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Comment on se-2021-46

Here follow our responses to the review by Fritz Schlunegger (RC2) of our manuscript submitted to Solid Earth.

Reviews are listed in black - italic while our answers are in blue - plain text.

Fritz Schlunegger (Referee)

Referee comment on "Chronology of thrust propagation from an updated tectonosedimentary framework of the Miocene molasse (western Alps)" by Amir Kalifi et al., Solid
Earth Discuss., https://doi.org/10.5194/se-2021-46-RC2, 2021

Dear Authors, dear Editor

It is usually a significant challenge to intergrate various sources of data into a comprehensive and conclusive framework. This paper is an excellent example of how this can be achieved. I congratulate the authors for their work, which I enjoyed reading. This has been very well done!

Thank you

The material is presented in such a way that the reader can follow the way of how the authors reach their conclusions, and why. The readers are given access to a wealth of material that has been integrated in this manuscript. Therefore, from a scientific point of view, this work is very solid, reproducible and should be published.
What has not been fully clear to me is the separation of previously published data (in the authors' Sedimentology paper) and their original contribution presented in this work. In this regard, chapter 3 (Materials and Methods) should be more specific and clear.

The sedimentology paper (Kalifi et al., 2020) aim was the description and interpretation of the facies and how they evolve in space and time. For this, sedimentological sections 4, 5, 13, 16 and 22 were presented in details, together with 57 Strontium ages which were published without stable isotopes results. In this paper we present 30 more sedimentological sections and ad 72 new Strontium ages to calibrate the log sections, together with biostratigraphy and magnetostratigraphy age constraints. Some sequence stratigraphy interpretations thus slightly evolved.

We modified the chapter 3 as follow:

Lines 208-217: "Sedimentological and stratigraphical analyses were conducted from 35 well-outcropping sections of the Miocene Molasse deposits (sections 4, 5, 13, 16, 22 are detailed in Kalifi et

al., 2020), and from partially preserved sections (<40m) outcropping in adjacent localities. Sedimentary successions, up to 1050 m-thick, were logged at the decimeter (dm) to meter (m) scale resolution in the field. Using the combined analyses of textural characteristics, clastic and biogenic components, bed thickness, bed organization and geometry, sedimentary structures and paleocurrent measurements, 25 facies grouped into 11 facies associations (FA) were previously defined by Kalifi et al. (2020). Building on these results and using the same methodology, depositional sequences were identified based on facies associations evolution and the main stratigraphical surfaces (Embry, 1993, 1995). Depositional sequences were identified, using Posamentier and Allen (1999) methodology on spontaneous potential (SP) and gamma-ray logs (GR) data from 28 well-logs located in the Bas-Dauphiné basin."

Line 226: "To the 57 samples published by Kalifi et al. (2020) we ad 72 new samples (Table S1)."

In table S1 samples published in Kalifi et al. (2020) are now denoted by asterisks (*).

It is true that chronological data for the Burdigalian is sparse for the Molasse deposits. However, the authors might have a look at the magnetostratigraphic work done at the Univ. Bern c. 25 years ago where some terrestrial sections of Burdigalian age have been calibrated through magnetostratigraphy and mammal biostratigraphy (Schlunegger et al., 1996, Eclogae Geol. Helv., Kempf et al., 1997, Int. J. Earth Sci.; Strunck and Matter, 2002, Eclogae Geol. Helv.). Therefore, the first sentences of the Abstract need to be tuned town. I understand that the authors refer to the Western part of the NAFB and the Alpine orogen, because it is not true that the chronological records are poor for the Swiss, German and Austrian segments of the NAFB (perhaps see also Hülscher et al., 2019, Front. Earth Sci.)

The first sentence of the abstract has been modified as follows:

*"After more than a century of research, the chronology of the deformation of the external part of the **western** Alpine belt **(France)** is still controversial for the Miocene epoch"*

As a final, but not mandatory aspect, I think it would be worth while placing the sedimentary history of the western part of the NAFB into a broader context, if possible. In particular, following Berger (2005; Int. J. Earth Sci.) and Ford and Lickorish (2004; Geol. Soc. London Spec. Publ.), the pre 20 Ma sediments in the western part of the NAFB are characterized by gypsiferous marls, freshwater carbonates and paleosoils, suggesting a sedimentary environment that is indicative for a basin margin which opened towards the Swiss, German and Austrian Molasse basin that was the depositional sink at that time. After 20 Ma and particularly after 18 Ma, the situation changed as the dispersal direction became reversed and as sediment was routed from the Eastern Alps and the Bohemian massif through the German and Swiss Molasse basins and finally to the French part of the NAFB, which started to take the role as a depositional sink. Interestingly, this is the time when active deformation at the orogen front started, as documented in this work, while thrust front activity came to a halt in the Austrian basin.

Another paper, which is in review in Geol Soc Sp. Pub., is dedicated to the paleogeographical evolution of the western alpine foreland basin. However, we do agree that we can briefly compare the timing of the tectonic phases from our results with those of the neighbouring molassic basins (Swiss and the Rhodanian). A new paragraph (5.3) was integrated and is

called "5.3: Comparison of deformation phases affecting the Miocene molasses in western Alps".

Finally, there are a couple of typos to be revised (my review might also contain typos, for which I apologize):
Line 184: samples collected in the field (not on the field) Done
Lines 189 and 190: The terms 'comprised' sounds odd to my in this context. Done ("Comprised" not essential, has been deleted)
Line 232: outlier samples and not outliers samples Done
Line 267: The term 'allocated' sounds odd to me in this context. Done, replaced by "provided"
Line 394: The marls did not deposited.... -> The marls were not deposited. Done. The sentence has been changed (line 505).
Line 396: They rather deposited....(they deposited what?) -> They rather accumulated
Done, the sentence has been changed to:

"These marls, previously mapped as Jurassic (Vif geological map; Barféty et al., 1967), are rather Early Cretaceous in age based on the occurrence of Berriasella (Gidon, 2020a)."
Line 401: a boxed anticline overlyied by -> overlain by. Done
Line 446: the faults strike N3, 40°E -> something is missing @N3 Done: N3°, 40°E
Line 566: I could not find the South Jura transfer zone on a map. The name was added in Fig. 1
Line 570: I could not find the left-lateral and right-lateral faults The left-lateral faults are in violet and the right-lateral faults are in blue, as it is mentioned in the legend of Fig.1
Lines 583 and 584: I guess that the thicknesses of 1838 m and 1716 m are taken from a seismic line, which will have their uncertainties. If correct, the precisions given here (to the meters) need to be tuned down.

These datas are from well log datas:

"Indeed, these deposits are ~200 m thick west of the Rumilly syncline (Fig. 9C, D) (Enay et al., 1970; Gidon, 1970b), while to the east, they reach 1838 m between the footwall of the FZ1 and the hangingwall of the SAL fault (**SLV2 well data**, Fig. 10A, B), and 1716 m at the footwall of the SAL fault (**SV-101 well data**, Fig. 10A, D)."
Line 600: Firstly -> First, then second (not secondly), and then third (not thirdly) Done
Line 629: use a different term than 'brutally' (perhaps appropriate for a movie, but not really in a scientific article) Done, replaced by "sharply"
Line 632: A thickening can also be associated with a backstepping of depocenters (in case where sediment supply is lower than formation of accommodation space). Therefore, the inference that a rapid accumulation of sediment implies a depocenter migration is only correct if the sedimentary facies is considered as well. Please adjust accordingly.

Done, modified as follows:

"This firmly demonstrates that a depocenter localized close to section 4 (Fig. 13) appeared during S2a. Subsequently, the thickest accumulation of the following sequence (S2b) lies further west, at the Forezan locality (275 m, section 5, Fig. 13). This lateral variation of the thickness is associated with significant lateral facies variation characterized by a dominance of proximal marine deposits to the east (950-1015 m, section 4, Fig. 13), while to the west, S2b is mainly represented by distal marine deposits (700-920 m,

section 5, Fig. 13), thereby suggesting a westward migration of the depocenter between sequences S2a and S2b."

Line 636: 'It was never recorded thicker' sounds a bit odd to me. Please rephrase Done, replaced by "while in the Rumilly-Chambéry synclines area (Fig. 13), the sequence S3 was probably much thinner."

Line 691: This interpretation of a complex inherited topography warrants further specifications. Done: "On the western edge of the Bas-Dauphiné basin, the absence of S2a-S2b deposits (to the northwest of PA-1, VAF-2 and MO-3 wells, Fig. 15A, B, C) and the thickness variations of the S3 sequence to the west of the Montmiral high (Fig. 15B, C) are attributed to a complex inherited paleo-topography (Kalifi, 2020) along the Oligocene West European Rift (Debelmas 1974; Curial 1986; Bergerat 1987; Ziegler 1988, 1990, 1994; Bergerat et al. 1990; Sissingh 2003)."

Line 759: According to DeCelles and Gilles (1996; Basin Research), Schlunegger and Kissling (2015; Nat. Comm.; my apologizes for this self citation), orogenic loads can have different components such as slab loads, topographic loads (both downward directed) and buoyancy forces exerted by a crustal root. Is it possible to be more specific when you talk about 'in response to orogenic load'?

Yes, thank you for the suggestion. It was detailed as follows:

"In a foreland basin, this geometry is consistent with a foredeep depozone located between the poorly subsiding proximal flank of the forebulge and the footwall of the active (tectonic) orogenic front, where the maximum of subsidence is recorded in response to the interplay between topographic loads and long-wavelength lithospheric deflection in response to subduction process (DeCelles and Giles, 1996; Schlunegger and Kissling, 2015)."

Line 773: Why is the deposit illustrated on the photo (the details are hard to see) a seismite? This interpretation is hard to appreciate without further information.

This interval was interpreted as the Facies F25 presented in Kalifi et al. (2020). It consists of a 15-meter-thick interval of tilted/disturbed autochthonous sedimentary layers containing 'Ball and pillow' structures. This unit is laterally continuous at tens of kilometerscale (Same unit was found in the same stratigraphic level, at the Forezan section n°5, 18km to the south). The organization of the autochtonous clasts of various size is chaotic suggesting earthquake-disturbed layers (i.e. seismites) and the lateral continuity at the basin scale indicate strong disturbance events.

Details are now given in lines 605-610 (modified in order to be more accurate): "Second, a 15m-thick interval (390-405m, Fig. 12A), containing disorganized monogenic clasts of various sizes (cm to pluri-m, Fig. 12C) and 'ball and pillow' structures (Fig. 12D), with a pluri-km lateral continuity (also described 18 km to the south, in section 5, at ~380 m, Fig. 2) suggesting an earthquake-disturbed layer (i.e. seismites, F25 of Kalifi et al., 2020)."

Line 833: What is the evidence for a rebound, and a rebound related to which process?

According to Deville et al. 1994, the isostatic uplift is linked with crustal thickening in response to new crustal imbrication under the molasses basin involved by a late active tectonic deformation (maybe the term "rebound" we used wasn't adapted). From Deville et al. 1994 :" (uplift from the Langhian below sea-level to the present mean altitudes ranging between 500-800m, e.g., much higher than the mean altitude of coeval sediments in the Bresse basin; Bergerta et al, 1990). This could be related to the late active tectonic deformation of the foreland. Indeed, a possible interpretation could be the present development, at depth, of a new crustal imbrication that is suggested by the ECORS deep seismic results where a thickening of the lower layered crust appears under the molasses basin (Guellec et al., 1990a). The crustal thickening could be responsible for an isostatic uplift of the foreland. Note also that an active strong uplift is currently taking place in the SE parts of the Jura (Fourniguet, 1977)."

The sentence was modified as follows: "The following structural history however strongly differ between the north and the south: at ~13 Ma in the Aar the deformation front appears to have quicly migrated more than 50 km to the NW to form the Jura, while it ended at ~12 Ma in front of central Belledonne. However, some observations suggest that the Bas Dauphiné experienced uplift after 12Ma. In the western and southern parts of the Bas-Dauphiné basin and the Crest basin (respectively, J, K, L zones, Fig. 3) the Miocene final sea retreat is recorded during deposition of sequence S7 (~10 Ma, Fig. S13, 14, 15, 16). The absence of marine deposits during S8 (~9,5 to ~8 Ma) is unexpected, as it corresponds to an eustatic transgression corresponding to a higher sea level (+40 m) than that of sequence S7 (+5-10 m, Miller et al., 2005, Fig. 4B). This implies that the ~10 Ma Miocene sea-retreat was induced by a basin-scale event. In the north-eastern part of the Bas-Dauphiné basin (F, H zones, Fig. 5), the uppermost marine deposits (sequence S6 regressive deposits, ~11 Ma, Fig. S10, 12) outcrop today at elevation of ~350 m.a.s.l. (Fig. 14B; Fig. 15A). The sequence S6 transgression involved a +25 m sea-level rise which suggests a post-sequence S6 (12 Ma) minimum uplift of ca. 325 m. This is in agreement with Deville et al. (1994)'s observations implyinged a post-Langhian uplift. These authors interpreted this uplift as the result of a crustal thickening due to a crustal imbrication under the molasse basins, implying the activation of out-of-sequence thrusts in an internal position of the subalpine massifs. However, these thrusts have not been clearly identified and it is unclear how such thrusts could induce uplift of the Bas Dauphiné. Other possible interpretations are that this uplift would be linked to the activation of late backthrusts such as those described along section C (bkt1 & bkt2, Fig. 11), or to a yet unclear deeper process."

Line 836: ECMs = external crystalline massifs (please in full) Done

Line 885: Seismite, same as above. See answer above (line 773).

Line 887: 'brutal', same as above Done, replaced by "rapid"

Please do not hesitate to contact me if you have questions on my review.
Sincerely
Fritz Schlunegger, Bern, August 12th