Solid Earth Discuss.,
https://doi.org/10.5194/se-2019-56-AC2, 2019

Solid Earth
Discussions
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EGU

Interactive comment on "Late Miocene thrusting in the North Alpine foreland: Driven by a deep-seated process and shaped by the local mechanical stratigraphy" *by* Samuel Mock et al.

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Received and published: 27 May 2019

Dear editor, dear referee,

We appreciate the referee's detailed and constructive comments on our manuscript. We are pleased to see that most of the comments are minor in nature. The referee's major points of concerns are (1) the ambiguity regarding to where the focus of the study is throughout the manuscript and the somewhat unclear terminology regarding the geographical and tectonic descriptions (e.g. Central vs. Eastern Alps), and (2) the lack of data to justify the along-strike comparison which we aim for in the manuscript.

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In general, we acknowledge the referee's suggestions and we are happy to also bring the Eastern Alps more into focus, especially in the introduction and the discussion part. In order to avoid confusion, we will pay our fullest attention to the correct use of the nomenclature of Alpine tectonic domains.

Regarding point (1), we would like to stress that although we compare our observations with data and observations from the Subalpine Molasse further east and west, our focus so far was indeed on the Central European Alps. The confusion about the nomenclature stems mainly from the different definitions of the terms Central, and Eastern Alps. We follow here the definition given by Kissling and Schlunegger (2018) and Rosenberg et al. (2018), who base their nomenclature on paleogreographical and tectonic considerations but also, importantly, on the lithospheric structures at depth (i.e. slab geometries), which have been shown to be inherently different for the Central and the Eastern Alpine slab, respectively. Following this argumentation, the domain of the Central Alps is roughly delimited by the Brenner Fault as its eastern limit, hence it extends further east than defined by the classic nomenclature (e.g. Schmid et al., 2004) and incorporates for example also the Engadine Window. We see the need to clarify this and will do so in the revised manuscript.

We agree with the referee and do see the need to discriminate more carefully between the different tectonic settings in the hinterland as well as in the foreland. Therefore, we distinguish more carefully between the detached, wedge-top part of the Molasse Basin (i.e. Plateau Molasse), which is located in front of the Jura fold-and-thrust belt and the non-detached part further east (i.e. Foreland Molasse) throughout the manuscript. Furthermore, in the revised manuscript, we put more emphasis on the differences between the Central and the Eastern European Alps with respect to proposed along-strike changes in the deep (lithospheric) structures and the important contribution of escape tectonics in the Eastern Alps.

Concerning the second point the reviewer raised: In this manuscript, we present new data from an admittedly small area in the Subalpine Molasse of central Switzerland and

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discuss the site-specific exhumation signal. However, in a second step, we broaden the scale in a review type manner by compiling published data on the amount and timing of late Miocene thrusting of the Subalpine Molasse at several, evenly distributed sites along the entire Subalpine Molasse from western Switzerland to the area west of Salzburg. These data all concur in the observation of a late Miocene thrust activity with an overall decrease in horizontal shortening from the west to the east. We agree that new thermochronological data covering the entire front of the Subalpine Molasse including the Bavarian and Austrian sections would be desirable to also test the timing signal of thrusting in these areas. However, for our scope, i.e. discussing the general trend of lesser shortening towards the east, it is enough to compile the extensive existing data on the amount of shortening. In the updated version of the manuscript, we tried to clarify this better, updating sections 5.2.1 and 5.2.2 accordingly, now particularly highlighting the general decrease of the amount of shortening.

Please see the attached revised manuscript with track changes.

With kind regards on behalf of the authors,

Samuel Mock

Response (R) to general comments (C):

C: In general, I find the abstract a little complex to understand. Line 9-11 I don't really understand what the Authors want to state with this sentence. I don't understand "vertically directed tectonics" but then they state that they have back-thrusting, that would rather fit into the normal accretion processes. I think this needs to be explained a bit better. 15-17 This sentence is a bit long and complex. I would split into separate sentences. General comment on the introduction. The geological background is after the introduction, thus the reader is loaded with information that are not easy to understand. Some of these information could be shifted to the geologic introduction. As discussed above, this chapter is focused on the Central Alps, but there is little on the evolution of the Eastern Alps, which is also part of the study area.

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R: To clear up misunderstandings, we want to stress that vertically directed tectonics are restricted to the inner realm of the orogen. We distinguish between vertical and horizontal tectonics during the evolution of Alpine orogeny based on (1) a temporal and (2) a spatial argument. We relate the phase of dominantly vertical tectonics to the evolution of the Central Alps since collision and until the late Miocene. This phase is characterized by important sub-vertically directed movement of crustal blocks along the collisional plate boundary, i.e. the Insubric line, and the subsequent steep rise of middle to lower crustal material as evidenced by the External Crystalline Massifs. Hence, during this phase, the orogen thickened substantially but did not widen (orogen-perpendicular) to a great amount. This picture changes dramatically in late Miocene times, when large amounts of deformation occur in the external parts of the Alps, i.e. the Subalpine Molasse, the Jura Mountains and the Southern Alps.

We are aware that the introduction part is complex in terms of geological terms specific to the Alps. However, in order to clearly state the objectives of the paper, we think it is vital to use these terms and concepts of Alpine geology already in the introduction. We are convinced that we sufficiently address these issues in section 2 following the introduction.

In response to this comment, we also adjusted section 2 accordingly and gave the description of the differences between the Central Alps and the western Eastern Alps more space.

Response (R) to specific comments (C):

C: Page 2 Line 8 I would add also the interesting studies of Hinsch (I think is on Acta Geologica Carpatica) on recent basin tilting and erosion, which could provide also some constrains for the current study.

R: We think the reviewer refers here to the paper by Gusterhuber et al., (2012) in Geologica Carpathica. We added this reference in the revised manuscript.

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C: Page 2 Lines 11 From this point on the Authors refer to the Northern Alpine foreland in Switzerland, whereas before they were considering the entire basin. Maybe a different nomenclature would help the reader understanding these differences.

R: A more careful use of the nomenclature has been implemented and we refer now to the wedge-top (i.e. detached) part of the Molasse Basin as the Plateau Molasse whereas the term Foreland Molasse is used for the non-detached, eastern part of the Molasse Basin. The term "Northern Alpine foreland" comprises all the Plateau and Foreland Molasse, the Subalpine Molasse, as well as the Jura fold-and-thrust belt. We define this nomenclature in section 2.1 of the revised manuscript.

C: Page 2 Line 20 There are many papers on that topic also in other sectors of the Alps (Hinsch, 2013; Beidinger and Decker, 2014 and so on).

R: References have been added.

C: Page 2 Line 32 I don't understand what the Authors mean with "change of thrust tectonics". Do they mean change of tectonic regime?

R: We refer here to the overall change in the kinematics from a more vertically directed (restricted to the hinterland, i.e. inner realm of the Alps) to a more horizontally directed component of tectonic movement. We adjusted the text accordingly.

C: Page 3 Line 10 In which sector of the Molasse?

R: Large-scale exhumation has been reported for the entire Molasse Basin. Missing references for the Bavarian Molasse Basin have been added (Genser et al., 2007; Zweigel et al., 1998).

C: Page 3 Line 15-20 As comment as above.

R: We added missing references for geological mappings and stratigraphic work from the Bavarian Molasse.

C: Page 4 Geologic Background If this is the introduction of the study area, then the

Authors should described also the Eastern Alps, as at page 3 (line 23) they state that the study area extends from Geneva to Salzburg. This point would need some corrections here and there in the entire paragraph. The nomenclature, the relationships and so is all limited to the Central alps.

R: We added a short paragraph about the Eastern Alps. For our use of the term "Central Alps", please see our response to the general comments above.

C: Page 4 line 23 I don't understand if the Authors are talking about the Molasse Basin in the Central Alps or in general, as in the references there are some papers on other sectors and they state the study area extends also in the Eastern Alps. This should be better specified. See also point above.

R: We adjusted the text and use the established Molasse nomenclature (defined in section 2.1) to better highlight the along-strike variations in the tectonic setting of the Molasse Basin.

C Page 5 line 21 Also here there a little of misleading information, as the Authors talk about Molasse Basin, but actually describe only the basin in the Central Alps. This paragraph need more space and figures, such as stratigraphic columns, correlations and so on. I would also point out the characteristics of the substrate of the Molasse, as this might play also a role in the development of the compressional structures.

R: The concepts of accommodation space formation through plate flexuring have been very well established by the literature cited in our manuscript and are well known in the scientific community. We therefore do not see the need to add additional figures or stratigraphic columns. We however agree that the focus of this section is very much on the Swiss part of the Molasse Basin, hence we adjusted the section accordingly and added information and references from the eastern part of the Molasse Basin.

C: Page 8 4-2 Late Miocene shortening estimates in this paragraph there is a little confusion between data from the Central Alps and from the Eastern Alps.

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R: We do not fully understand the referee's comment. In this section, we present a compilation of published and well-established late Miocene shortening estimates alongstrike the Northern Alpine foreland (i.e. Subalpine Molasse and Jura fold-and-thrust belt). The signal of a decreasing amount of horizontal shortening seems to be robust, despite the admittedly large uncertainties with respect to estimates in the Subalpine Molasse (see e.g. Burkhard and Sommaruga, 1998; von Hagke and Malz, 2018; Ortner et al., 2015). As stated below (see next comment), there is no evidence for late Miocene shortening further east than ca 12.8° E as shown by the studies of Hinsch (2013) and Beidinger and Decker (2014). The reference to the latter study has been added in the revised manuscript.

C: Page 8 line 15 This part is a little confusing. The Authors stop their estimation of shortening in the area of Salzburg, but further to the East the shortening is significant, tens of km! Furthermore, I don't understand how they extrapolated a less than 1kmof shortening in the area of Salzburg. They should explain this part better. Is this shortening estimated just from map data? Is there any balanced section available? This needs to be explained. Check also the paper of Hinsch that contains data in this area.

R: Yes, we agree that the Subalpine Molasse in the area of Salzburg and further east records substantial shortening. However, we want to clearly stress that we are only looking at estimates of horizontal shortening taken up during the late Miocene. Based on geological and seimic interpretation, both, Hinsch (2013) and Ortner et al. (2015), have documented no shortening east of ca. 12.8° E (west of Salzburg) during the late Miocene. Beidinger and Decker (2014) corroborate this observation for the Austrian Molasse further east (this reference has been added in the revised manuscript).

C: Page 9 line 5 what is the meaning of a syn-tectonic strike-slip fault? Any fault is syn-tectonic by definition. Explain better.

R: Many thanks to the reviewer for spotting this confusing term. We meant a strike-slip fault which is active synchronously to thrusting. This has been adjusted accordingly in

the revised manuscript by using the term “syn-thrusting”.

C: Page 9 line 13-16 Instead of strain release pattern I would rather use something like change of structural style and thrust-spacing. The term strain partitioning refers to a very specific condition.

R: We added the term “thrusting pattern” in order to help the reader to understand the meaning of “strain release pattern”.

C: Page 9 line 15-18 I understand the meaning of this sentence, but is a little complicated. Maybe I would suggest to explain better what the Authors want to state.

R: We paraphrased the corresponding sentence accordingly.

C: Page 9 line 20 If the Authors want to use the term “strain partitioning”, they need to bring some more evidences supporting that. Different thrust spacing with the same tectonic directions can be generated by many tectonic processes.

R: Based on the suggestion of the referee we avoid the use of the specific term “strain partitioning” and instead use “pattern of strain release”, i.e. “thrusting pattern”, throughout the revised manuscript.

C: Page 9 24 Why re-activated. Please explain better.

R: This has been shown by the work of von Hagke et al. (2012) and is correctly cited as such in the manuscript.

C: Page 9 29 I would make clear that this is valid for the Subalpine Molasse in the Central Alps, as in the Eastern Alps the tectonic framework is completely different.

R: We fully agree with the referee and adjusted the text accordingly by defining the extent of the Subalpine Molasse supposedly affected by the uplift of the ECM.

C: Page 10 line 5 Actually the Easternmost part of the Molasse is described also by Hinsch2013 and Beidinger and Decker 2014.

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R: We fully acknowledge the work by Beidinger and Decker (2014) and Hinsch (2013). Their findings corroborate the absence of late Miocene thrusting east of ca. 12.8 ° E, which has been discussed in section 4.2.

C: Page 10 line 15-22 I find this part a little weak. There should be a more comprehensive discussion on the tectonic of the entire frontal part of the Alps, or otherwise to limit the model only to the Central Alps, leaving the rest out. For example, in that time-span there a lot of syn-thrusting strike slip faulting in the frontal part of the Eastern Alps that should be considered (See Peresson and Decker 1997 and many others). There are also other large tectonic elements in the game that could play a role in the deformation of the Molasse.

R: We fully acknowledge the concern raised by the referee. We will therefore introduce the matter of extrusion tectonics, which was facilitated by Carpathian slab retreat and rifting in the Pannonian Basin in section 2. Furthermore, we will discuss the effects of extrusion tectonics in section 5.2.2 of the revised manuscript.

C: Page 11 line 18. As far as I remember Hinsch describes laterally varying structures and timing in the eastern part of Eastern Alps. This data needs to be discussed in the present paper.

R: We are fully aware of and mention the work by Hinsch (2013) on numerous occasions throughout the manuscript. Most importantly, we discuss his work, which corroborates the non-existence of late Miocene deformation in the Subalpine Molasse east of Salzburg, in section 4.2. Hence, his work supports the observation of others (Beidinger and Decker, 2014; Ortner et al., 2015) that the eastward limit of late Miocene deformation in the Subalpine Molasse is located near Salzburg.

C: Comments on the figures. Fig. 1 As in the text there is are many comments on the ECM, I would put them on the map. I would also include the major tectonic elements, such as the various tectonic windows and other elements that could play a role. The tectonic section shows the structure of the Central Alps, but how about the rest of the

Molasse Basin? I would add a section also further to the East, where the deformation in the Molasse happened in a completely different tectonic framework.

R: We appreciate the referee's comment on Fig. 1 and will follow his suggestions by marking the position of the ECMs and other important tectonic features. To this end, we use an adapted figure from Schmid et al. (2004), showing the important tectonic features of the Alps. However, as the focus of this study is on the Central Alps with its eastern boundary roughly aligning with the Brenner Fault, we think it is sufficient to show one profile only. We discuss the differences between the Central and the Eastern Alps in the text of the revised manuscript (section 2.1 and 5.2.2) and give references accordingly.

C: Fig. 2 It took me 10 minutes to understand why the SW-NE striking thrust-faults look E-W oriented. Please, rotate the map with North oriented vertically.

R: We are aware of this, however, rotating the map would also make it larger. Since we think it is important for the reader to compare the data from the map and the cross-sections together in one figure, we would prefer not to rotate and thus enlarge the map. We placed the north arrow very prominently and we think the reader should be able to read the map accordingly. We will though additionally alert the reader by adding this information in the figure caption.

C: Fig. 5 I would extend this picture further to the East, and add more details on the major tectonic elements here, to show what is going on at the Eastern end of the Molasse. Furthermore, how was that shortening estimated? This is not clear in the text and apparently does not fully agree with some of the data published.

R: The estimated amounts of horizontal shortening are published data, which we have adopted from Ortner et al. (2015), von Hagke et al. (2014), von Hagke et al. (2012), Burkhard and Sommaruga (1998), and Philippe et al. (1996) for the Bavarian, and the eastern and western Swiss Molasse Basin, as well as the Jura fold-and-thrust belt respectively. Again, we want to stress that the shortening estimates shown in Fig.

5 record only late Miocene shortening as reported from the authors above. We are aware that other estimates exist (e.g. Kempf et al., 1999; Hinsch, 2013), however these values do either not distinguish between late Miocene and pre-late Miocene shortening (Kempf et al., 1999) or they document no occurrence of late Miocene shortening at all (Hinsch, 2013). In the updated version of the manuscript, we tried to clarify this better, updating sections 5.2.1 and 5.2.2 accordingly, now particularly highlighting the general decrease of the amount of shortening.

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Please also note the supplement to this comment:
https://www.solid-earth-discuss.net/se-2019-56/se-2019-56-AC2-supplement.pdf

Interactive comment on Solid Earth Discuss., https://doi.org/10.5194/se-2019-56, 2019.