elements were analysed by XRF and ICP-MS.

Answer: Corrected. A related designation has been added to the Table. – Please see Appendix D Table 4

Comment: Line 203 (and 224). “Diagenesis” is not the most appropriate term, as it refers to post-depositional, low-temperature processes in sedimentary rocks. It may be applied to pyroclastic rocks only when describing processes occurring at very low temperatures ($< \sim 200$ °C). Are you sure is this the case? Welding, devitrification, and vapour-phase processes are not considered diagenetic. I suggest using more appropriate terms, such as “post-depositional alteration” or “low-temperature alteration.”

Answer: Corrected. We thank the reviewer for this comment. We agree that processes such as welding, devitrification, and vapor-phase crystallization are not diagenetic in nature. To avoid ambiguity, we have revised the text to distinguish between syn-depositional/high-temperature volcanic processes and subsequent low-temperature post-depositional alteration. The term “diagenesis” has been replaced where appropriate. – Please see lines 219-224 and 245-248 in the document with track changes.

Comment: Lines 227-230. “These values exceed the pressure conditions inferred from the b_0 lattice parameter of white mica (Appendix B), which yields moderate pressure estimates ($b_0 = 9.04\text{--}9.08$ Å).”. Give the values of those moderate pressures inferred from the b_0 parameters.

Answer: Corrected. We have revised the text to include the pressure range inferred from the b_0 lattice parameter. The measured b_0 values of white mica range from 9.0473 to 9.0660 Å, corresponding broadly to medium-pressure conditions of approximately 0.6-0.8 GPa. Please see lines 255 in the document with track changes.

Comment: Figs 1 and 12. Figure 12 differ from Fig. 1 for having been updated by incorporating the results from this study. However, it is difficult to promptly see the novelties from this paper in Fig. 12 because of graphical issues and because these two figures also differ for other aspects. It seems that Fig.12 is a simplified version of Fig.1 as it does not show anticlines and synclines and other things. Finding the core differences in two figures that are already graphically different is challenging. I suggest to uniform these two figures for their common features and highlight in Fig 12 the novelties from this paper.

Answer: Corrected. The suggested modifications were made to Fig. 1 and Fig. 12, as well as to the caption of Fig. 12.

Editorial comments/suggestions

Comment 1) A careful cross-check between the in-text citations and the reference list is necessary. I have identified several missing and uncited.

Answer: Corrected. All references have been checked throughout the text and reference list and corrected where necessary.

Comment 2) In the file I downloaded, all superscripts and subscripts appear to be missing. This may be an issue on my end; however, I kindly ask the authors to verify the text for this problem.

Answer: Corrected. All superscripts and subscripts have been checked throughout the text and corrected where necessary.

Comment 3) I suggest to add a key for symbols within the graphs instead of giving it in caption. This suggestion applies to figs. 4-7 and 9-10, as well as to Fig. G1.

Answer: Corrected. Please see Figs. 4-7, 9-10 and Appendix E: Fig 1 in the RM.

Other editorial or language issues

Lines 120, 122, 123, 127, 131, 134 and 135: **Corrected.**

Lines 141-145: **Corrected.** A related designation has been added to the Table. Please see Appendix D.

Lines 161, 170, 185, 186, 203, 224, 229, 230 and 246: **Corrected.**

Line 260: **Corrected.** This has been verified throughout the text.

Line 308: Corrected.

Line 315: Corrected. The suggestion is accepted throughout the text.

Line 354: Corrected. The suggestion is accepted throughout the text.

Line 496, 507, 508, 509 and 578: Corrected.

Line 580: Corrected. Please see Appendix A, D, F in the track changes.

Line 655: Corrected.

Line 656: Corrected. Please see Appendix E and Fig. 1 in the track changes.

Line 735: Corrected. Reference Fodor et al. (2008) is cited in the text. Reference Fodor et al. (2001) is removed from the text.

Line 800: Corrected. Reference removed from the reference list.

Line 815: Corrected. Reference Lustrino et al. (2011) removed from the reference list, reference Lustrino et al. (2019) added in the reference list.

Line 835 and 837: Corrected. References Pamić (1984) and Pamić et al. (1995) are removed from the reference list.

Line 852: Corrected. Reference Prince et al. (2024) removed from the reference list.

Lines 963 and 965: Corrected. Reference von Blanckenburg et al. (1998 and 1999) are removed from the reference list.

Line 967: Corrected. Reference Vrabec (1999) removed from the reference list.

Line 969: Rejected. Reference Vrabec and Fodor (2006) exist in the text.

Response to the comments by Franz Neubauer

General comments

Comment 1) Present more details on phengite measurements like back-scattered electron images because the grains seem to be very small. Is there any variation in the composition? The sericite is clearly grown during deformation and metamorphism.

Answer: **Corrected.** The explanation is given in the text. Please see lines 225-227, 205 and Fig. 3g in the track changes.

Comment 2) Present all constraints for the temperature estimate.

Answer: We do not have a geothermometer for the investigated ignimbrites. All ignimbrite samples exhibit a schistose texture with synmetamorphic foliation defined by white mica (phengite). However, no additional diagnostic metamorphic parageneses were identified. Possibly, Kübler index measurements of phengite crystallinity were not performed.

Therefore, the temperature estimate of ~300 °C should be regarded as an approximate value. It was adopted as a representative mean temperature for very low-grade metamorphism following the classification of Winkler (1979), who places phengite-bearing assemblages within the very low-grade metamorphic degree. We acknowledge that peak temperatures may have been somewhat higher.

Nevertheless, a temperature of approximately 300 °C appears reasonable because correlative nearby units yielded comparable maximum temperatures based on conodont alteration index (CAI), vitrinite reflectance, and illite crystallinity data (Árkai et al., 1991; Kukoč et al., 2023; Vukovski et al., 2024).

Comment 3) The calc-alkaline nature of the widespread Southalpine Middle Triassic volcanics is well studied in the area adjacent to the west, and the results of these studies should be included in the interpretation (e.g., Köver et al., 2018; De Min et al., 2020 and references therein).

Answer: **Corrected.** The text has been amended as suggested. Please see line 75-77 in the document with track changes.

Comment 4) If the interpretation of the deformed ignimbrites explained as affected by blueschist metamorphism is correct, other blueschist occurrences must be discussed, too, which have also the potential to explain this specific rock. These include such of the Medvenica Mts., which are mentioned in the manuscript but especially the Meliata blueschist in Western Carpathians (Putiš et al.,

2019 and references therein), from which similar HP rocks are also found in the Eastern Alps. High-pressure rocks of Dinarides cannot also not a priori excluded Putiš et al., 2025.

Answer: Corrected. All localities proposed by the reviewer have been additionally addressed in the text, and it has been explained why we consider these rocks not to be directly related to the investigated rocks. For the explanation see lines 475-482 in the document with track changes.

Comment 5) Figures 1 and 12 give an entirely different interpretation of area SE of the Pohorje. That of Figure 12 is not constrained by hitherto interpretations but is also different from what Regional Geology discussed up to now. Therefore, more discussion is needed and the interpretation must be more substantiated.

Answer: Corrected. Additional modifications were made to Fig. 12 and its caption. Proposed interpretation has been further substantiated in the text.

Comment 6) The interpretation given in Figure 11 following Hinsbergen et al. (2020) Balkan Paleo-Tethys is interesting but looks complicated. I agree with the basic idea but there is no need for two rifts. The figure needs more explanation.

Answer: Partly adopted. The Figure 11 has been corrected and supplemented with the necessary data available in the paper by van Hinsbergen et al. (2020).

However, we do not agree with the proposal to eliminate the two rifts. Please see the paper by Slovenec and Šegvić (2024) in which the existence of the two rifts is explained.

(Slovenec, Da., Šegvić, B., 2024. *The evolution of the Mesozoic lithosphere of northwestern Neotethys: A petrogenetic and geodynamic perspective. Journal of the Geological Society, 181, jgs2023-132.*).

Specific comments and editorial remarks

Figure 1: Write Margečan and Kjumberski areas into the map. Explain abbreviations PFS, MHZ in captions. What is the nature of the boundary between Dinarides and Southalpine unit in the eastern part of the map?

Answer: Corrected.

Figure 2: In legend to Fig 2: correct to brackish. siltites = siltstones; low-grade schist: say rather phyllite or whatever; schist is more coarse-grained. Instead of complicated numbering 1 - 9, write sample names directly into the map. In legend, correct “riolites” to “rhyolites”.

Answer: Partly adopted. All suggestions made by the reviewer were accepted, except for the suggestion to directly label the sample names on the maps at their respective locations. This suggestion could not be implemented for technical reasons, as some localities contain a large

number of samples, making it impossible to display all labels while maintaining acceptable visual clarity and readability of the figures.

Lines 91, 93, 128, 183, 187, 190, 204, 227, 259, 260, 264, 289 and 302: Corrected.

Figure 8: In Fig. 8b: There are potentially two age populations. Calculate average $^{206}\text{Pb}/^{238}\text{U}$ ages for these separate groups. Add rock type and sample no. directly to the figure.

Answer: Corrected. We have calculated average $^{206}\text{Pb}/^{238}\text{U}$ ages for two potential zircon populations and these ages were mentioned in the text. Additionally, new figure with concordia diagrams for both potential populations was created and added as Appendix H. We have added rock type and sample number directly on the figures.

Lines 308 and 409: Corrected.

Figure 11: Fig. 11a: Figure needs much more explanation. E.g., what represents the greenish color N and E of the Balkan Paleotethys Ocean? Legend to 11b: Explain 1 - 4 directly in the figure.

Answer: Corrected.

Figure 12: The North Karawanken unit (= thrust sheet) did not reach very low-grade conditions. See papers of Rantitsch, Rainer, Heberer et al. (2017; International Journal of Earth Sciences).

Answer: Corrected.