Author response: We would like to thank the referee for the time and effort he dedicated in reviewing our manuscript. We appreciate the referee's insightful comments and suggestions and carefully addressed them. Please see below, in blue and italic font, for a point-by-point response to the reviewer's comments. Provided page numbers refer to the revised manuscript file with tracked changes.

RC1: 'Comment on se-2021-59', Jay Quade, 30 Jun 2021 reply

This is an excellent paper that builds upon the foundations of Campani (2012) and Methner (2020) to reconstruct paleoelevation of the Swiss Alps in the mid-Miocene optimum. This review took me extra time because I had to read those papers. This paper fills in the picture by studying low-elevation paleosols from three mid-Miocene sections from the foreland basin.

1) The dating of these looks exceptional, but for the purposes of assessing the diagenesis history, a clear gap on the paper was the lack of discussion on the burial depths and burial temperature history of the molasse basin from other published sources.

- *We would like to thank the reviewer for this insightful comment and agree that this issue could have been stated more prominent in the manuscript. We acknowledge that diagenetic alteration of terrestrial carbonates can be challenging to assess. Initial stable and clumped isotopic compositions of pedogenic carbonate nodules can be altered by diagenetic overprint and burial metamorphism due to increased burial temperatures. In the following we want to discuss why we assume that diagenetic overprinting Molasse Basin's paleosols had no (major) impact on our study:*
    1) *Carbonate-bearing sediments of the Swiss Molasse Basin show primary soil structures (e.g. root traces, mottling, structures from bioturbation and wetting and drying) and remain poorly consolidated lacking signs of diagenetic hardening. This indicates that diagenetic impact on the collected pedogenic carbonate samples has, if at all, remained small.*
    2) *Vitrinite reflectance and apatite fission track data yield maximum erosion estimates ranging from 350 m to 2100 m and maximum burial temperatures of 40°–110°C for Central and Eastern Switzerland. Sedimentation of the youngest basin fill (OSM) ended between ~10 Ma and ~5Ma in the Swiss Molasse Basin. Considering the low carbonate clumped isotope temperatures (30–36°C) and the rather short time interval of max. 10 million years of burial, during which collected carbonate nodules from the OSM were overburden, we can exclude any solid state reordering within the carbonate minerals as the time and temperature are not sufficient (Henkes, G. A., Passey, B. H., Grossman, E. L., Shenton, B. J., Pérez-Huerta, A. and Yancey, T. E.: Temperature limits for preservation of primary calcite clumped isotope paleotemperatures, Geochim. Cosmochim. Acta, 139, 362–382, doi:10.1016/j.gca.2014.04.040, 2014.)*
    3) *Diagenetic overprint should result in rather homogenized $\delta^{18}O$ values, and should shift the $\delta^{18}O$ compositions to lower values (assuming high diagenetic temperatures and ^{18}O-depleted (meteoric) waters). However, SMB records show high variability in both $\delta^{13}C$ and $\delta^{18}O$ values, which covers 9.7‰ ($\delta^{13}C$), and 5.8‰ ($\delta^{18}O$) for the Jona section. Moreover, a potential lowering of $\delta^{18}O$ would ultimately result in underestimating rather than overestimating inferred paleoelevations.*

- *However, we agree with the reviewer that the paper would benefit from a more detailed assessment of diagenetic impact on Swiss Molasse Basin carbonates. We have therefore included a new paragraph (see lines 327–332 in revised manuscript) and add more details in the Supplementary Material (SI4) addressing estimated amounts of erosion, inferred burial temperatures and potential diagenetic impact on the collected samples.*

2) If this were my paper I would add depth of soil carbonate nodules below the top of the paleosol. Depth has a big influence on d13C, d18O, and D47 values. In the general the paper does not record soil carbonate distribution with depth, and how this varies among soils. But they took so many samples that I assume that that got a representative suite from shallow to deep, which serves the purpose of the paper well enough

- *We very much appreciate this comment and agree with the reviewer that variations of $\delta^{13}C$ and $\delta^{18}O$ with increasing sampling depth have to be taken into consideration.*
- *Based on our field observations we found that carbonate-bearing horizons in the Swiss Molasse Basin occur mainly in sequences of stacked paleosols with eroded A-horizons. In this setting the top horizons of sampled paleosols were sharply truncated by erosional surfaces, which makes it difficult for us to state precise sampling depths for the collected carbonate nodules. Nevertheless, the absence of the upper (A-) horizon in stacked paleosols gives some constraints on the sampling depth and led us to assume that sampling of collected carbonate nodules was performed from below critical near-surface horizons (uppermost ~20–30 cm).*
- *Furthermore, where possible, we tried to identify individual paleosol profiles for the critical time interval of paleoelevation reconstruction (15.5–14.0 Ma) in order to assess depth-related variations of soil carbonate $\delta^{13}C$ and $\delta^{18}O$ values. For these individual profiles (e.g. "Jona" 18EK199-18EK203 (horizons with carbonate nodules: 577.0 m - 577.4 m), 18EK165-18EK177 (488.7 m - 487.6 m)), both $\delta^{13}C$ and $\delta^{18}O$ values show no strong correlation with the sampling depth, which led us to assume that carbonate samples have not been influenced by near surface-related biases of isotopic compositions.*
- *We clarified this in the manuscript and point out that sampled carbonate nodules were mainly collected from former B-horizons (see lines 191–193 in revised manuscript).*

3) Some things that struck me about the results, which might be expanded upon in the revised version, was how high the d13C values of the soil carbonates, averaging -2 to -3‰±1‰. In the absence of C4 plants and high pCO2 (neither are indicated for this period), this indicates fairly modest respiration rates and dry desert conditions of formation, typical of sagebrush covered steppe or drier in the Great Basin (see Quade et al 1989 GSA Bull. Systematic variations…). I wonder: are there other indicators of such aridity in the molasse basin of the mid-Miocene, such as evaporites? I am surprised it was as dry as the Great Basin, given the region is so wet today. Perhaps this reflects some strong rainshadow effects, although I would have thought storms came out of the west, then as now. I find this really intriguing.

- *We fully agree with the reviewer that Swiss Molasse Basin pedogenic carbonate $\delta^{13}C$ compositions are in the higher range for carbonates formed in terrestrial soils (this applies in particular for Jona and Aabach sections). The most plausible driver for elevated pedogenic carbonate $\delta^{13}C$ values of the mid-Miocene North Alpine foreland* *basin are diminished soil respiration rates, as suggested by the reviewer. We agree with the reviewer that on a very local scale SMB pedogenic carbonate might have been formed during rather dry conditions. Dry conditions with pronounced soil evaporation and associated higher $\delta^{13}C$ values can be found in proximal alluvial fan settings where soil carbonate forms in coarse host rock and soil water retention potential is likely to be diminished (Schwartz, Theresa & Methner, Katharina & Mulch, Andreas & Graham, Stephan & Chamberlain, Charles. (2019). Paleogene topographic and climatic evolution of the Northern Rocky Mountains from integrated sedimentary and isotopic data. Geological Society of America Bulletin. 131. 10.1130/B32068.1.).*

- *However, no paleobotanical and paleozoological evidences are given for a general arid setting with moderate, or even desertic vegetation cover for the Mid-Miocene Swiss Molasse Basin. (Bolliger, T., Neuhausen, H. G. and Hantke, R., Zur Geologie und Paläontologie des Zürcher Oberlandes, Vierteljahrsschrift der Naturforschenden Gesellschaft Zürich, 133(1), 1–24, 1988.) report numerous plant and fossil sites for the OSM of the Hörnli alluvial megafan and reconstruct a humid subtropical climate with rather high precipitation rates interrupted occasionally by drier and/or cooler climate phases. Evidences for warm, humid to tempered climate characterized by subtropical and deciduous forests for Early to Middle Miocene are also found by (Böhme, M., Bruch, A. A. and Selmeier, A.: The reconstruction of Early and Middle Miocene climate and vegetation in Southern Germany as determined from the fossil wood flora, Palaeogeogr. Palaeoclimatol. Palaeoecol., 253(1–2), 107–130, doi:10.1016/j.palaeo.2007.03.035, 2007.) who provides mean annual precipitation rates ranging from ~830–1350 mm.*
- *Given these high MAP estimates, it would be hardly possible to form or preserve any pedogenic carbonate (under modern atmospheric conditions) (Breecker, D. O., Sharp, Z. D. and McFadden, L. D.: Seasonal bias in the formation and stable isotopic composition of pedogenic carbonate in modern soils from central New Mexico, USA, Bull. Geol. Soc. Am., 121(3–4), 630–640, doi:10.1130/B26413.1, 2009, and Zamanian, K., Pustovoytov, K. and Kuzyakov, Y.: Earth-Science Reviews Pedogenic carbonates : Forms and formation processes, 157, 1–17, doi:10.1016/j.earscirev.2016.03.003, 2016.)*
- *This suggests that either the climate in the Northern Alpine Foreland Basin was very seasonal with pronounced dry periods or that the ρCO_2 levels were higher than previously thought. The latter is under investigation and more recent studies (e.g. Sosdian, S. M., Greenop, R., Hain, M. P., Foster, G. L., Pearson, P. N. and Lear, C. H.: Constraining the evolution of Neogene ocean carbonate chemistry using the boron isotope pH proxy, Earth Planet. Sci. Lett., 498, 362–376, doi:10.1016/j.epsl.2018.06.017, 2018.) have proposed that the atmospheric ρCO_2 levels were indeed higher than the first estimates for this time period.*
- *This topic has been touched in the paper of Methner et al. (2020). In this study we prefer to focus on paleoelevation reconstruction based on inferred $\delta^{18}O$ values in precipitation.*

4) This brings me to my chief concern about the paper's conclusion that paleoelevation was ~4200 m. That is: if the setting was that desertic, how can one be confident that evaporation does not influence even the lowest d18O values. I understand that the authors tried to minimize this by using only the lowest 25% quartile. That should help. But were this my paper, I would think this through very carefully, and perhaps be more conservative. Evaporation would expand the difference between isotopic values from low and high elevations and lead to overestimates of paleoelevation. In two papers from 2007, I tried to assess the effects and limits of evaporation on isotopic values from soils in dry climates (there are probably better papers on there on this topic that I am unaware of):

Quade, J., Garzione, C., and Eiler, J., 2007, Paleosol carbonate in paleoelevation reconstruction, *in* M. Kohn, ed., Paleoelevation: Geochemical and Thermodynamic approaches. Reviews in Mineralogy and Geochemistry, Mineralogical Society of America Bulletin, v. 66, p. 53-87.

Quade, J., Rech, J., Latorre, C., Betancourt, J., Gleason, E., Kalin-Arroyo, M., 2007, Soils at the hyperarid margin: the isotopic composition of soil carbonate from the Atacama Desert. *Geochimica et Cosmochima Acta* 71, 3772-3795.

This manuscript cites the first paper but I am not sure they fully internalized the meaning of the results, because mid-elevation (say up to 2000 m) soil carbonate from the Great Basin is the best analog for carbon isotopes in the molasse basin, and those soils show pretty strong (but variable) evaporation effects. In short, I come away with the feeling that there was some evaporation effect even in the lowest 25% quartile of d18O values, and therefore that 4200 m is a maximum estimate.

I don't expect the authors to change the manuscript on this point. They are free to disagree. But I urge them to think more carefully on this point and revise the manuscript if they see fit to do so, or not at all.

- *We acknowledge the concern of the reviewer on this point. We agree with the reviewer that if all obtained $\delta^{18}O$ data (included the lowest 25%) was impacted by evaporation, this would result in inferred paleoelevation estimates biased towards maximum elevation differences.*
- *For the following reasons we assume that Swiss Molasse Basin $\delta^{18}O$ records were not systematically affected by evaporation:*
  1) *Comparison with data from GNIP stations in Switzerland (~250–600 m.a.s.l.) shows, that modern precipitation $\delta^{18}O_w$ compositions reach values of ~ -8‰ – -2‰ for the summer months (June–August), which is in good agreement with our inferred near sea level $\delta^{18}O_w$ value of -5.8‰ for the Swiss Molasse Basin (we included this in the revised manuscript, see lines 381–383). Moreover, considering higher mid-Miocene summer temperatures compared to today, we can assume that precipitation $\delta^{18}O_w$ values may have been more elevated during the mid-Miocene.*
  2) *Reconstructed $\delta^{18}O_w$ values from volcanic ash layers* (Bauer et al., 2016) *yield values between -6.1 and -2.9‰ and are in consent with our SMB $\delta^{18}O_w$ estimate (see lines 377–381 in revised manuscript).*
  3) *Presumably the moisture in the Northern Alpine Foreland Basin came partly from the Molasse Sea, which was located in closer proximity to collected SMB deposits in the Miocene. Thus, vapour masses which travelled inland had to cover shorter distances between the source water body and their destination area. Consequently, according to the isotopic continental effect, mid-Miocene precipitation $\delta^{18}O_w$ values are not supposed to obtain lower values than modern precipitation $\delta^{18}O_w$ values.*

4) *As replied in the comment to remark 3) we consider a dry, desertic climate very unlikely for the mid-Miocene Swiss Molasse Basin as various paleobotanical studies indicate a temperate to humid climate with moderate to high precipitation rates and (qualitatively) high plant density. However, we cannot completely exclude that individual SMB carbonate samples were affected by (soil) evaporation on a local scale. For this reason, and in order to reduce potential soil evaporation-derived bias, we calculate paleoelevation estimates only with the lowest 25% $\delta^{18}O$ values and consider this as a sufficient precautionary measure.*
5) *Difference from the previous study (Campani et al., 2012) is given by i) a newly measured ambient temperature for mineral-water isotope exchange during soil carbonate formation and ii) a different choice of sea level reference section, which contribute to +1.9‰ and +1.2‰, respectively (see lines 374–376 in revised manuscript). In the case of a systematic evaporation bias (which we do not expect, see arguments above), first, the Aabach section would be the most affected, and second, evaporation would result in +1.2‰ between the Fontannen and Jona sections. Given the modern isotopic lapse rate of -2.0‰/ km (Campani et al., 2012) this results in a Δz(m) of "only" +600 m, and cannot be resolved from the calculated propagated error in paleoelevation of ±770m.*

5) I was surprised by the really high soil T°C (47) found by the Methner paper; it will be interesting if this can be reproduced elsewhere for the MMO.

- *We agree with the reviewer that Δ_{47} soil temperatures for the Swiss Molasse Basin section "Fontannen" as provided by Methner et al. (2020) are rather high, but maybe more interestingly, comprise a large temperature span of ~15°C, also providing low Δ_{47} soil temperatures within the same section. We find similar high temperatures for the two other sections Jona and Aabach in this study.*
- *Furthermore, in order to exclude technical errors, we tested material from two different carbonate samples on a second mass spectrometer with a different technical setup (coupled with the automated carbonate device KIEL IV) and we obtained comparable temperature within the error range.*
- *As explained in the comment to remark 1) we suggest that sampled carbonate nodules have not been exposed to diagenetic overprint.*
- *We conclude that the rather high Δ_{47} soil temperatures found for the Swiss Molasse Basin sections is a very interesting finding and we intend to conduct further studies in this context.*

Here are a few line-by-line comments and edits

14: omit , however; omit geochemistry

- *We changed the text according to this suggestion and deleted the terms "however" and "geochemistry".*

16: sea-level here and elsewhere, where used as an adjective

- *We changed the text according to this suggestion and added a hyphen whenever the term sea-level was used as an adjective.*

22: state the range of dD values

- *We specified the phyllosilicate δD value which was used for paleoelevation calculation.*

76: molasse

- *We changed the text according to this suggestion.*

96-97: were predominantly composed

- *We changed the text according to this suggestion and replaced "are predominantly composed" with "were predominantly composed".*

103: is the Molasse Sea a formal name? otherwise no caps

- *The term "Molasse Sea" represents a formal name.*

114: astronomically tuned

- *We changed the text according to this suggestion and replaced "astronomically-tuned" with "astronomically tuned".*

156: What typical depths are the nodules below the top of the paleosol?

- *See comment on remark 2).*

205: VSMOW

- *We added an explanatory sentence in the method chapter 3.2 introducing the term VSMOW for $\delta^{18}O$ values. See also reply to comment on sentence 242.*

235: While mostly true, in some settings soil carbonates can form in the cool season, if summer are wet. Huntington's group at Washington has documented this. This scenario should be considered.

- *We clarified this in the manuscript by referring to studies which provide evidence for cool season carbonate formation (see lines 283–284 in revised manuscript).*

242 onward: here and in following paragraphs it is essential to insert VSMOW where referring to d18O values, since in many papers, VPDB is the convention for carbonates. This will clear up any confusion.

- *We clarified this by including an explanatory sentence, stating which reference frame has been used for the isotopic systems (see lines 212–213 in revised manuscript).*

295: yes, I agree here, but to develop +1.2‰ carbon isotope values requires dry conditions (mid-elevations of the Mojave Desert are good analogs), near-surface depths of nodule formation, or high pCO2. The last is not indicated from mid-Miocene records elsewhere, although perhaps the mid-Miocene optimum should be lookd at more carefully. That leaves some combination of the forst two explanations: moderate, desertic vegetation cover and a mix of soils depths 0-100 cm deep). Quade et al., 1989, 2008 (on paleoaltimetry) and Breecker et al, 2009 are the authoritative papers on this.

- *See detailed comment on remark 3).*

300: this covariance is also observed in modern soils (Cerling 1984) and other papers.

- *We included the study of Cerling (1984) and Cerling and Quade (1993).*

305: how do you know the Jona section is the best? Explain. From Fig. 2, the Jona section looks the most variable isotopically, and therefore the most impacted by evaporation.

- *We agree with the reviewer that the Swiss Molasse Basin section Jona shows the highest variability in both, pedogenic carbonate $\delta^{18}O$ and $\delta^{13}C$ values. We give detailed explanations on Jona pedogenic carbonate $\delta^{18}O$ and $\delta^{13}C$ values in the comment on remark 2) and 3), respectively.*

323: which mineral pairs? Clarify how this was done.

- *According to the suggestion of the reviewer we clarified and included in the text, that we used the smectite-water oxygen isotope fractionation factor of Sheppard and Gilg (1996) to recalculate Swiss Molasse Basin $\delta^{18}O_w$ values from the $\delta^{18}O$ values of volcanic ashes.*

328: no new paragraph?

- *We changed the text according to this suggestion and removed the paragraph.*

352: good! Few people know about the Sharp paper, but it is ahead of its time

- *We fully agree with this comment.*

394: million years

- *We changed the text according to this suggestion and replaced "Myr" with the term "million years" as recommended by the reviewer.*

Citation: https://doi.org/10.5194/se-2021-59-RC1