Reply to RC1 of Claudio Rosenberg

Dear editors, dear referee,

We thank the referee for his very detailed and constructive comments on the manuscript. The referee is an expert on the tectonics of the Alps and has carried out extensive work on the along-strike architecture and evolution of the orogen. We very much appreciate the suggestions and criticism advocated by the referee and are convinced that with the revisions done we can now present a strongly improved version of the manuscript.

The referee's major points of criticism address: (1) The use of the terms "vertical" and "horizontal" tectonics, and the inferred change from one tectonic regime to the other; (2) The interpretation of foreland shortening estimates with respect to ECM exhumation; (3) The inferred link between the Central Alpine slab as a lithospheric driver and late Miocene thrusting in the Subalpine Molasse.

Regarding point (1), we clarified the meaning of the terms "vertical" and "horizontal" tectonics in section 1 of the revised manuscript. This distinction is based on published work on ECM exhumation (Herwegh et al., 2017, 2020).

With respect to point (2), we realized that we did not adequately describe the pattern of foreland shortening. In the revised manuscript, we made an effort to describe more precisely how horizontal shortening changes along-strike. We also further elaborate on the influence of uncertainties in the estimation of horizontal shortening.

Taking up the third point of criticism by the referee (3) we adjusted sections 2.1, 5.2.2 and 5.2.3 of the revised manuscript in order to show more convincingly why late Miocene thrusting in the Subalpine Molasse is likely be attributed to the dynamics of the Central Alpine slab at depth.

Extensive replies (R) to these general and other detailed comments (C) are given below.

With kind regards on behalf of the authors,
Samuel Mock

General comments
C: The paper presents some new AHe thermo-chronologic data and discusses them in the frame of geodynamic models of Alpine collision. The paper is well written and well illustrated. The data provide consistent results that allow one to constrain the age of thrusting of the Alpine front. The results show that the Alpine front in the western Central Alps is consistent with its age further east and this is a very interesting result. However the authors discuss these data in the context of lithospheric-scale kinematic models and the discussion becomes very speculative and mostly based on other inferred conceptual models rather than on the data of the paper itself. Parts of the Discussion section as that on the Bavarian Molasse are very far from the results presented by this manuscript and the Discussion section in general is rather far from the actual data of the paper.

I disagree with some of the interpretations in the Discussion section. One concerns the inferred general transition from vertical to horizontal tectonics in the Central Alps: I don't think that the tectonics of the Alps were ever vertical, and I don't think that a significant change of style before and after 12Ma took place. In addition the term "vertical tectonics" needs to be clarified and the evidence for such a change needs to be presented more convincingly in the introduction part. The authors state that there is no correlation between along-strike changes of shortening in the northern part of the Alps and along-strike changes of uplift (exhumation?) in the ECM. I think that the along-strike change of shortening goes together well with the one of exhumation in the ECM (see detailed comments).

R: Please see section 1 of the revised manuscript for a clarification. Herwegh et al. (2017, 2020) use the term "vertical tectonics" to describe the early stage in the evolution of an ECM, i.e. a phase of buoyancy-driven extrusion of a European basement unit after its delamination from the lithospheric mantle. This occurs by reverse faulting along steeply dipping structures resulting in differential subvertical uplift of the Massif. Based on structural, thermochronological, and geophysical data, this has been suggested for the Aar Massif to have occurred between ca. 22-13 Ma. According to Herwegh et al. (2020), a similar scenario is probably applicable also to the Mont Blanc and Aiguilles Rouges Massifs. In the Aar Massif, this phase of "vertical tectonics" is then superseded by en-bloc exhumation related to the activation of NW-verging basal thrusts in combination with dextral strike-slip shearing in the south starting at ca. 13-12 Ma. Herwegh et al. (2020) use for this thrusting-dominated phase the term "horizontal tectonics" and suggest that this concept might also be valuable for the Mont Blanc and Aiguilles Rouges Massifs. It is during this second phase of thrust-related en-bloc exhumation of the ECM, when deformation propagated into the Jura FTB. This is also the time frame during which we dated thrusting in the Subalpine Molasse. Hence, during this phase of "horizontal tectonics", shortening in the Aar Massif and probably also the Mont Blanc and Aiguilles Rouges Massifs is kinematically linked to shortening in the Jura FTB and the Subalpine Molasse. However, the variation in horizontal shortening in the foreland does not seem to reflect the different levels of exhumed basement blocks in the hinterland. This can be attributed to the fact that the ECMs were largely already in existence and that large parts (ca. 10 km for the central Aar Massif) of uplift is related to pre-12 Ma buoyancy-driven vertical reverse faulting (i.e. vertical tectonics) as reported by Herwegh et al. (2020). We incorporated this argumentation/clarification in the revised version.

With respect to the along-strike changes of shortening, it is important to note that shortening estimates for the Subalpine Molasse are subject to substantial uncertainties and likely represent minimum estimates due to: (i) the unconstrained large parts of proximal Subalpine Molasse which are hidden below the frontal thrusts of the Helvetic nappes and Penninic Klippen units, and (ii) the usual non-preservation of the hanging-wall cut-offs of individual thrust sheets. We adjusted the text in the revised manuscript accordingly in order to be clearer on this. Furthermore, Ortner et al. (2015) indicate that the decrease in shortening towards the east may to some extent also be due to the increase in the uncertainties of shortening estimates due to the lack of subsurface information.

Overall, we observe an eastward decrease in shortening in the Jura and complementary to that an eastward increase in shortening in the Subalpine Molasse until ca. 10° E. At least between ca. 7.5° and 10.5° E (a distance of ca. 250 km) cumulative shortening hovers between 24-18 km, which, given the expected large uncertainties described above, can be considered as being quite constant. Farther east, shortening in the Subalpine Molasse then decreases rapidly over just ca. 120 km. Hence, we would argue that shortening is not strictly progressive from west to east. Although, there seems to be a slight but poorly constrained decrease from the Jura to ca. 10.5° E, a rapid decrease to zero shortening is observed farther east until Salzburg.

C: A simple distinction between shortening along the Alpine front in the west and no shortening in the east is made and the transition is suggested to coincide with the inferred change of slab polarity. However, the Subalpine Molasse does not generally disappear east of Salzburg, it just disappears along a 100 km long segment, before re-appearing again further east. Shortening is still significant there (Beidinger and Decker, 2014). In addition, the area of the inferred transition is difficult to define precisely based on tomography (see detailed comments).

R: The idea of a slab polarity change is currently intensely advocated for in the literature. However, we fully acknowledge that it is highly debated and that there are various studies which disagree with this hypothesis. We also acknowledge that our data & hypotheses do not necessarily require a subduction polarity reversal. All tomographic studies do, however, image an anomaly in the deep structure somewhere below the Tauern Window and describe an along-strike change in the slab geometry at depth, despite disagreeing on the exact nature of this change (Hetényi et al., 2018; Kästle et al., 2020; Lippitsch et al., 2003; Mitterbauer et al., 2011; Qorbani et al., 2015; Zhao et al., 2016). At no point in the manuscript do we link unequivocally the eastward end of late Miocene activity in the Subalpine Molasse with a slab polarity change at depth. We do, however, make the link to the unanimously described segmentation of the orogen at depth and infer from the various tomographic studies the area where this segmentation is most likely to occur to be between the Brenner Fault and ca. 13° E.

Linking this to the orogen, we see that the amount of late Miocene thrusting in the Subalpine Molasse decreases rapidly roughly north of the Brenner Fault and that late Miocene thrusting diminishes completely just before Salzburg (ca. 12.8° E). Hence, we argue that the fade out of late Miocene thrusting in the Subalpine Molasse fits well with the conjectured transition in the slab geometries at depth. We are fully aware that there is also a Subalpine Molasse (or imbricated Molasse) farther east in Upper Austria. However, this part of the Subalpine Molasse was not active during late Miocene times as has been described by Beidinger and Decker (2014), Hinsch (2013), and Ortner et al. (2015).

C: The authors interpret their age data as the result of a deep (slab) driver, instead of a more "local, upper crustal one". I don't think that this distinction is very useful. The paper dates (very nicely!) an upper crustal thrust that is an expression of syn-collisional upper crustal shortening. Collision affected the entire lithosphere, hence there is no doubt that shortening in the Subalpine Molasse is related to a deep (slab) driver. But this is not a special case related to the Subalpine Molasse...it is true for any other shortening structure of the Chain. The question is not if there is such a surface-to depth relationship, but rather if we are able to identify it. Trying to link these different levels of the orogen in the Discussion is a worthy effort, but it makes the Discussion speculative and largely unrelated to original data of the Results sections.

R: We agree with the reviewer that based on the arguments given in the reviewer's comment this distinction is indeed not very useful. As the reviewer points out, the important question is whether we are able to identify the influence of a deep orogenic driver on upper crustal processes (in this case the tectonics of the Subalpine Molasse). We are fully aware that making this link is anything else than straightforward and, due to the lack of direct observations, prone to speculation. However, based on the observation of an agreement in (i) spatial location, (ii) wavelength, and (iii) temporality, we think it is valid to discuss the scenario of a possible link between the dynamics of the Central Alpine slab and Subalpine Molasse tectonics:
The along-strike extent of late Miocene thrusting in the foreland correlates spatially remarkably well with the proposed extent of the steeply south-dipping Central Alpine European slab imaged by seismic tomography (Fig. 9; Kästle et al., 2020; Lippitsch et al., 2003; Zhao et al., 2016).
The large spatial wavelength of tectonically driven late Miocene exhumation of the Subalpine Molasse reflects the Central Alpine slab as lithospheric-scale tectonic driver acting at that wavelength.
The proposed segmentation of the deep structure of the Central and Eastern Alps (Handy et al., 2015; Hetényi et al., 2018b; Kästle et al., 2020; Kissling et al., 2006; Lippitsch et al., 2003; Mitterbauer et al., 2011; Schmid et al., 2004), which is expected to have induced a geodynamic and tectonic reorganization along the Alpine chain by the end of mid-Miocene times, could explain the subsequent late Miocene tectonism restricted to the foreland of the Central Alps until ca. Salzburg and thus decoupled from the Eastern Alps.

Please see our revised manuscript, where we clarified these points in section 5.2.2.

Detailed comments

Page2

C: line 2 : replace Âń . They also Âż , by Âń ..., but they also Âż

R: I guess you want us to replace the full stop by a comma followed by a "but"? Done!

C: line 19: late stage? What do you mean by that?

R: Fold-and-thrust belt development in the Jura and the Subalpine Molasse as well as the development of the ECMs does not occur in the early stages of continent-continent collision, but rather late in the evolution of the Alps, hence, the term "late-stage". We replaced the term with "ongoing", since we think this better suited here.

C: Line 21: “However...”: this sentence suggests that classical propagation of thrusts towards the foreland should be continuous and that this is in contrast to the Miocene Alps. Sequence thrusting is discontinuous per definition and in the Miocene Alps still rather continuous I would say...the question is only what the absolute time interval between distinct thrusts is, in order to infer HOW discontinuous it really is. . .

R: We adjusted the text accordingly and rearranged the sentences.

C: Lines 24-25: “In addition...”: in addition to what? The previous sentence states a difference between Alps and classical wedge tectonics, this one states that something is not resolved yet.

R: Has been changed accordingly.

C: Line 25: “In the same sense”: ?

R: Has been changed to “Likewise”.

C: Line 27: abbreviation ECM is not mentioned and explained in text yet, just in the abstract.

R: This is a misunderstanding; we already defined the term ECM on page 2, line 15.

C: Line 32: These mechanisms? You have not mentioned any mechanisms yet.

R: Has been changed accordingly.

Page 3

C: Line 6: “In regions”: give some examples or references.

R: We added references in the revised version of the manuscript.

C: Lines 14-15: not really a summary, it is the 1st time that the new LT geochron data are mentioned.

R: We deleted “In summary,”.

C: Line 18: “late-orogenic large-scale change...”: this has not been mentioned before and it is written as if it was rather obvious. . .

R: We removed this in the revised version of the manuscript. We also rearranged the paragraphs in order to be more concise.

C: Lines 21-23: this statement on the along-strike change needs a reference. Ortner et al. 2015?

R: We added the missing references (Beidinger and Decker, 2014; Hinsch, 2013; Ortner et al., 2015)

C: Line 25: the reference is Kästle et al., 2020 (Int J Earth Sci), not 2019 (SE).

R: At the time of submission, the Kästle et al. paper was not yet under review at Int J Earth Sci. We gladly update the reference, thank you for the notice.

C: Line 27: replace deriving by derived

R: Done.

C: Line 28: replace deriving by derived

R: Done.

C: Line 31: I fully agree with placing the limit Central/Eastern Alps further East, but not with justifying this by the changing geometry of slabs at depth, which remains highly speculative, highly debated and controversially interpreted. By contrast, the limit based on the tectonic "transverse" system Giudicarie Fault- Brenner Fault is clearly mapped and its position will not change in the next years. . .

R: We acknowledge that Rosenberg et al. (2018) did not base their location of the Central-Eastern Alps boundary on the deep structure and modified the text in the revised manuscript accordingly. However, since one aim of this manuscript is to show possible inferences of slab dynamics on the late Miocene tectonic evolution of the Northalpine foreland, we think it is appropriate to use a definition on the orogens segmentation based on its deep lithospheric structure. We follow here a similar definition, which has already been used in Kissling and Schlunegger (2018). With respect to the changing slab geometries at depth please see here our reply to the comment below regarding page 14, line 1-12.

Page 4

C: Lines 1 and 2: this sentence would be more appropriate at the end of section I.

R: In order to give the reader our reason on why we use the aforementioned definition on the boundary between the Central and the Eastern Alps, we think it is evident to put this sentence already here.

C: Line 5: delete Schmid et al. 1996 if the reference is about the relationship of Central Alps to the slabs.

R: Done.

C: Line 6: "The": you never mentioned it was bivergent in the previous text.

R: This term is not so important here and since it seems confusing we deleted it in the revised manuscript.

C: Line 6: I am not sure that Cretaceous subduction is related to the bivergent structure, but a paper showing this is : ....

R: See reply to comment above.

C: Line 9: 1. nobody really knows if there was a slab breakoff, hence it should be written as an “inferred” process. 2. Nobody knows the age of this event in case it took place, but 32Ma is the age of the plutons inferred to derive from slab breakoff. Hence breakoff must be older.

R: We adjusted the text accordingly

C: Line 10: “period of fast uplift”: based on which evidence? Uplift or exhumation?

R: You are right. It is better to use here exhumation, since Hurford (1986) use cooling ages to determine cooling rates of the sampled rocks. Hence, what is effectively measured is exhumation. By combining the data with structural and tectonic analysis, Schmid et al. (1987) interpret the exhumation rates as uplift rates. We think that by giving the reader the appropriate references to follow up on the details, it is not necessary to go into much more detail here.

C: Lines 13-14: I would recommend that either the authors thoroughly discuss the matter of slab break off here with points in favor and against it or they drop this sentence with its citation.

R: We added this information at the request of a previous reviewer. However, since a full discussion on this matter is beyond the scope of this manuscript, we agree with the current reviewer and deleted this sentence in the revised manuscript.

C: Line 15: “over several tens of km “. . .of what?

R: We mean here “…over ‘a distance of’ several tens of kilometers…”. We adjusted the text in order to avoid any misunderstandings.

C: Lines 20-24: I am not sure if it is necessary to describe the Eastern Alps in this section. However if you do so, please do not forget that lateral extrusion goes together with one of the most spectacular upward folding of the nappe pile.

R: We added here information about the Eastern Alps following the request of a reviewer’s comment of the previous version of this manuscript. We added the information about upward folding, respectively.

C: Line 25: “The late stage”: it sounds as a clearly defined event, but it is not the case.

R: We certainly did not intend to use this term as a clearly defined event, but rather to say that what we describe is mainly concerning the late stages of Alpine orogeny (i.e. happening in a late time window of orogeny). We adjusted the text in order to make it clearer.

C: Line 27: not “to the Southern Alps”, they are themselves growing southward.

R: We adjusted the text accordingly.

C: Line 28: this change from dominantly vertical to dominantly horizontal growth is very critical to this paper, but it cannot be assumed so simply. I see no reason for a general change from vertical to horizontal tectonics during this ”Late stage”.

R: We adjusted the text in the revised version of the manuscript and removed the sentence. We added information and a definition of “vertical” and “horizontal” tectonics in section 1 and 5.2.1 of the revised manuscript. Please see also our reply to the reviewer’s general comment above and to his comments regarding page 11, line 28-29 and page 12, line 4.

C: Line 30: FTB in the S-Alps starts in the Eocene (pre-Adamello thrusts) and the post-15 Ma shortening is about 50% based on Schönborn (1992), it is not the largest part.

R: We changed the text accordingly.

Page 5

C: Line 31: add Molasse after Subalpine

R: Done

C: Line 32: not very clear: you mean “where the deep slab is present? Attached? What is this “configuration”?

R: We have deleted the second part of this sentence since it rather belongs into the discussion part of the manuscript.

Page 6

C: Line 1: So there is a phase of uplift at 20 Ma (Herwegh et al.), one at 10 Ma (Glotzbach et al.) and one at 5 Ma? Can we really distinguish these three events within 15 Ma? I doubt it. . .

R: I think this is a misunderstanding . Herwegh et al. (2017, 2020) document thrust-related en-bloc exhumation of the Aar Massif starting at ca. 12 Ma, and not 20 Ma. This is in general agreement with the findings of thermochronometric studies (Glotzbach et al., 2010; Valla et al., 2012; Vernon et al., 2009; Weisenberger et al., 2012) and, in turn, occurs in the same time window as thrusting in the Subalpine Molasse as documented in this study and von Hagke et al. (2012, 2014) and Ortner et al. (2015) and main deformation in the Jura FTB (see Becker, 2000).

C: Line 6: delete “the” before eroded

R: Done.

Page 7

C: Line 22: replace “estimates when” with “estimates about the time...” or something similar. . .

R: Done.

C: Line 24: replace technology with method

R: Done.

Page 8

C: Line 13: “max degree of freedom”: explain

R: By using only a few well constrained constraints, we can give the model a high degree of freedom and do not force it beyond given constraints. We changed the text to make it clearer.

C: Line 21: what do you mean by “reproducing”?

R: We mean that the single grain ages of one sample are all within the error bars of each other. Text has been adjusted to clarify.

C: Line 30: Add “compared” before to? Or reformulate otherwise. Not very clear.

R: Done

Page 9:

C: Line 2: I still think that reproducing is not the appropriate term

R: has been changed to “…group within their margins of error.”

C: Line 6: yes, but is it then an out of sequence thrust?

R: Not necessarily. Unfortunately, we have no age data from the front-most thrust (cutting the Burdigalian deposits), which would allow us to define the exact sequence of thrusting in this part. However, the timing of activity correlates well with out-of-sequence thrusting east of the Aare valley at ca. 6Ma. As we discuss later in the manuscript, the site where thrusting occurs seems to be very variable along-strike the Subalpine Molasse and is mainly controlled by the mechanical stratigraphy.

C: Line 9: what is a balanced map?

R: In order to explain the kinematic evolution of the Jura, Philippe et al. (1996) use an approach where they balance palinspastic maps by restoring structural map units, which are delimited by tectonic boundaries. We adjusted the text to make this clearer.

C: Line 9: if there are own data in the figure they should be described.

R: We added additional information in the supplementary material. Furthermore, we also moved the appendix of the manuscript, which describes the apatite separation and picking methods to the supplementary material.

C: Lines 20-21: I fully disagree with this statement, both with its content and its formulation. A “peak of high uplift domain” is a very vaguely defined term that should be avoided here. Max. shortening in the west concides with the position of the Mt Blanc Aiguilles Rouges ECM: the “peak of highest uplift”. Shortening decreases in front of the Aar ECM, which is less exhumed than the Mt Blanc, and it decreases even less in front of the Engadine Window, which is a sort of proto-ECM. Finally there is nearly no shortening east of Munich, but no ECM exists there.

R: With respect to along-strike changes in shortening estimates please see our detailed reply to your comment regarding page 13, line 20. Yes, there is a slight decrease in shortening from west to east, however, the variation in horizontal shortening does not seem to reflect the different levels of exhumed basement blocks in the hinterland. As a simple observation this holds true. We reformulated the sentence. We further elaborate on this observation in section 5.2.1 of the revised manuscript. Studies from the ECMs show that the massifs were already in existence when deformation propagated into the foreland. Hence, late Miocene thrusting and shortening of the foreland is kinematically linked to northward thrusting along the northern front of the ECMs (referred to as “horizontal” tectonics by Herwegh et al., 2017, 2020). This, however, seems to occur regardless of the maturity of an ECM or whether an ECM is present in the hinterland or not.

C: Line 23: After reading 5.1. I don’t really understand why the section should have “Downscaling as a title”.

R: We removed this in the revised version of the manuscript.

Page 10

C: Line 11: replace “strain release (i.e. thrusting pattern)” simply by “the pattern of thrusting”.

R: Done.

C: Line 13: replace “released” by “accommodated” and replace “much more distributed” by: “in a much more distributed fashion”

R: Done.

C: Lines 17-18 redundant. Delete.

R: Done.

C: Line 19: replace release

R: Done.

C: Line 20: sampled area, or better: study area

R: Done.

C: Line 21: replace release

R: Done.

Page 11

C: Line 7: Post 12 Ma is ok, but there must be some pre-12 Ma thrusting too to justify cooling at 20 Ma.

R: We are not aware of any reported cooling ages from the Subalpine Molasse east of Lake Constance. However, from tectono-sedimentological data (e.g. Hinsch, 2013; Kempf et al., 1999; Ortner et al., 2015; Schlunegger et al., 1997), it is known that the Subalpine Molasse was of course already tectonically active before 12 Ma and became subject to thrusting already in the early Miocene or even earlier. In this case, however, we focus on the late Miocene tectonism in the Northalpine foreland, i.e. the Subalpine Molasse and the Jura FTB, and correlate this with the documented late Miocene en-bloc exhumation along shallow-dipping thrusts below and in the ECM.

C: Line 9: coevally

R: Done.

C: Lines 12-14: This should rather be in the geological setting.

R: We moved this into the geological setting and just shortly refer here to it.

C: Line 24: as stated above I disagree!

R: Please see our response to the reviewer’s comment above regarding page 9, line 20-21. In order to clarify, we adjusted the whole paragraph in the revised version of the manuscript.

C: Lines 25-26: But why should they be a CONSEQUENCE of the exhumation of the ECM? I wouldn't know which process could possibly explain this. But as you write they are kinematically LINKED, which means that the Subalpine thrusts root in the ECM, hence the Subalpine Molasse is shortened together with the ECM.

R: We agree with the reviewer and deleted this sentence. We adjusted the whole paragraph in the revised version of the manuscript.

C: Lines 28-29: This statement is very strong and clear, but where is a sound evidence to support it? I don't think that the Alps ever went through this change in Miocene times.

R: We acknowledge the comment of the reviewer and see the need to clarify this point. Please see also our reply to the reviewer's general comment above and to his comment regarding page 12, line 4. We adjusted the whole paragraph in the revised version of the manuscript. We have realized that we need to re-dimension this observation / statement to the northern Central Alps (i.e. the Jura FTB – Molasse – ECM system). We base this statement on the following arguments.
Based on tectonic, thermochronological, and geophysical arguments, studies from the Aar Massif have suggested that the Massif uplifts differentially during an early and mid-Miocene buoyancy-driven stage ("vertical tectonics"), which is then followed by a thrusting-dominated stage ("horizontal tectonics"), when the whole Massif is exhumed en-bloc above a series of basal thrust ramps (Herwegh et al., 2017, 2020). Although this has been showed exemplarily for the Aar Massif, a similar evolution is probably also applicable for the Mont Blanc and the Aiguilles Rouges Massif (see Herwegh et al., 2020).
During the buoyancy-driven uplift of the Aar Massif, the northern deformation front remained stationary in the Subalpine Molasse (triangle zone; Burkhard and Sommaruga, 1998; von Hagke et al., 2014; Ortner et al., 2015). It was not until 12 Ma when deformation propagated into the Jura FTB (e.g. Becker, 2000) and widespread activity of thrusting in the Subalpine Molasse occurred (von Hagke et al., 2012, 2014; Ortner et al., 2015; this study). This occurred coevally and is kinematically linked with low-angle thrusting in and below the Aar and Aiguilles Rouges Massif.

C: Line 29: this has been described in the Aar Massif, but not in the other ones. The plural and generalization are not appropriate here.

R: We agree with the reviewer that we cannot generalize this for the other ECMs. However, in their review article, Herwegh et al. (2020) have proposed a similar scenario also for the Mont Blanc and Aiguilles Rouges Massifs. We adjusted the text accordingly and distinguish more carefully between the different ECMs.

C: Line 31: why "reactivation"? Were they ever disactivated?

R: changed to "activation"

Page 12

C: Line 3: Schmid et al. 1996 quote Schönborn, 1992, which is really THE reference. Schönborn writes about Mid Miocene. So I would suggest either to say Mid-Miocene or 16 Ma.

R: Done.

C: Line 4: I do not agree with a general statement assessing the existence of a phase of vertical tectonics in the Alps before 12 Ma in the core of the Alps. And what is the core of the Alps? The Lepontine? Was the Lepontine affected by vertical tectonics before 12 Ma? In this case the term "vertical tectonics" should be defined precisely.

R: Please see here also our reply to the reviewer's general comment above and to his comment regarding page 11, line 28-29. We refer here to recent publications (Herwegh et al., 2017, 2020) where the authors describe a phase of buoyancy-driven uplift of the Aar Massif between ca. 23-13 Ma based on a geodynamic scenario of slab rollback (Fry et al., 2010; Kissling, 2008; Kissling and Schlunegger, 2018; Schlunegger and Kissling, 2015; Singer et al., 2014). Due to the sub-vertical direction of movement along steeply dipping reverse faults, they simplify this as "vertical tectonics". Starting at 13 Ma, they see evidence for low-angle northward thrusting along a series of thrusts in and below the Aar Massif, which leads to en-bloc exhumation of the entire Massif. It is the latter event, which they are referring to as "horizontal tectonics" and which is kinematically linked to thrusting in the Subalpine Molasse and the Jura FTB. Based on thermochronometric arguments, they also suggest a similar style of en-bloc exhumation above basal thrusts of the Aiguilles Rouges Massif, which similarly is also kinematically linked to foreland deformation. Hence, with our new age data from the Subalpine Molasse, we can further corroborate the timing of this inferred transition, from buoyancy-driven "vertical tectonics" (ca. 23-13) to "horizontal tectonics" represented by basal thrusting of the Aar and Aiguilles Rouges Massifs and thrusting in the Subalpine Molasse and the Jura FTB.

In summary, the term vertical tectonics describes the buoyancy-driven differential uplift of delaminated (supposedly within the lower crust) European basement units along steeply dipping shear zones. This has been suggested for the Aar Massif based on structural, thermochronometric, and geophysical arguments, but may also have played a role for the evolution of the Mont Blanc / Aiguilles Rouges Massif. The term "horizontal tectonics" describes the subsequent phase of en-bloc exhumation of the Aar and Aiguilles Rouges Massifs due to foreland verging thrusting along low-angle thrust domains. This is kinematically linked with thrusting in the Subalpine Molasse and the Jura FTB.

Please see our adjustments to sections 5.2.1 and 5.2.2 of the revised manuscript.

C: Lines 6-7: these statements cannot be applied so simply to "the Alps" in general.

R: We agree with the reviewer and adjusted this whole paragraph in the revised version of the manuscript.

C: Line 15: I am not sure that I understand the term "delamination" in this context. It should be specified.

R: we deleted the term here and specified it a few lines later in revised version of the manuscript.

C: Line 18: The relationship between slab unloading and backthrusting along the Insubric Line is extremely speculative, and anyway not explained by these sentences. Note that backthrusting is very significant in the western Central Alps and disappears in the eastern Central Alps. How does this match with such a large-scale interpretation, where the cause of these structures is seen in the deep slab?

R: Since, this seems to be quite speculative and not so important for the purpose of this manuscript, we decided to remove this sentence from the revised version of the manuscript.

C: Lines 19-21: on line 19 it is stated that the EU slab is delaminated, on line 21 “crustal delamination” is mentioned. Are you talking about the same process here?

R: Yes, we are talking about the same process here. Kissling (2008) proposed that the crust delaminates (i.e. separates) from the mantle somewhere within the lower crust, enabling the mantle slab to sink while the less dense and buoyant crust becomes accreted to the orogen. Later this concept has been refined further and put into a slab rollback model for the Alps (Fry et al., 2010; Kissling, 2008; Kissling and Schlunegger, 2018; Schlunegger and Kissling, 2015; Singer et al., 2014). We clarified the usage of the term “delamination” in the revised version of the manuscript.

C: Lines 21-22: “as evidenced”: the Helvetic nappes are the evidence of shortening in the cover during collision, not the evidence that crustal material was entering the subduction system during rollback…

R: We adjusted the text accordingly.

C: Lines 21-23: Is it really necessary to propose these speculative interpretations?

R: We follow here an argumentation of a published roll-back subduction model. However, we adjusted the wording and used the subjunctive where appropriate.

Page 13

C: Line 4: Rosenberg et al. did not state this.

R: Rosenberg et al. (2018) did however observe a “…gradient of crustal thickening, increasing westward, associated to an eastward decrease of average elevation.” We reformulated the sentence accordingly.

C: Line 9-12: The very progressive eastward decrease in the amount of shortening as illustrated in fig. 6 is not satisfyingly explained by a process of decoupling in one specific area.

R: Our statement of a decoupling is based on two observations: (i) while west of Salzburg, late Miocene thrusting occurred in the Subalpine Molasse, there is no such evidence for the Subalpine Molasse east of Salzburg (Beidinger and Decker, 2014; Hinsch, 2013; Ortner et al., 2015), (ii) Current estimates on cumulative horizontal shortening, certainly when considering the presumably large uncertainties with respect to shortening within the Subalpine Molasse, do not call for a progressive decrease from west to east. However, what we observe is a rather rapid decrease in late Miocene horizontal shortening east of ca. 10.5° E to zero shortening east of Salzburg. With respect to the shortening estimates please see our detailed reply to your comment regarding page 13, line 20. We also adjusted the text to make this last argument clearer.

C: Lines 15-17: a bit speculative, but again, the shortening data would call for a progressive change, not an abrupt one.

R: The use of the subjunctive wording should already indicate that this is a possibility and not at all an unambiguously describable fact, which we would like to discuss. With respect to the shortening estimates please see our reply to your comment regarding page 13, line 20.

C: Line 18: this interpretation is also made difficult by the fact that there is no unanimous agreement on the deep structure of the slabs. See the different interpretations of Lippitsch et al. (2003), and the one of Mitterbauer et al. 2011.

R: It is true that there is no uniform opinion on the slab geometry at depth and especially about their origins (Adria vs. Europe) and possible mechanisms (e.g. slab break-off, subduction polarity change, overturning slabs, etc.). However, nobody doubts (i) the existence of an attached and steeply south-dipping slab of European origin below the Central Alps, and (ii) the existence of an anomaly somewhere below the Tauern Window and a segmentation of the slab geometry along-strike, although the nature of this segmentation is very much debated. See also our reply to your comment regarding page 13, line 25.

C: Line 20: I agree that there is less shortening eastward, but again, the evidence is that of a PROGRESSIVE decrease that starts already in the Jura Mts.

R: It is important to note that shortening estimates for the Subalpine Molasse are subject to substantial uncertainties and likely represent minimum estimates due to: (i) the unconstrained large parts of proximal Subalpine Molasse which are hidden below the frontal thrusts of the Helvetic nappes and Penninic Klippen units, and (ii) the usual non-preservation of the hanging-wall cut-offs of individual thrust sheets. We adjusted the text in the revised manuscript accordingly in order to be clearer Furthermore, Ortner et al. (2015) indicate that the decrease in shortening towards the east may to some extent also be due to the increase in the uncertainties of shortening estimates due to the lack of subsurface information.

In summary, we observe an eastward decrease in shortening in the Jura and complementary to that an eastward increase in shortening in the Subalpine Molasse until ca. 10° E. At least between ca. 7.5° and 10.5° E (a distance of ca. 250 km) cumulative shortening hovers between 24-18 km, which, given the expected large uncertainties described above, can be considered as being quite constant. Farther east, shortening then decreases rapidly over just ca. 120 km. Hence, we would argue that shortening is not strictly progressive from west to east. Although, there seems to be a slight but poorly constrained decrease from the Jura to ca. 10.5° E, a rapid decrease to zero shortening is observed farther east until Salzburg.

C: Line 21: No references are given for the seismic tomography here. This is a problem, because several, but not all of the published tomographies support this last statement.

R: We added the missing references. They all describe the lateral termination of a steeply S-dipping Central Alpine slab somewhere in the area of the Giudicarie Fault.

C: Line 22: Why the term “individual tectonic pulses”? They are just thrust sheets.

R: We adjusted the text accordingly.

C: Lines 22-23: I frankly disagree with this attempt of categorizing the possible driver of shortening in the Molasse into two classes: deep (slab) driver, and crustal, local driver. If the authors argue that the driver of shortening is the displacement of the slab I certainly agree, but this generally true in convergent systems! The question here is not if the driver is somewhere outside the slab “(upper crustal phenomena”). All upper crustal phenomena are supposed to be related to very deep ones. The question is whether we are able to make this link from the outcrop-scale to the orogen-scale to finally arrive at the lithospheric one. In this paper the authors are very keen on linking their relatively small observations to the very large one with the risk of being speculative.

R: We realized that it is probably better to use the term ‘exhumation’, since this is the signal we can measure by using thermochronometry. We very much appreciate your comment regarding the possibility to infer a link between upper crustal processes and deep-seated processes. Please see also our response to the reviewer’s general comment above. We adjusted section 5.2.2 of the revised manuscript accordingly.

C: Line 23: “bigger players such as plate tectonics”: I don’t understand the problem. Did anybody ever (since 50 years) doubt that the frontal Alpine thrusts are related to Plate Tectonic processes?

R: We very much appreciate the reviewer’s comment and adjusted the text accordingly.

C: Line 25: The references are not all consistent with the statement of a polarity change. Mitterbauer is not, and Kästle (2020, not 2019) isn’t really. . .

R: Yes, this is true. Mitterbauer et al. (2011) argue against a subduction polarity change. However, they too report an along-strike change in the slab configuration between ca. 12°-14° E, with the change from a shallow slab to a deep, possibly detached slab configuration. They also image the along-strike change from a south-dipping to a north-dipping shallow slab. Hence, although not agreeing with the polarity change theory, they also clearly report an important along-strike change in the slab configuration. Kästle et al. (2020) show very nicely that the European slab extends eastward until 12.5°, which correlates with the extent of the late Miocene Subalpine Molasse. For the purpose of this manuscript it is not the aim to give a definitive solution on this problem; and we dare not to do so, since it is not our field of expertise. In addition, the variety in the tomographies and their interpretations certainly do not allow for a concise solution at this point. Hence, we deleted the proposed mechanisms here in the text.

C: Line 27-28: Not only the amount of shortening progressively drops even WITHIN the Central Alps, but in addition it increases again in the eastern Eastern Alps (Beidinger and Decker, 2014). Therefore there is a complex pattern that I cannot reconcile with the simple one of one slab in the Central Alps terminating at its eastern boundary.

R: We agree that the amount of shortening does decrease towards the east within the Subalpine Molasse. However, it is important to note that shortening estimates for the Subalpine Molasse are subject to uncertainties and likely represent minimum estimates due to: (i) the unconstrained large parts of proximal Subalpine Molasse which are hidden below the frontal thrusts of the Helvetic nappes and Penninic Klippen units, and (ii) the usual non-preservation of the hanging-wall cut-offs of individual thrust sheets. We adjusted the text in the revised manuscript accordingly in order to be clearer. With respect to shortening in the Subalpine Molasse of Upper Austria please see our reply to the comment below (p. 14, l. 1-12).

C: Line 29: Again, I see no reason to infer such a macro-tectonic regime in general for the Central Alps.

R: We adjusted the text in order to specify that we describe this transition for the northern Central Alps (i.e. the Jura FTB – Molasse – ECM system). Please see our reply to the reviewer's general comment above and to his comments regarding page 11, line 28-29 and page 12, line 4.

Page 14

C: Lines 1-12: this paragraph discusses the spatial coincidence between the eastern termination of the subalpine Molasse close to Salzburg and the inferred change in subduction polarity in the Eastern Alps. The first is clearly defined in space, the second is not. Its position varies as a function of depth and its resolution in space is in the order of +/- 100 km. Thus stating that the two coincide is a vague statement. The other problem I see is that the Subalpine Molasse does not really end in the area of Salzburg, it is just absent for ca; 100 km and starts again further east. So the Alps are not so simply separated into a western part with a Subalpine Molasse and an Eastern one without it. They are rather a chain with a Subalpine Molasse that is missing in a small segment between Salzburg and Linz.

R: Yes indeed, there exists an imbricated Molasse, or Subalpine Molasse, east of Salzburg, a fact which we also mention in the geological setting. However, there clearly seems to be no evidence of late Miocene shortening in the Subalpine Molasse east of Salzburg as several publications indicate (Beidinger and Decker, 2014; Hinsch, 2013; Ortner et al., 2015). This is an argument, which we state very clearly in the manuscript (see page 5, line 30-32 of the unrevised manuscript). It is true that the transition in the slab geometries at depth is subject to large uncertainties and we discuss this adequately in the manuscript by citing the many tomographic studies and interpretations (Hetényi et al., 2018; Kästle et al., 2020; Lippitsch et al., 2003; Mitterbauer et al., 2011; Qorbani et al., 2015; Zhao et al., 2016). Please note that in the revised manuscript, we added a missing reference from the AlpArray tomographic study (Hetényi et al., 2018). We can infer that a segmentation in the deep structure of the Alps occurs somewhere below the Tauern Window; an observation on which all of the publications imaging and interpreting the Alpine slab structure in this area concur on. Furthermore, the various tomographic studies allow us to infer the area where this segmentation is most likely to occur, i.e. between the Brenner Fault and ca. 13° E. When we compare that to the Subalpine Molasse, we see that the amount of late Miocene thrusting decreases rapidly roughly north of the Brenner Fault and late Miocene thrusting diminishes completely just before Salzburg and does not occur farther east. Hence, we argue that the fade out of late

Miocene thrusting in the Subalpine Molasse fits well with the conjectured transition in the slab geometries at depth.

C: Lines 13-31: These paragraphs are about the tectonics of the Eastern Alps and their relationship to the Molasse Basin, which is however speculative and very far from the data of this paper. I wonder if they are really necessary.

R: We added this paragraph at the request of both reviewers of a previously submitted version of this manuscript. Since, there is literature, which specifically discusses the influence of lateral extrusion on the tectonics of the Subalpine Molasse (see Ortner et al., 2015), we think it is appropriate to discuss this and include it in our considerations about the late Miocene tectonic evolution of the Subalpine Molasse.

Page 15

C: Line 7: replace release

R: Done

C: Line 11: all the Discussion emphasizes the along-strike tectonic change...why is it remarkably constant here?

R: We changed the text accordingly.

C: Line 14: what is a “tectonic signal”?

R: See reply to comment below.

C: Line 15: so the “signal” is shortening?

R: Yes, the signal is thrust-related shortening. We adjusted the text accordingly.

C: Line 15-16: structure of the sentence needs to be readjusted

R: Done.

C: Line 17: so the thrusting is the large-wave length structure? Not the exhumation of the Molasse in general?

R: Indeed both. Exhumation of the Subalpine Molasse has been constrained by cooling ages between Lake Thun and Lake Constance and has been attributed to wide-spread thrusting, which, for the same time frame, has also been observed for the Subalpine Molasse farther east.

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Reply to RC2 of Giovanni Luca Cardello

Dear editors, dear referee,

We thank the referee for his detailed and constructive comments on the manuscript. The referee is an expert in structural geology and on the tectonics of the Alps. We very much appreciate the suggestions and criticism brought forward by the referee and are convinced that with the revisions now implemented we can present a strongly improved version of the manuscript.

Based on the reviewer's comment we carefully revised the manuscript and adjusted the text and the figures following the reviewer's suggestions. Where appropriate, we added references to literature, which we have not considered in the original manuscript. We carefully revised section 5.2.2 following the second referee. This section deals with the geodynamic implications for the Central Alps. We are convinced that we can now present a more robust discussion on this topic. Furthermore, we updated section 5.1 on the mechanical stratigraphy and its influence on the trusting pattern.

Being aware that each referee sets a different focus during his review, we are convinced that we can present now a well-balanced revision, which meets the requests and suggestions of both referees.

Extensive replies (R) to the reviewer's comments (C) are given below.

With kind regards on behalf of the authors,
Samuel Mock

General comment

C: This paper documents the thrust-related exhumation of the Subalpine Molasse during the late Miocene made by interpreting the thermochronometry results of 13 apatite (UTh-Sm)/He, contextualizing them into the regional structural geology and trying to make an upscale comparison with the broader geodynamics at the disputed transition between the western and eastern sector of the European Alps. As far as I know, the manuscript has not been published previously. The title is conforming with the contents of the Ms and the approach and results and conclusions intelligible from the abstract alone. I have proposed some changes in the text organization and minor changes in figures. The manuscript presents an interesting topic, which should catch the attention of the readers of Solid Earth. It is based on some fieldwork and it is quite well structured although field evidences would deserve a to be more deeply described. I found the results too short with respect to the discussion and the Introduction part. If the aim is the attribution to the large-wavelength deformation style as responsible of exhumation in the Alpine thrust front, solving the upscaling problem is crucial. In that case, the authors could consider in their review to contextualize their study area on broader regional map and make considerations on the structures that have allowed exhumation. So far, they are not well documented in this paper. I found interesting the mentioned change of deformation with the lithotype involved in the Molasse units (i.e. conglomerates, sandstones, pelites), but it was not shown as it is in the field or tightly described as referred to the figures. In reinforcing the results section, this topic would be easily solved by the authors that have a great knowledge of the area and could possibly be strengthen in the discussion as associated to the exhuming structures (see later in the detailed comments). I found the geodynamic part not so essential for the general implications of the paper that would anyway fit, without it, a large public when the thermochronometric interpretation will be presented with a reinforced documentation of the thrust-related exhuming structures. After all, the general slab dynamics are still so debated as they nicely reported. The regional role of their structure is to me more interesting and could provide general information on how exhume at a thrust front a proximal molassic deposit affected by lateral facies changes. Notwithstanding these potential limitations, and considering that addressing these would lie beyond the intended scope of the manuscript, I feel that the paper needs some more work to have that detail for making an informative and well-balanced account that deserves publication in Solid Earth.

R: We thank the reviewer for the assessment of the manuscript and the suggestions. In the new version of the manuscript we have accommodated the points as follows:

We updated section 5.1 regarding the mechanical stratigraphy along and across strike and its influence on the thrusting pattern in the Subalpine Molasse. We gladly follow the advice by the reviewer and added a section about the litho-tectonic architecture of the Subalpine Molasse in the Lake Thun area to the results, thus also extending the results part of the manuscript. However, as this paper has to some extent a review character the remaining imbalance between the results and the discussion part is expected, since corresponding results from other studies are embedded in the discussion part of the manuscript.

In order to put our sampling area and its significance into the broader context of the Central Alps, we added information about why we consider the Lake Thun area as a key area for understanding Subalpine Molasse tectonics (section 3.1 of the revised manuscript).

We have carefully revised the part of the manuscript regarding the link to the geodynamic context. Based on the comments of both reviewers we have strengthen section 5.2 of the revised manuscript.

Please see our detailed responses to the technical points raised by reviewer below.

Major points of strength/weakness

C: There are some points where a revision is necessary. In general, the Ms needs just some iteration to enrich a few aspects of the text in the results and shorten the geological setting, updating the literature with respect to the recent works (see detailed comments). The references are quoted finely although lacking of an update on some of the more recent works on the Pennine and Helvetic nappe emplacement recently reported in the Swiss literature and Alps). I found only a reference to check, the rest should be fine. The upscaling to faultâARfault and regional (and eventually) geodynamic setting relationships at map scale needs to be somewhat better shown. That could be due by following the more detailed suggestions and if possible including additional changes to figures combining simplified crossâARsections, mostly in the results. I have suggested some minor changes in the rest of the text. I believe that length is fine at this first review. Tables and figures look fine. Supplementary Data are used appropriately.

R: In our new version of the manuscript, we have accommodated all these comment. We have revised the geological introduction and updated our reference list and have revised the section on bridging the scales. See also detailed comments for more extensive replies.

Technical points

Suggestions for improving technical points have been provided with detailed comments that will help preparing the next version of the manuscript.

C: Page 1 – Abstract Line 20. tectonic forces: you can be more specific; Line 20. This resulted in a change: you may wish to specify what change you imply (i.e; time and space?)

R: We changed the sentence respectively to further specify that the change occurs from a buoyancy-driven tectonic regime, here referred to as vertical tectonics, to horizontal tectonics related to compressional forces and plate tectonics.

C: Page 1 – Introduction Line 26. Davies and von Blanckenburg, 1996 in the reference list

R: Davies and von Blanckenburg (1995) is already given in the reference list. As far as we are aware, there exists no Davies and von Blanckenburg (1996) publication.

C: Line 28. To consider eventually further on, you may wish to consider as well the implications related to asymmetric slap polarity with respect to the westward drift of the lithosphere (e.g. Carminati and Doglioni, 2012) in the frame of changes in the subduction polarity across the alps. Carminati, E., & Doglioni, C. (2012). Alps vs. Apennines: the paradigm of a tectonically asymmetric Earth.Âă Earth-Science Reviews,Âă 112(1-2), 67-96.

R: This is an interesting paper and the westward drift of the lithosphere is point, which could influence the stratigraphic development of the Molasse. We mentioned this mechanism in the revised version, but decided not to fully discuss these processes as we expect a major signal east of Salzburg, which is beyond the scope of our paper.

C: Page 2 – line 3. considering the relevance of this concept and that you have it also in the title, you may consider to shortly describe what is large-wavelength deformation and to what is usually referred to.

R: The word wavelength describes here in relative terms the spatial extent of a certain process or feature, in this case tectonic processes. In order to clarify what type of wavelength we are referring to, we added the word “spatial” in the revised version of the manuscript. In the same sense, large-wavelength deformation describes the spatially large extent of a certain deformation event.

C: Line 4. North Alpine foreland basin - eg. citation Pfiffner 1986

R: Pfiffner (1986) is already listed here.

C: Line 12. have a look at Egli 2017, 2019 and Cardello et al. 2019 JSG on the nappe emplacement during Oligocene to Miocene time. In the latter, you can find also some more references if you find them interesting.

R: Many thanks for hinting us to these publications. However, we could not find a publication by Egli et al. (2019). We are aware that there are more publications which look into the timing of Alpine nappe emplacement. However, we want to address here the studies, which specifically addressed the deformation history of the Alpine foreland, i.e. the Subalpine Molasse, Plateau Molasse, Foreland Molasse, and Jura Mountains. We added an “e.g.” to the list of references in order to show that our selection is incomplete. We cite the study by Cardello et al. (2019) later in the manuscript.

C: Line 15. You may cite who was directly the first stating the link between ECM exhumation and Jura thrusting.

R: We added Laubscher (1961) and Boyer and Elliot (1982) to the list of references, as these publications are to our knowledge among the first which made the link between ECM exhumation and Jura thrusting.

C: Line 25. You can cite a few works here who have so far the attempted to fulfil this aim? and why they did not succeed completely.

R: We added Burkhard (1990)

C: Page 3 – Line 6. which at a larger scale is also due to the curvature of the Alpine arc.

R: Between Lake Geneva and Salzburg, where the Subalpine Molasse is outcropping most prominently, the Alpine arc is not curving that much. Furthermore, we talk here specifically about local-scale variations in deformation styles, which occur over just a few kilometers.

C: Page 4 – Line 8. more recent studies to mention would be appreciated. You can find a summary of previous works in Cardello et al. 2019 (journal of structural Geology)

R: We added some text and the reference in the revised manuscript.

C: Line 16. You can possibly mention the role of the Pennine nappes. You can find references in the Matzenauer’s thesis http://doc.rero.ch/record/32247/files/MatzenauerE.pdf and in the work of Jon Mosar.

R: We added information and references about the emplacement of the Penninic nappes in the preceding paragraph.

C: Line 18. see also Glotzbach et al. 2008..., Mancktelow and Seeward, Campani (Simplon), Cardello and Mancktelow 2014, Egli et al. 2016, 2017.

R: Thank you for hinting us to these interesting publications. We added here Egli et al. (2017) and Glotzbach et al. (2011). Cardelloand Mancktelow (2014) is a very interesting paper about syn-sedimentary normal faulting during the Cretacous in the Wildhorn nappe. However, we don't think that it is here a suitable reference with respect to the Miocene exhumation history of the ECMs

C: Line 25. you mean prism growth? orogen-parallel to perpendicular stretching: have a look at Mancktelow's work on the Simplon Fault in the Central Alps.

R: We simply mean that in the late stages of the Alpine orogeny, deformation propagated into the Alpine forelands (comprising also the Subalpine Molasse and the Jura FTB). This goes together with a general widening of the orogen perpendicular to its strike, as the deformation front steps outward.

C: Line 28. isn't this a repetition from above?

R: We deleted this sentence in the revised version of the manuscript.

C: Page 5 – line 2. they are deposits derived from the progressive erosion of the Alps since...

R: Thank you for clarification. This has been changed accordingly.

C: Line 5. is this a distinction from Sinclair et al. 1991?

R: We define here the nomenclature for the Molasse Basin which we use throughout the manuscript. This is not a distinction from Sinclair et al. (1991). The term Foreland Molasse is generally used in German and Austrian literature and describes the portion of the Molasse Basin which is not detached from its substratum. Contrary to that, the Plateau Molasse describes the detached part of the Molasse basin and is mainly used in Swiss literature. Throughout the manuscript, we use the term "Subalpine Molasse" instead of "imbricated Molasse". The former term is mainly used in the Swiss literature, while the latter is used predominantly in German and Austrian literature.

C: Line 12. you may find interesting reading this thesis of Tobias Ibele, where you can find useful references and some fine detailed work on the high angle faults and structures of the Swiss Molasse. https://doc.rero.ch/record/28382

R: We are aware of the thesis of Ibele (2011). However, he mainly focuses on the gently deformed Plateau Molasse, whereas this study has its focus on the imbricated and folded Subalpine Molasse. We correctly cited here the relevant work describing the geometry and architecture of the Subalpine Molasse.

C: Line 21. due to tear faulting or?

R: This is rather due to the existence or non-existence of an evaporite-cored décollement level within the Triassic units. With the development of the Jura FTB, a fundamental change in the tectonic setting of the Molasse Basin occurs. While the western Molasse Basin became detached above an intra-Triassic décollement zone, the eastern Molasse Basin remained in a non-detached configuration.

C: Line 26. Have a look at Fox's works http://www.ajsonline.org/content/316/6/505.short https://pubs.geoscienceworld.org/gsa/geology/article/43/5/379/131816/Rapid- exhumation-in-the-Western-Alps-driven-by

R: We added Fox et al. (2016) as they also describe fast exhumation for the same time window.

C: Line 28. paleomagnetic indications from Cardello et al. 2016 have shown similar indications in that sense, being the most recent ones associated with the Rhone-Simplon faulting in the ECM rear.

R: We thank the reviewer for hinting us to this publication. However, we think that this topic dealing with inneralpine deformation structures is not so evident with this respect to the Alpine front in the Molasse.

C: Page 6 – line 16. As so far you were mentioning time in Ma, you can help the reader by providing the age constraints in Ma to the two corresponding megasequences.

R: We adjusted the text accordingly.

C: Page 7 – Line 3. Why there are only 12 samples on the map of Fig. 3 and on Fig. 4 and here 13 samples?

R: Thank you for spotting this error. We adjusted the text accordingly.

C: Line 4. some are strangely positioned within the crystalline basement with no displacement associated to them. You may also consider about drawing the basal thrust trajectory as it is widely accepted that the basal thrust of the Jura is branching off the Alps thus at the base of the Molasse mesozoic cover. Further please have a look at the cross-sections B-B' and C-C' for the upper thrust and explain why, in your interpretation, is not propagating in this sections as in the A-A' cross-sections.

R: We don't quite understand. No samples are positioned in the crystalline basement. All the samples are were collected at the surface and are from the Molasse deposits. In the revised manuscript, we added the intra-Triassic décollement zone as a stippled line. Regarding the differences in the tectonic style and thrust geometries from west to east please see the discussion part in section 5.1 of the manuscript.

C: Line 28. Very minor question: can the Saxon genitive be used in Solid Earth?

R: Yes, we think so. As far as we know, there are no guidelines regarding this issue.

C: Page 9 – line 25. notice of little importance, would you choose Aar or Aare? Please consider if it should be called Aar valley and Aar Massif consistently.

R: Both “Aare Valley” as a geographical term as well as “Aar Massif” as a geological term are well established, so we remain with them. The reasons for this difference are unknown to us.

C: Secondly, there are strike slip fault traces which could help partitioning the deformation at the edge of the Pennine Salient. You may consider mentioning them as one of the causes of different styles of deformation at the thrust front. By the way, in the block diagram they are not dashed but they are a continuous line crossing different structural units also in the more external part of the basin in the map. Possibly you have them in an en-echelon disposition and they have recorded right-lateral kinematics. If you have some measurements to add on that it would be great although not extremely necessary for the purpose of this work.

R: As we mention in the manuscript, strike-slip faults have been proposed by some authors (Mock and Herwegh, 2017; Pfiffner, 2011; Vollmayr, 1992) to run along the Aare valley and the Lake Thun axis. This is mainly based on the interpretation of seismic lines and the observation of distinctive differences in the tectonic architecture west and east of the Aare valley. However, the quality of the corresponding seismic lines is very limited due to (i) the thick Quaternary cover resulting in a very poor signal to noise ratio and (ii) the poorly resolved Molasse strata as a result of the frequency, which was chosen in order to optimize for the targeted Mesozoic horizons below. We added some more information in the revised version of the manuscript.

For a quality assessment of the 2D reflection seismic data please refer to Mock and Herwegh (2017; *Tectonics*). By using the mechanical stratigraphies, i.e. the stark contrast in the well mapped lithologies east and west of the Aare valley to explain the E-W differences in the tectonic architecture, it is not necessary to invoke a strike slip fault. Instead, we can present a better constrained solution to explain the E-W differences in the Lake Thun area, one of the key areas of the Subalpine Molasse.

C: Page 10 – line 1 and 9. Aare valley

R: see reply to comment above

C: Line 8. would that fit with a lateral ramp similar to what experienced at the sw edges of the Molasse basin on the NNE-striking Vuache Mountains (see Charollais works), where you find a transpressive ramp overthrusting the carbonates on top of the Aquitanian sandstones of the Rumilly Basin?

R: The Falkenfluh-anticline is a thrust fault which dies out towards the east where mechanically stronger conglomerates are present. Strain is probably accommodated along thrusts further south. Hence, we probably have an en-échelon pattern here which resulted due to the lateral change in the mechanical stratigraphy. There is no need for a lateral ramp. However, since the lateral distribution of mechanically weak lithologies is rather heterogeneous, we can expect that intra-Molasse décollement levels change laterally. Hence, in general, the occurrence of lateral ramps is very well possible.

C: Line 12. This is more of a result and would be nice to show if there is any space and if it is useful to support discussion.

R: We appreciate the reviewer's comment and are fully aware that it is not always so simple to decide whether something belongs into the results or the discussion part of a manuscript. We shortly describe the distribution of the lithotypes already on the description of the sampling area. Here, it is important to take this information up again in order to bring clarity to the discussion.

C: Line 16. constant through part of the dataset (specify please the samples you want to point at).

R: We added the corresponding sample numbers.

C: Line 17. can you please explain a little more on the relationship between deformation style and exhumation pattern, why should, in your case, one influence the other? Considering this is a crucial point of the paper you could show them as they are in the field and make a schema that shows this relationship (optional) and decide to put it here or in the introduction, depending if you want to make it a starting hypothesis or a proven outcome of your work.

R: This is a very important point, and we thank the reviewer for raising it, as we really want to convey the right message. It is not so much the exhumation which is controlled by the mechanical stratigraphy but rather the thrusting pattern and hence the geometry of the thrust belt itself (which arguably of course then influences exhumation). We can expect that we have a clearer picture of exhumation ages where we have large tectonic slices which were thrusted en-bloc, since we can clearly attribute multiple ages to one tectonic slice. In a sand- and mudstone dominated scenario, we observe more narrowly spaced thrusts and the identification of tectonic slices is much more difficult. Hence, in this case it is not so straightforward to attribute exhumation ages to tectonic slices. The important point here is that although we can observe at least two exhumation events at ca. 10 and 6 Ma along the Subalpine Molasse, the location and geometry of the thrusts along which the rocks were exhumed are changing along-strike due to lateral changes in the mechanical stratigraphy. Please see our changes to the text in section 5.1 in the revised version of the manuscript.

C: Line 29. 's genitive Saxon, as above a very minor comments: can that be used in Solid Earth?

R: Yes, see also reply to comment above

C: PAGE 11 – line 14. what type of association?

R: We changed the sentence to make it clearer.

C: Line 15-16. is that a repetition?

R: Not as such. While we briefly mention break-back thrusting already in section 2.2, we pick it up here again in order to further elaborate the related mechanisms in this discussion part of the manuscript.

C: Line 19. is that implying that the backthrust was longer active and that was occurring over 16 Ma?

R: We see break-back thrusting starting at ca. 12 Ma, hence postdating the activity of the frontal triangle zone, which includes the frontal backthrust.

C: Line 25. In the next section, you dig some more into this concept but maybe this statement occurs too early here

R: We think since section 5.2.1 discusses the link to the exhumation of the ECMs, this statement is important here as it acts as a concluding remark of this section.

C: Line 30. please add some more references from Pfiffner et al. 2011, Egli et al. 2016, 2017 and the model of Cardello et al. 2016 and 2019. And more references more to the east?

R: We thank the reviewer for pointing out these papers and we have updated our work with articles, which we did not consider in the previous version. We specifically mentioned the Cardello et al. work where we discussed the Alpine processes in a broader context.

C: Page 12 line 14. you may find interesting having a look also at more recent findings ot out-of-sequence thrusting of the Pennine Nappes over the European foreland and the flip back to in-sequence thrust propagation in this time frame.

R: We thank the reviewer for his input. This is an interesting mechanism. However, we lack the required information from the Molasse basin to link these processes with the constraints we have from the basin.

C: Line 21. you may have a look also at recent papers on the Helvetic alps (2016 geological society of london)

R: We thank the reviewer for his input. However, we do not see here the immediate link of this publication with our work. The aforementioned article concerns the formation of the Rawil Depression based on findings from paleomagnetism and structural data, and we lack the required information to draw a straightforward link to our work.

C: Line 24 genitive Saxon

R: see reply to comment above

C: Line 26. indeed, Megathrust reactivation (Cardello et al., 2019) corresponds with the convergence rate deceleration from about 1.6 cm/a to âLij0.9 cm/a at âLij28 Ma reported by Stampfli et al. (2002) and recently discussed in the Journal of Structural Geology.

R: We discuss here the reported decrease in convergence rates at ca. 20 Ma.

C: Line 30. specify here please if related to strike-slip and/or reverse kinematics

R: Thank you for raising this point. The rise of the ECMs occurred along steeply dipping reverse faults. This occurred however in conjunction with strike-slip faulting as a consequence of strain partitioning in a transpressive framework. We added this information in the text of the revised manuscript.

C: Page 13 – line 6. How is that fitting with AlpArray tomographic results?

R: Thank you for this important remark. New tomographic results from the Eastern Alps (Hetényi et al., 2018) image the deep lithospheric structure at 13.3°E longitude and the author propose the presence of a steeply north-dipping slab being attached to the Adriatic plate. However, such an interpretation is highly debated (see section 5.2.3). We added the reference of these new findings here.

C: Line 12. Is that your observation or needs a citation?

R: We added the missing references here.

C: Line 22. You may wish here to specify what you mean as individual tectonic pulses? Why should have a broader implication related to plate tectonics or slab dynamics?

R: By tectonic pulses we refer to distinct thrusting events which can be traced by means of AHe dating at least from Lake Thun to Lake Constance. In order to clarify this, we added "i.e. distinct thrusting events" in the revised manuscript. However, the main point is that the large spatial wavelength (i.e. continuous over large distances) of these thrusting events needs also a major contribution of a large-scale driving force, such as plate tectonics or slab dynamics. We have clarified this in the revised manuscript.

C: Line 25. wouldn't be the other way around: the segmentation in the thrust front being the result of a change in the slab retreat dynamics.

R: We do not quite understand. Which other way around? This is how we write it. The deep structure along the Alps seems to be segmented as observed by many studies (Handy et al., 2015; Kästle et al., 2019; Kissling et al., 2006; Lippitsch et al., 2003; Mitterbauer et al., 2011; Schmid et al., 2004). This in turn leads to different slab dynamics and hence to different upper crustal tectonic responses and an along-strike tectonic reorganization. We think, therefore, that our wording complies with the comment by the reviewer.

C: Page 14 – line 20. well you have structures accommodating doming and stretching paralellel to the orogen and with similar role also in the Simplon area and to some extent as well in the Engadine and Rawil depression, but if and how that is affecting the foreland evolution during collision, is to argue a little deeper.

R: Slip along the Simplon fault is indeed an important process, which yields in the rapid exhumation of the Lepontine dome at c. 20 Ma. However, we lack the required information to properly link this mechanism in the rear of the Alps to the tectonic processes in the Molasse basin. We made a related statement in the revised manuscript.

C: Line 23. tectonic processes such as.. try to link better this discussion with your data that may work as an example for...

R: We adjusted the text in the revised version of the manuscript in order to clarify that we talk about the processes discussed in section 5.2.2.

C: Line 25. you mean mantle-related slab dynamics vs. lateral extrusion of the eastern alps in the upper crust?

R: Yes, this is exactly what we mean. The Bavarian portion of the Subalpine Molasse is situated in a transitional domain, where the effects of processes exerted by the Central Alpine slab are supposedly masked by upper crustal processes of the Eastern Alps, i.e. lateral extrusion. The latter have been considered as a result of the indentation of the Dolomite indenter as well as slab retreat processes beneath the Carpathians. We adjusted the text slightly in order to make our statement clearer.

C: Page 15 – line 7-9. you can stress on how it is influenced, saying where salient and recesses occur with respect to the dominant lithology occurrence in the Molasse litho- types.

R: We gladly follow your suggestion here and adjusted the text accordingly.

C: Line 13-14. Isn't that a repetition from second bullet point here above (line 7-9)?

R: It is indeed a short repetition of the second bullet point. However, we think is necessary here in order to contextualize the findings and put them in relationship to one another.

C: Line 16. sentence to rearrange

R: done.

C: Line 17. upper crustal signal - You may wish to say to what you refer to (i.e., the decollement at the base of the mesozoic cover deposits? or rather deeper into the crystalline and carbonate deposits? Maybe already in the block-sheme of Fig. 5 you can highlight what is the most relevant structure allowing the large-wavelength deformation

R: We refer here to the discussed late Miocene thrusting in the Subalpine Molasse (from where we presented AHe data) and the Jura FTB. We think it is not necessary to go more into detail in the conclusion part of the manuscript. We did, however, mention these points in the results and discussion part of the manuscript.

C: Line 18. As it is put here, it seems more a point of discussion rather than a concluding remark. In case you wish to leave it here, as it is relevant to the title, you may wish to explain the reason of this interpretation.

R: We discuss this more extensively in sections 5.2.1 and 5.2.2 of the revised version of the manuscript.

C: Line 21. I would suggest you here to simplify and reinforce what you mean as tectonic pulses in the first bullet point of the concluding remarks.

R: We adjusted the first bullet point in order to clarify.

C: Line 24. this is a major outcome of your work that should be more reinforced in the discussion (maybe reducing somewhat the geodynamic relevance and increasing the documentation on the lithotypes involved and their geometry and associated tectonics).

R: Based on the different reviews which we were given to and which were highlighting different parts of the manuscript, we had to find a balance to meet the requests and suggestions of the reviewers. We think that with the current revisions, we can present a well-balanced version.

C: Page 30 Fig. 1 Periadriatic is not correct being the name Periadriatic firstly used in literature as referred to main thrust in Friuli. Best would be to say Insubric (as you do for the Insubric Fault) or simply Tertiary Intrusions.

R: We use the term “Cenozoic intrusions” in the revised version of the manuscript.

C: Fig. 3 see comments in the text referred to the basal decollement and the role of tear faults

R: We added the intra-Triassic décollement level as a stippled line.

Large-wavelength late Miocene thrusting in the North Alpine foreland: Implications for late orogenic processes

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Abstract. ~~Additional to classical nappe tectonics, the Oligocene to mid-Miocene post-collisional evolution of the Central European Alps was characterized by vertically directed tectonics, with backthrusting along the Insubric Line and the subsequent uplift of the External Crystalline Massifs (ECMs). Thereafter, the orogen experienced axis-perpendicular growth when deformation propagated into its external parts. For the North Alpine foreland between Lake Geneva and Lake Constance, in the past, this has been kinematically and spatially linked to the uplift and exhumation of the ECMs. Based on apatite (U-Th-Sm)/He thermochronometry, we constrain thrusting in the Subalpine Molasse between 12-4 Ma, thus occurring coeval to main deformation in the Jura fold-and-thrust belt (FTB) and late stage exhumation of the ECMs. However, this pattern of tectonic activity is not restricted to areas which are bordered by ECMs, but is consistent along the northern front of the Alps between Geneva and Salzburg. Therefore, late Miocene foreland deformation is not necessarily a consequence of uplift and exhumation of the ECMs. While the local geometry of the Subalpine Molasse results from lateral variations of the mechanical stratigraphy of the foreland basin sediments, we suggest that the large-wavelength tectonic signal is the response to a shift in tectonic forces possibly caused by deep-seated geodynamic processes. This resulted in a change from dominantly vertical to horizontal tectonics and orogen-perpendicular growth of crustal thickening. We constrain the onset of this major tectonic change to ca. 12 Ma in the North Alpine foreland, resulting in thrusting and folding in the Subalpine Molasse west of Salzburg and in the Jura FTB until at least 4 Ma.~~

In this paper, we present new exhumation ages for the imbricated proximal Molasse, i.e. Subalpine Molasse, of the northern Central Alps. Based on apatite (U-Th-Sm)/He thermochronometry, we constrain thrust-driven exhumation in the Subalpine Molasse between 12-4 Ma. This occurs synchronously to main deformation in the adjacent Jura fold-and-thrust belt farther north and to late stage thrust-related exhumation of the basement massifs (i.e. External Crystalline Massifs) in the hinterland. Our results agree with other findings along the North Alpine foreland. While site-specific variations in the mechanical stratigraphy of the Molasse deposits influence the pattern of thrusting at the local scale, we observe that late Miocene thrusting is a large-wavelength feature occurring along the North Alpine foreland between Lake Geneva and Salzburg. The extent of this thrusting signal as well as the timing suggests that late Miocene thrusting in the North Alpine foreland coincides with the geometries and dynamics of the attached Central Alpine slab at depth. Interestingly, this implies that the slab geometry at depth

does not coincide with the boundary between Eastern and Central Alps as observed in the surface geology. Using this observation, we propose that thrusting in the Subalpine Molasse and consequently also late-stage thrust-related exhumation of the External Crystalline Massifs, as well as main deformation in the Jura fold-and-thrust belt are linked to changes of slab dynamics.

1 Introduction

Deep crustal processes and slab dynamics have been considered to~~ strongly~~ influence the evolution of mountain belts (e.g., Davies and von Blanckenburg, 1995; Molnar et al., 1993; Oncken et al., 2006). However, these deep-seated signals may be masked by tectonic forcing at upper crustal levels and by enhanced surface erosion related to climate change (e.g. Champagnac et al., 2007; Chemenda et al., 2000; Ganti et al., 2016; Whipple, 2009; Willett et al., 2006). In near surface crustal domains, it is thus challenging to isolate the exhumation signal related to slab dynamics. In this context, foreland basins offer suitable archives as they potentially bear information that allows to resolve the influence of deep-seated processes on mountain building. This is the case because these basins not only record signals that are related to surface dynamics such as changes of sediment fluxes and eustacy (e.g. Pippèrr and Reichenbacher, 2017; Sinclair and Allen, 1992~~). They~~), but they also preserve information on tectonic processes at the crustal and possibly mantle scales that operate at long timescales and large spatial wavelengths (e.g. DeCelles and Giles, 1996; Garefalakis and Schlunegger, 2018; Leary et al., 2016). The North Alpine foreland basin, or Molasse Basin, is particularly suited to constrain the geodynamic evolution of the collisional Alpine orogen because the history of this sedimentary trough has been well established through numerous magneto- and tectonostratigraphic (e.g. Burkhard and Sommaruga, 1998; Ganss and Schmidt-Thomé, 1953; Homewood et al., 1986; Kempf et al., 1999; Pfiffner, 1986; Schlunegger et al., 1996; Sinclair et al., 1991), seismic (Hinsch, 2013; Mock and Herwegh, 2017; Ortner et al., 2015; Sommaruga et al., 2012), and low-temperature thermochronological analyses (Cederbom et al., 2004, 2011; Gusterhuber et al., 2012; von Hagke et al., 2012, 2014b; Mazurek et al., 2006).

Studies from the forelands of the European Alps have shown that the most external parts of the orogen were incorporated into the orogenic wedge in Miocene times (e.g. Becker, 2000; Burkhard, 1990; von Hagke et al., 2012, 2014b; Hinsch, 2013; Ortner et al., 2015; Pfiffner, 1986; Schmid et al., 1996; Schönborn, 1992). In the case of the Swiss Molasse Basin, late Miocene deformation has been kinematically and spatially linked to the uplift and exhumation of the External Crystalline Massifs (ECMs~~)~~), which represent basement units derived from the subducting European plate~~, and~~. This late Miocene deformation phase was also linked to the main deformation in the Jura fold-and-thrust belt (FTB) situated at the northern margin of the Molasse Basin (Figs. 1 and 2; e.g. Boyer and Elliot, 1982; Burkhard, 1990; Burkhard and Sommaruga, 1998; von Hagke et al., 2014b; Laubscher, 1961, 1992; Mosar, 1999; Pfiffner, 1986; Sommaruga, 1999). The inferred linkages between the uplift of the ECMs, the imbrication of the proximal Molasse deposits, and the main deformation in the Jura FTB are mainly based on a classical scenario of ~~late-stage~~ongoing continent-continent collision, where compressional wedge tectonics and shortening result in crustal thickening of basement units in the hinterland and a propagation of the orogenic wedge towards the foreland, including imbricate thrusting (Pfiffner, 1986; Rosenberg and Berger, 2009; Schmid et al., 1996). ~~However, foreland propagation of deformation was not continuous as shown by structural, chronostratigraphic, and low-temperature thermochronological data, indicating that the Alpine thrust front advanced rather discontinuously during Miocene times (Beidinger and Decker, 2014; Burkhard and Sommaruga, 1998; von Hagke et al., 2014b; Ortner et al., 2015). In addition, the along strike partitioning of strain between the Jura FTB and the Subalpine Molasse has only incompletely been resolved so far. In the same sense~~

However, new studies from the Aar Massif of the Central Alps challenge this view. Based on geometric, kinematic, metamorphic, and geodynamic arguments, Herwegh et al. (2017, 2020) suggest for the exhumation of the eastern ECMs (Aar, Mont Blanc, and Aiguilles Rouges Massifs) switches between ’horizontal’ and ‘vertical tectonics’. Note that the terms ‘vertical’ and ’horizontal tectonics’ as used by Herwegh et al. (2017, 2020) are based on geometric and kinematic considerations, i.e. they imply a steeper or less steep orientation of the main faults along which strain is accommodated. Thus, in a compressional framework, these terms describe whether the vertical or the horizontal displacement components play the dominant role at a given point in time. Hence, the evolution of the Helvetic fold-and-thrust belt with the associated nappe stacking represents an Oligocene stage of ‘horizontal tectonics’. A major switch to ‘vertical’ tectonics occurred in early Miocene times when major parts of the Aar and Mont Blanc/Aiguilles Rouges Massifs experienced a strong vertical uplift component mainly along steep to sub-vertical reverse faults (Herwegh et al., 2017, 2020). This resulted in the differential uplift and doming of these eastern ECMs as well as a passive upward bulging of the entire nappe stack above. From a geodynamic point of view, (i) a retreating European slab, (ii) delamination of lower crust from the mantle, and (iii) a buoyancy-driven uplift component within a compressional regime were suggested by aforementioned authors to be the driver for this ‘vertical tectonic’ forcing. It is important to stress that this ‘vertical’ exhumation component became dominant at a time when the not to only weakly thinned part of the buoyant former European passive continental margin entered the subduction channel. This stage of ‘vertical tectonics’ was followed by late Miocene ‘horizontal tectonics’, where en-bloc exhumation of the Aar Massif was accomplished through slip along shallow south-dipping basal thrust systems (Berger et al., 2017; Herwegh et al., 2017, 2020; Mair et al., 2018). This scenario is described in a similar way for the Mont Blanc and Aiguilles Rouges Massifs for the same time interval (Burkhard and Sommaruga, 1998; Lacombe and Mouthereau, 2002; Bellahsen et al., 2014; Boutoux et al., 2016; Egli et al., 2017).

In addition to this ECM-related information, structural, chronostratigraphic, and low-temperature thermochronological data (Burkhard and Sommaruga, 1998; von Hagke et al., 2014b; Ortner et al., 2015) suggest that the Alpine deformation front remained stationary within the Subalpine Molasse during the time of the inferred buoyancy-driven ‘vertical tectonics’. The deformation then propagated to the Jura FTB during the late Miocene when the ‘vertical tectonics’ was superseded by the thrust-related exhumation in the Aar Massif (e.g. Burkhard and Sommaruga, 1998; von Hagke et al., 2012; Herwegh et al., 2020). The corresponding along-strike partitioning of strain between the Jura FTB and the Subalpine Molasse has, however, only incompletely been resolved so far. Likewise, it has been unclear whether the amount of shortening within the Subalpine Molasse is consistent along strike, particularly with respect to the highly non-cylindrical architecture of the Alpine hinterland ~~(Fig. 2).~~as well as the lentoid-shaped map appearance of the eastern ECMs (Fig. 2; Burkhard, 1990). However, this information is vital for understanding how deformation in the ECMs is potentially linked to foreland FTB tectonics. Accordingly, as a first and major contribution of our paper, we aim at reconstructing the chronology and amount of shortening of the Molasse sequences during the late stage of Alpine orogeny since the mid-Miocene. ~~Hereto, we build upon detailed and~~We present new low-temperature thermochronological data from a key region in the western Subalpine Molasse and compare them with previously published data from farther east (von Hagke et al., 2012, 2014b). We combine this information with data from well-established work on the chronology, tectonics, and stratigraphy of the ~~proximal foreland (~~thrusted Subalpine Molasse between 6.8° E (Lake Geneva) and 12.8° E (near Salzburg; e.g. Burkhard and Sommaruga, 1998; von Hagke et al., 2012, 2014b; Hinsch, 2013; Kempf et al., 1999; Ortner et al., 2015; Pfiffner, 1986; Schlunegger et al., 1997; and many others~~). We will relate these mechanisms~~) in order to better constrain the timing and spatial pattern of thrusting in the Subalpine Molasse. We will relate this to the history of shortening of the Jura FTB, and to Alpine tectonic events in an effort to identify possible relationships to ~~possible~~the geodynamic forcing at ~~the~~a larger scale.

Geological mapping of the Subalpine Molasse (e.g. Ganss and Schmidt-Thomé, 1953; Haldemann et al., 1980; Schlunegger et al., 2016; Weidmann et al., 1993; Zaugg et al., 2011) as well as stratigraphic work (e.g. Bachmann and Müller, 1992; Kempf et al., 1999; Lemcke, 1988; Schlunegger et al., 1993, 1997; Schlunegger and Kissling, 2015) has shown that the proximal basin border is characterized by large orogen-parallel lithologic variations where km-thick conglomerate suites with high mechanical strengths alternate with mudstones and sandstones with low at-yield conditions over lateral distances of a few kilometers. As a consequence, the patterns of thrust faults and folds within the Subalpine Molasse change along-strike. In regions where~~ the~~ km-thick conglomerate packages are present, the geometry of the Subalpine Molasse is characterized by km-spaced thrust faults with ~~a~~ relatively large ~~displacement.~~displacements on them. In areas however, where the foreland mechanical stratigraphy mainly consists~~ mostly~~ of sandstone-mudstone alternations, the structural style is characterized by closely-spaced folds and thrust faults with possibly smaller displacements~~.~~ (e.g. Kempf et al., 1999; Ortner et al., 2015; Schlunegger et al., 1993, 1997). We expect that these differences in mechanical stratigraphy leave ~~a distinct~~an imprint on where strain ~~is~~was accommodated during late orogenic shortening. Therefore, as a related second contribution, we aim at exploring how lithological variations within the foreland basin, which were controlled by the paleogeographic conditions, contributed to the spatial distribution of late orogenic strain.

~~In summary, we present new low-temperature thermochronological data from a key region in the western Subalpine Molasse and compare them with previously published data from farther east (von Hagke et al., 2012, 2014b). We combine this with tectono-sedimentological data along the thrusted Subalpine Molasse between 6.8° E (Lake Geneva) and 12.8° E (near Salzburg) in order to better constrain the timing and spatial pattern of thrusting in the Subalpine Molasse and the associated late-orogenic large-scale change from dominantly vertical to dominantly horizontal tectonics.~~

2 Geological and tectonic setting

2.1 The Central Alps

~~We focus our study on the Central Alps because the inversion of the proximal basin part by imbricate tectonics during late Miocene times terminates near Salzburg (Fig. 1). This is also the region where the configuration of the lithospheric mantle slabs at depth changes along-strike. Seismo~~Classically, the boundary (or transition) between the Central and the Eastern Alps has been located in eastern Switzerland. There, remnants of the Piemont-Ligurian Ocean separate units of European origin (Central and Western Alps) from thrust nappes that are part of the Adriatic continental plate (Figs. 1 and 2; Eastern Alps; Schmid et al., 2004). However, this surface observation is not reflected in the slab geometry at depth. Instead, seismo-tomography studies have disclosed that the subducting European slab beneath the Central Alps extends to the east until ca. 12.5° E, i.e. the area of Salzburg, ~~while~~whereas farther east, a segmentation of the slab structure is observed (Hetényi et al., 2018; Kästle et al., ~~2019~~2020; Lippitsch et al., 2003; Mitterbauer et al., 2011; Zhao et al., 2016; see further details in the discussion section). ~~Classically, the boundary (or transition) between the Central and the Eastern Alps has been located in eastern Switzerland where remnants of the Piemont-Ligurian Ocean separate units deriving from the former European passive margin (Central and Western Alps) from units deriving from the Adriatic Plate north of the Insubric Line (Figs. 1 and 2; Eastern Alps; Schmid et al., 2004). However,~~Similar to Rosenberg et al. (2018), we ~~place~~shift the boundary between the Central and Eastern Alps farther east. But instead of placing it at the Giudicarie-Brenner fault system (Rosenberg et al., 2018), we follow the argumentation given above, which is also advocated by Kissling and Schlunegger (2018), and place the Central-Eastern Alps transition where the current slab configuration changes at depth~~, following hereby a definition recently used by others (Kissling and Schlunegger, 2018; Rosenberg et al., 2018).~~. This is particularly important when the influence of subduction mechanisms on the surface geology during the past few millions of years is ~~addressed~~considered, which is the scope upon discussing the results at the end of this paper. ~~We will~~In this study, we therefore focus ~~in this section~~ on the ~~geological~~Central Alps because late Miocene thrusting in the Subalpine Molasse terminates near Salzburg (Fig. 1; Beidinger and ~~tectonic setting~~Decker, 2014; Hinsch, 2013; Ortner et al., 2015), which spatially coincides with the aforementioned along-strike changes in the configuration of the ~~Central Alps, but~~lithospheric mantle slabs at depth. However, we will elaborate on the influences of Eastern Alpine tectonic processes in the discussion part of this paper.

The Central Alps are situated almost entirely on top of the subducted Central European lithospheric slab (Figs. 2a and 2b; Schmid et al., ~~1996,~~ 2017), which steeply dips into the asthenospheric mantle as imaged by teleseismic tomography (Lippitsch et al., 2003). The ~~bivergent~~ orogen is the result of the Late Cretaceous to Eocene ~~ocean-continent~~ subduction of the oceanic part of the European plate under the Adriatic ~~plate and subsequent post~~continental platepost-35 Ma continent-continent collision (e.g. Schmid et al., 1996). Subduction initially affected the European oceanic lithosphere, which was followed by subduction of the distal spur of the Iberian plate that became the Penninic thrust nappes. During the Eocene, subduction started to involve the distal and stretched European continental margin, (e.g. Cardello et al., 2019; Mosar et al., 1996; Stampfli and

Marchant, 1997). The subduction system then became clogged when the thick and buoyant European crust started to enter the subduction ~~zone, which resulted in~~channel. As a result, the subducted oceanic slab ~~breakoff~~of the European plate supposedly broke off, which has been inferred from widespread plutonism ca. 32 Myr ago (Davies and von Blanckenburg, 1995). Slab unloading and basal accretion of crustal segments to the upper plate resulted in ~~a period of fast~~the rock and surface uplift, ~~which~~giving way to the incipient rise of the Alpine topography. Uplift was mainly ~~accommodated~~accomplished through backthrusting along the Insubric Line (Hurford, 1986; Schmid et al., 1996~~). The signal of slab breakoff is~~), and was also manifested in the ~~rapid build-up of topography and in the subsequent~~ increase of sediment discharge into the Alpine foreland (Schlunegger and Castelltort, 2016; Sinclair, 1997). ~~Recently, the idea of slab breakoff has been challenged and instead the volcanic and tectonic signal has been attributed to slab steepening and consequently enhanced corner flow (Ji et al., 2019).~~ At 20 Ma and therefore synchronous to the ‘vertical’ tectonic stage of the exhumation of the eastern ECMs, slip along the Simplon fault zone resulted in rapid exhumation of the Lepontine dome that is situated between the Aar Massif and the Insubric Line (Berger et al., 2011; Boston et al., 2017; Todd and Engi, 1997). However, we do not consider that tectonic exhumation of the Lepontine had an influence on the history of thrusting in the proximal Molasse basin since there is no mechanical link (Schmid et al., 1996). Therefore, in the following, the deformation along the Simplon fault zone will not be considered.

During the Oligocene, Europe-derived sedimentary units were sheared off from their substratum and emplaced to the north over a distance of several tens of kilometers thereby forming the present-day Helvetic cover nappes (Pfiffner, 2011, and references therein). Ongoing ~~orogeny~~convergence resulted in delamination of lower European crustal segments from the lithospheric mantle (Fry et al., 2010~~),~~). This mechanism eventually ~~inducing~~resulted in buoyancy-driven ~~subvertical uplift (~~sub-vertical ~~tectonics)~~uplift of the thickened crust (Kissling and Schlunegger, 2018) along steeply dipping shear zones and in exhumation of the ECMs ca. 20 Myr ago (Fig. 2a; e.g. Egli et al., 2017; Glotzbach et al., 2011; Herwegh et al., 2017, ~~in press~~2020). Farther east, between the Aar Massif and the Brenner Fault (a segment, which we here consider as the eastern Central Alps), such Europe-derived crustal blocks are not exposed at the surface. East of the Brenner Fault (Fig. 1), northward indentation of the Dolomite indenter resulted in eastward-directed lateral extrusion of crustal blocks, which started in early Miocene times (Frisch et al., 1998; Handy et al., 2015; Ratschbacher et al., 1991). ~~Associated~~This process was associated with ~~this was~~ the exhumation of the Tauern Window, which was accomplished by upward folding and erosion of the nappe pile, and by normal faulting along its bounding low-angle normal faults (see Rosenberg et al., 2018).

~~The late stage~~Late stages in the evolution of the Central Alps ~~is~~are dominated by orogen-perpendicular growth ~~due to~~when the ~~propagation of~~ deformation ~~to its~~ front on either side of the Alps propagated to the external parts, ~~i.e., to~~resulting in the ~~Molasse Basin and~~development of the Jura fold-and-thrust belt (FTB) and the Subalpine Molasse in the north, and ~~to~~ the Southern Alps ~~in~~on the ~~south~~southern side of the Alps (Figs. 1 and 2; Burkhard, 1990; Caputo et al., 2010; Castellarin and Cantelli, 2000; Nussbaum, 2000; Pfiffner, 1986; Schmid et al., 1996; Schönborn, 1992~~), thereby marking a change from dominantly vertical to horizontal tectonics (Schlunegger and Simpson, 2002). In the Southern Alps, fold-and-thrust belts evolved from late~~

~~Oligocene times on onwards, but the largest amounts of shortening occurred after ca. 15 Ma (Caputo et al., 2010; Castellarin and Cantelli, 2000; Schmid et al., 1996; Schönborn, 1992).~~).

2.2 The Molasse Basin

2.2.1 Structures and tectonic evolution

The Molasse Basin of the North Alpine foreland, which contains ~~erosional products~~deposits derived from the progressive erosion of the evolving Alps since 32 Ma (Sinclair et al., 1991), ~~is~~can tectonically be subdivided into three parts: (i) The Plateau Molasse is the gently folded part of the basin, which evolved into a wedge-top basin (e.g. Willett and Schlunegger, 2010) during late Miocene main Jura FTB deformation, when it became detached above a main décollement zone within the Triassic evaporites. (ii) To the east, with the Triassic evaporites diminishing and the Jura FTB tapering off, the basin gradually changes into a non-detached configuration, the Foreland Molasse~~.~~ (e.g. Berge and Veal, 2005; Ortner et al., 2015; Pfiffner, 1986). (iii) At the southern, proximal basin border, the Subalpine Molasse extends continuously as a narrow band of imbricates from south of Geneva to Salzburg, where it disappears ~~below~~beneath Helvetic and Penninic units before it emerges again in upper Austria. In this contribution we mainly focus on the Subalpine Molasse between Lake Geneva and Salzburg, i.e. the part of the fold-thrust belt ~~that can~~where the tectonic processes may be ~~considered being~~ associated with the subduction of the European lithospheric slab of the Central Alps.

The Subalpine Molasse consists of south-dipping imbricated thrust sheets~~ and in~~. In large parts and predominantly northeast of the Lake Thun area, the structures of the Subalpine Molasse also include the north-dipping backthrusts ~~forming~~that form a triangle zone at the transition to the Plateau and Foreland Molasse (Fig. 2; Berge and Veal, 2005; Fuchs, 1976; Müller et al., 1988; Ortner et al., 2015; Schuller et al., 2015; Sommaruga et al., 2012). The Subalpine Molasse started to become incorporated into the orogenic wedge shortly after deposition in Oligocene times (Hinsch, 2013; Kempf et al., 1999; Pfiffner, 1986). After ca. 20 Ma, contemporaneously with the development of the frontal triangle zone, the northern Alpine thrust front remained stationary in the area of the Subalpine Molasse (Burkhard and Sommaruga, 1998; von Hagke et al., 2014b; Ortner et al., 2015). It was not until ca. 12 Ma when parts of the deformation in the western Molasse Basin (i.e. the Molasse west of Lake Constance) propagated along a basal décollement zone within the Triassic evaporites into the thin-skinned Jura FTB (Becker, 2000; Burkhard and Sommaruga, 1998; Laubscher, 1961; Philippe et al., 1996), although already in the late Oligocene some deformation occurred in the area of ~~the~~ today's Jura FTB (Aubert, 1958; Liniger, 1967). Hence, during the late Miocene, the Molasse Basin experienced along-strike changes in tectonic style and locus of deformation. While sediment accumulation in the eastern Molasse Basin (i.e. here the Foreland Molasse between Lake Constance and Salzburg) occurred still in a foredeep setting, the western part evolved at this stage into a wedge-top basin (i.e. Plateau Molasse; Willett and Schlunegger, 2010~~), as it was detached above the basal décollement zone.~~). Both, the evaporite basal décollement and the thrusts of the Subalpine Molasse are considered to root below and in the ECMs. Accordingly, they were kinematically linked to the late Miocene exhumation of the ECMs (Fig. 2a; e.g. Burkhard, 1990), which was driven at that time by north-directed thrusting along shallow dipping faults (Herwegh et al., 2017, ~~in press~~2020), thereby causing a phase of accelerated exhumation at ca. 10 Ma (Fox et al. 2016; Glotzbach et al., 2010; Valla et al., 2012; Vernon et al., 2009; Weisenberger et al., 2012). Based on stratigraphic data, Haus (1935) inferred already in 1935 that the Subalpine Molasse of Central Switzerland was subject to major thrusting in late Miocene times. Recently, studies have revisited this topic and documented that the Subalpine Molasse was subject to break-back thrusting between ca. 13 Ma and 4 Ma (von Hagke et al., 2012, 2014b; Ortner et al., 2015; Schuller et al., 2015), which was thus coeval to folding and thrusting in the Jura FTB. We note that late Miocene thrusting is not recorded ~~for~~in the Subalpine Molasse east of Salzburg (Beidinger and Decker, 2014; Hinsch, 2013; Ortner et al., 2015~~), i.e. where the deep slab configuration of the Eastern Alps is present.~~).

After 10 Ma, but possibly as late as 5 Ma, the entire Molasse Basin was uplifted, resulting in basin-scale erosion (Baran et al., 2014; Cederbom et al., 2004, 2011; Genser et al., 2007; Gusterhuber et al., 2012; von Hagke et al., 2012; Mazurek et al., 2006; Schlunegger and Mosar, 2011; Zweigel et al., 1998). Since 5 Ma, compressional thin-skinned tectonics in the wedge-top part of the basin and the Jura FTB are superseded by thick-skinned tectonics (Giamboni et al., 2004; Guellec et al., 1990; Madritsch et al., 2008; Mock and Herwegh, 2017; Mosar, 1999; Philippe et al., 1996; Ustaszewski and Schmid, 2007).

2.2.2 Stratigraphic development

The clastic infill of the Oligocene to Miocene peripheral Molasse Basin consists of~~ the~~ eroded sediments of the evolving Alps, and in the northern parts partly of material shed from the Black Forest and the Bohemian Massif. Accommodation space was formed through subsidence, classically related to flexural bending of the European plate in response to the combined effect of subsurface slab loading and topographic loading of the advancing Alpine thrust wedge during Paleogene and Neogene times (Allen et al., 1991; Burkhard and Sommaruga, 1998; Karner and Watts, 1983; Pfiffner, 1986; Zweigel et al., 1998). For the Central Alps, this view has recently been challenged by Schlunegger and Kissling (2015), who favor a slab rollback mechanism, to explain foreland plate ~~flexuring~~flexure and accommodation space formation. In this scenario, slab rollback is driven by the interplay between vertically-directed slab loads exerted by the subducted European lithospheric mantle and buoyancy-driven crustal delamination (Kissling and Schlunegger, 2018).

In the Swiss part of the basin, the Molasse sediments form two regressive and coarsening-upward megasequences (Homewood et al., 1986; Kuhlemann and Kempf, 2002; Schlunegger et al., 2007). The first megasequence describes the transition from Rupelian (ca. pre-30 Ma) sedimentation in underfilled conditions to Chattian-Aquitanian (ca. 28-20 Ma) sedimentation when the basin was overfilled. The Burdigalian (ca. 20-17 Ma) and post-Burdigalian (ca. post-17 Ma) stratigraphic records then chronicle the second megasequence during filled to overfilled conditions (Sinclair and Allen, 1992). West of ca. 11° E, large alluvial megafans developed at the mountain front during the overfilled stage of the basin (Frisch et al., 1998; Kuhlemann and Kempf, 2002; Ortner et al., 2015). In their cores, close to the apex, large and km-thick conglomerate ~~bodies~~sequences were deposited, while at the margins, the sedimentation was mainly sand- and mudstone dominated. At the proximal basin border, numerous locally-derived bajada fans discharged sediments into the foreland and thus further contributed to the high along-strike stratigraphic variability at the proximal basin border (Kempf et al., 1999; Schlunegger et al., 1997; Spiegel et al., 2001). Farther east, the Molasse Basin prevailed in an underfilled stage ~~during this time~~until at least 17 Ma, when sedimentation of sandstones and marls occurred under brackish to shallow marine conditions (Hinsch, 2013; Kuhlemann and Kempf, 2002; Lemcke, 1988; Ortner et al., 2015). Large alluvial fans are missing due to the channelizing effect of the paleo-Inn river, which transported the erosional detritus effectively farther to the east (Frisch et al., 1998; Kuhlemann and Kempf, 2002). For more details on the laterally varying stratigraphy, including Wheeler diagrams, the reader is referred to Kempf et al. (1999), Schlunegger et al. (1997), and Schlunegger and Norton (2013) as well as Hinsch (2013), Kuhlemann and Kempf (2002), Lemcke (1988), and Ortner et al. (2015) for the Molasse Basin west and east of Lake Constance, respectively.

3 Methods

3.1 ~~Sample~~Selection of sample sites and litho-tectonic architecture

We consider the Lake Thun region as a key area for the understanding of Subalpine Molasse tectonics for the following reasons:

(i) With the Aar Massif being one of the best studied ECM in the Alps in terms of its Alpine tectonic evolution and geodynamic significance, information on the history of thrusting of the Subalpine Molasse in front of the Aar Massif is of great importance if the scope lies on reconstructing the post-collisional tectonic evolution of the Central Alps.

(ii) The thickness of the basal décollement zone within the Mesozoic cover sediments below the Molasse Basin decreases significantly west of ca. 7° E (Landesgeologie, 2017; Mock and Herwegh, 2017; Sommaruga et al., 2012; Sommaruga et al., 2017). Hence, the Lake Thun area is located in an ideal place where we can expect the eastward transition from the detached Plateau Molasse to the non-detached Foreland Molasse.

(iii) While east of the Lake Thun area, the frontal part of the Subalpine Molasse is often delineated by a backthrust and a triangle zone, this feature is largely missing farther west, where predominantly northwestward imbricate thrusting occurs.

We collected ~~13~~12 samples across the Subalpine Molasse east and west of Lake Thun for apatite (U-Th-Sm)/He (AHe) dating (Fig. 3). The northernmost samples represent coarse-grained Burdigalian sandstones of the Plateau Molasse. Further to the southwest, we sampled Chattian-Aquitanian and Rupelian sandstones within the Subalpine Molasse. Samples have been collected in the hanging- and footwalls of the individual thrusts (Fig. 3). To control the depositional age of the sediments, samples were taken in the vicinity of sites with known mammal ages and magneto-polarity based chronologies (Schlunegger et al., 1996; Strunck and Matter, 2002) wherever possible.

~~In the sampling area, mapping shows that the litho-tectonic architecture of the Subalpine Molasse contrasts between both sides of Lake Thun (Fig. 3). On the eastern side, the basin is made up of amalgamated conglomerates and a relatively large spacing between the major thrust faults, while the tectonic style of the Subalpine Molasse to the west of Lake Thun is characterized by more evenly distributed thrust sheets made up of alternated sandstone and mudstone beds. The same pattern can be found along strike where the distribution pattern of conglomerates, sandstones, and mudstones tends to condition the location and the spacing of thrust faults.~~ In order to test the influence of along-strike changes in the mechanical stratigraphy of the Subalpine Molasse on the thrusting pattern, w~~W~~e ~~thus~~ compiled more details about the geological architecture of the proximal Molasse from published geological maps (Landesgeologie, 2005) and use available tectonic sections (Ortner et al., 2015; Sommaruga et al., 2012) to illustrate the related tectonic style.

3.2 (U-Th-Sm)/He (AHe) thermochronology and thermal modeling

We determined the most recent exhumation history of the Subalpine Molasse of the Lake Thun region through AHe dating. This method is based on the α-decay of ^{238}U, ^{235}U, ^{232}Th and ^{147}Sm isotopes, and the retention of its radiogenic product ^{4}He in the crystal lattice below a certain temperature (e.g., Farley, 2002). Diffusive loss of ^{4}He in the lattice depends on the grain size, shape, chemical composition, distribution of the mother isotopes, radiation damage density, as well as the time-temperature evolution of the crystal (Farley, 2002; Wolf et al., 1996). Consequently, AHe ages can provide estimates about the time when the mineral passed through the diffusion-sensitive temperature interval between ca. 80°C and 40°C (Wolf et al., 1996), which is referred to as the partial retention zone (PRZ). Hence, this ~~technology~~method allows constraining the tectono-thermal history of the studied rocks in the uppermost few kilometers of Earth's crust. Detrital apatite grains deposited in sedimentary basins primarily carry a cooling history of the hinterland at the time of erosion. Subsequent burial due to sedimentation or tectonic loading may reheat the detrital grains to temperatures above the closure temperature, thereby resetting the chronometer. Subsequent exhumation will chronicle the basin's exhumation, whereas grains that have not been reset during the basin's burial history still carry a signal of older cooling events. Consequently, the relation between cooling age and stratigraphic age may provide estimates on the burial as well as the exhumation history (e.g., Reiners and Brandon, 2006).

We used a combination of standard techniques for the separation of apatite minerals, which particularly includes electrodynamic disaggregation, and magnetic and heavy liquid separation. Single crystals were handpicked under a binocular and checked for inclusions and imperfections under an optical microscope with cross-polarized light (more information on the mineral separation techniques and picking criteria are given in Text ~~A1~~S1 in the supplementary material). Helium extraction and measurement of parent isotope contents has been conducted at the GÖochron laboratories of University of Göttingen. Raw ages were corrected for α-ejection (Table 1). We measured four to eight single grain ages per sample and calculated average ages using the unweighted arithmetic mean for completely reset samples. We excluded single grain ages for subsequent geological interpretation based on the following criteria (Table 1): (i) high analytical errors (>10%), (ii) very low U-content (<10 ppm), (iii) a substantial amount of He on the first re-extract (>4%), or erroneous old ages stemming most likely from U-

Th rich mineral inclusions which produce parentless He. For the latter case, we plotted the He content versus the present-day He production rate in order to detect these ages (for details see Vermeesch, 2008).

We constrained the thermal histories of the sampled sediments (Fig. 4) by modeling of the AHe age data with the HeFTy software (Ketcham, 2005). We gave the algorithm a ~~maximum~~high degree of freedom~~. Model~~ by using only a few modeling constraints~~ included~~: the age of sedimentation, the paleo-temperature (Mosbrugger et al., 2005), the present-day annual average temperature, and maximum post-depositional heating rates inferred from maximum sedimentation rates (Schlunegger and Norton, 2015) and a paleo-geothermal gradient of 28°C/km (Schegg and Leu, 1998).

4 Results

4.1 AHe age data

Samples SM-7 and SM-16 from the Plateau Molasse show a wide spread in AHe ages, indicating a partially exhumed fossil PRZ. Hence, they did not experience enough post-depositional heating for a full reset of the thermochronometer (Fig. 3b and Table 1). All other samples show single grain ages ~~reproducing~~which plot within error for each sample. Ages are significantly younger than the corresponding depositional ages and are thus considered to represent completely reset ages (fully exhumed fossil PRZ), hence inferring substantial post-depositional burial and heating.

Average ages for completely reset samples range from 6.0 ± 0.4 Ma to 10.8 ± 0.6 Ma (Fig. 3b and Table 1). All samples from the Subalpine Molasse show post-depositional burial and heating to >60°C (Fig. 4). Sample SM-7 from the Plateau Molasse did not experience enough post-depositional heating to fully reset the thermochronometer (Fig. 4). Thermal modeling supports the young exhumation of the Subalpine Molasse between 12 Ma and 5 Ma (Fig. 4). The thermal histories of SM-7 and SM-13 indicate an exhumation signal of the Plateau Molasse at ca. 10 Ma.

Samples SM-8, SM-11 and SM-15 were collected from the same tectonic sliver (Figs. 3a and 5), and corresponding average ages of 6.0 ± 0.4 Ma, 6.6 ± 0.4 Ma and 6.1 ± 0.4 Ma ~~reproduce~~group well within their margins of error. A jump ~~of~~in average ages occurs across the thrust to the adjacent tectonic slivers and the Plateau Molasse in the north, where samples SM-12, SM-13, and SM-14 yield average ages of 9.2 ± 1 Ma, 8.9 ± 0.7 Ma, and 10.8 ± 0.6 Ma, respectively, thus also ~~reproducing~~grouping within their margins of error. This pattern is also reproduced by the modeled thermal histories, where a jump in exhumation ages across tectonic boundaries is recognized (Fig. 4). In the western area, the average ages do not show such a close correlation with the tectonic position (Figs. 3a and 5). However, the thermal models for samples SM-5 and SM-6 indicate younger cooling than for samples SM-4 and SM-7 (Fig. 4), thus suggesting a tectonic control on exhumation.

4.2 Litho-tectonic architecture of the Lake Thun area

In the sampling area, mapping shows that the litho-tectonic architecture of the Subalpine Molasse contrasts between both sides of Lake Thun (Fig. 3). On the eastern side, the basin is generally made up of amalgamated conglomerates which are cut from west to east by two narrow sand- and mudstone dominated bands. The south-dipping thrust north of the Falkenfluh anticline as well as the three tightly spaced thrusts further south all emerge along these mechanically weaker bands (Fig. 3a). In between these thrust domains, we observe large tectonic slices made up of mechanically strong conglomerates of Burdigalian (north) and Chattian-Aquitanian age (south). The latter is bordered to the north by three thrusts for which we can infer from cross-cutting relationships in map view a break-back sequence of thrusting (i.e. out-of-sequence; Fig. 3a). To the south, across a south-dipping thrust, Rupelian sand- and mudstones crop out. West of the Aare valley, conglomerates are largely absent and the stratigraphy is sand- and mudstone dominated. Compared to the Subalpine Molasse east of the Aare valley, the FTB is much narrower, thrusts are more evenly distributed, and the tectonic slices are less wide (Fig. 3). Across the whole area we can see a clear correlation between the distribution of mechanically weak sand- and mudstones and the location and alignment of thrust faults. The subsurface continuation of the thrusts has been inferred from seismic interpretation (for more details see Mock and Herwegh, 2017). It suggests that the thrusts merge in a detachment level at a depth of ca. 2km (Fig. 3b). The type of lithology of the detachment remains however unknown, since the poor signal-to-noise ratio of the seismic images does not allow a clear distinction with this respect. Due to the lack of subsurface data further south it also remains speculative on how the structures extend southward. As indicated in the sections (Fig. 3b), it is though likely that the thrusts root within the Rupelian sand- and mudstones at the base of the Molasse sequence on top of the Mesozoic cover sediments. In summary, we observe pronounced differences both in the mechanical stratigraphy as well as in the structural configuration of the Subalpine Molasse west and east of the Aare valley. We discuss this in detail in section 5.1 below.

4.3~~2~~ Late Miocene shortening estimates

Based on published restored cross-sections (Burkhard and Sommaruga, 1998; von Hagke et al., 2014b; Ortner et al., 2015), retro-deformed and balanced palinspastic maps (Philippe et al., 1996), thermochronological age data (von Hagke et al., 2012, 2014b), and own cross-section restorations~~,~~ (see Text S2 and Figure S1 in the supplementary material), we estimated the amount of late Miocene horizontal shortening of the Subalpine Molasse and the Jura FTB from Lake Geneva to Salzburg (Fig. 6b). Post-12 Ma horizontal shortening in the Jura FTB decreases from a maximum of ca. 32 km in the west to 0 km at the eastern tip (Philippe et al., 1996). Contrariwise, minimum horizontal shortening in the Subalpine Molasse increases from ca. 10 km in the west (Lake Geneva) to ca. 20 km farther east (Lake Constance), before decreasing again to below 1 km in the area near Salzburg (Beidinger and Decker, 2014; Burkhard and Sommaruga, 1998; von Hagke et al., 2012, 2014b; Hinsch, 2013; Ortner et al., 2015). These values do not account for shortening taken up by the frontal triangle zone between ca. 20 Ma and 12 Ma (von Hagke et al., 2014b; Kempf et al., 1999; Ortner et al., 2015). ~~Despite the uncertainty in the~~ We acknowledge that shortening estimates ~~within~~for the Subalpine Molasse are subject to uncertainties (Burkhard and Sommaruga, 1998; von

Hagke and Malz, 2018; Ortner et al., 2015~~),~~) and likely represent minimum estimates due to: (i) the unconstrained large parts of proximal Subalpine Molasse, which are hidden below the frontal thrusts of the Helvetic nappes and Penninic Klippen units, and (ii) the non-preservation of the hanging-wall cut-offs of individual thrust sheets. Despite these uncertainties, we observe that late Miocene cumulative shortening of the Subalpine Molasse and the Jura FTB decreases ~~constantly~~slightly from the west to the east from >30 km near Geneva to 20 km near Lake Constance, before ~~finally~~rapidly decreasing to <1 km ~~near~~between ca. 10.5° E and Salzburg (12.8° E; Fig. 6b). It is thus noteworthy that the along-strike variation in late Miocene shortening in the foreland does not ~~correlate with the peaks of high-uplift domains of~~seem to reflect the different levels of exhumed European basement units (i.e. ECMs) in the hinterland (Fig. 6c).

5 Discussion

5.1 ~~Downscaling:~~ Local-scale stratigraphic architecture conditioning the pattern of strain ~~release~~accommodation

In the sampling area, mapping discloses along-strike differences in the litho-tectonic architecture of the Subalpine Molasse (Fig. 3). The sediments are thrusted northwestward along SW-NE striking thrusts. East of the Aare valley, a ~~back thrust~~backthrust emerges to the surface and forms a frontal triangle zone (Figs. 3 and 5), a structure which is also known from parts of the Subalpine Molasse farther east (Fig. 7; e.g. Berge and Veal 2005; Müller et al. 1988; Schuller et al. 2015; Sommaruga et al. 2012; Stäuble and Pfiffner 1991, Ortner et al. 2015). The Aare valley, running across the study area, is characterized by a low relief and is filled by >100 m-thick Quaternary deposits (Fig. 5; Dürst Stucki et al., 2010). Accordingly, the structural configuration of this part of the study area is only poorly resolved. However, the structures of the Subalpine Molasse change abruptly across the Aare valley (Figs. 3 and 5), as has been described by many authors (Beck, 1945; Blau, 1966; Haus, 1937; Pfiffner, 2011; Rutsch, 1947; Vollmayr, 1992). Based on this observation and under the consideration of available interpreted reflection seismic lines, the presence of a possible syn-thrusting strike-slip fault zone running along the valley axis has been proposed (Mock and Herwegh, 2017; Pfiffner, 2011; Vollmayr, 1992). The presence of such a fault is, however, speculative due to the low resolution of the seismic data. The latter stems from (i) the thick Quaternary cover resulting in a very poor signal-to-noise ratio and (ii) the poorly resolved Molasse strata as a result of the frequency, which was chosen in order to optimize for the targeted Mesozoic horizons below (Mock and Herwegh, 2017). An alternative explanation for the sudden along-strike change in the tectonic architecture has first been proposed by Rutsch (1947). He reported that the change from a mainly conglomeratic (east) to a sand- and mudstone dominated (west) lithofacies coincides with an increase in the folding intensity along the frontmost anticline (Falkenfluh anticline; Fig. 3a). Indeed, while conglomerates are the dominant lithofacies in the eastern part of the study area, they are vastly absent west of the Aare valley, where mainly alternating sequences of sandstones and mudstones are outcropping (Figs. 3 and 7; Landesgeologie, 2005). This difference in mechanical stratigraphy east and west of the Aare valley is probably a result of an asymmetric dispersal system with a distinct northeastward direction of sediment discharge (Schlunegger and Norton, 2015). The distribution of mechanically different lithologies seems to control the pattern of ~~strain release (i.e. ~~thrusting~~ pattern).~~. While east of the Aare valley, the mechanically stronger thick conglomeratic sequences deform en-bloc and thrusts are concentrated in narrow bands following mechanically weak zones of sand- and mudstones, strain is ~~released~~accommodated in a much more distributed pattern along more closely spaced thrusts in the western part of the study area~~.~~ (Fig. 3). The pronounced mechanical contrast between conglomerates and sand-/mudstones leads to en-bloc thrusting of the large tectonic slice made up of amalgamated conglomerates east of the Aare valley, and it is also manifested in well-defined and constant AHe ages of ca. ~~6 Ma (Figs. 3 and 5). AHe ages west of the Aare valley, however, chronicle a more evenly distributed deformation and exhumation pattern, which is most likely conditioned and thus controlled by the low mechanical contrast of the involved lithologies.~~6 Ma within this tectonic slice (samples SM-8, SM-11, and SM-15; Figs. 3 and 5).

The observation that along-strike variations in the stratigraphic architecture lead to complex patterns of strain ~~release~~accommodation is not unique to our ~~sample~~study area, but can be also made~~ also~~ at the Mont Pèlerin, the Rigi, or the Hörnli in western, central, and eastern Switzerland, respectively (Fig. 7). ~~In particular,~~Salients seem to occur at the apex of former alluvial megafan depositional systems, while recesses are observed in regions in between these large dispersal systems, where thick conglomerate sequences are missing. The lithological control on the strain ~~release~~accommodation and exhumation pattern is particularly well observed in the Rigi area (profile 3 in Fig. 7; Sommaruga et al., 2012). The thick conglomerate sequence of the Rigi thrust sheet was (re-)activated en-bloc at ca. 5 Ma, while the adjacent sand- and mudstone dominated part to the north experienced a period of thrusting at ca. 9 Ma along evenly spaced faults (von Hagke et al., 2012). Similar dependencies between the style of deformation and lateral changes in lithology have also been described for the Subalpine Molasse in Bavaria and western Austria (for detailed information see Ortner et al., 2015), as well as for the basal detachments of the Subalpine Molasse and the Jura FTB (von Hagke et al., 2014a). While large alluvial fans ~~deposited~~formed thick conglomerate-sandstone sequences in western Bavaria, brackish to shallow marine conditions prevailed farther east where marls and sandstones were deposited (Frisch et al., 1998; Kuhlemann and Kempf, 2002). This lateral change of the Molasse's mechanical stratigraphy has been described to have a direct influence on the deformation style of the Subalpine Molasse (Ortner et al., 2015). While stacks of tectonic horse structures and a pronounced triangle zone developed in western Bavaria, the deformation style changes to buckle folding farther east, which decreases in amplitude and the triangle zone disappears (a detailed description is provided in Ortner et al., 2015). Numerical models of syntectonic sedimentation support that sediments shed on an evolving FTB strongly control its geometry, and may include formation of backthrusts (e.g. Fillon et al., 2013).

5.2 ~~Upscaling:~~ Implications for late orogenic processes

5.2.1 The link to exhumation of the External Crystalline Massifs

Classically, thrusting in the Jura FTB and the Subalpine Molasse between Lake Geneva and Lake Constance has been kinematically and spatio-temporally related to the uplift and exhumation of the ECMs, and to the propagation of the deformation front towards the foreland (Burkhard, 1990; Burkhard and Sommaruga, 1998; Pfiffner et al., 1997). The Aar, and possibly also the Mont Blanc, and Aiguilles Rouges Massifs were exhumed in early to mid-Miocene times during a stage of buoyancy-driven differential uplift along sub-vertical reverse faults (‘vertical tectonics’; Herwegh et al., 2017, 2020). This stage of ‘vertical tectonics’ was followed by late Miocene en-bloc exhumation along a series of shallow southwest-dipping basal thrusts at the massif’s northwestern front (Egli et al., 2017; Herwegh et al., 2017, 2020;). It is during this late (ca. post-13 Ma) thrusting-dominated phase (i.e. ‘horizontal tectonics’) when deformation was translated northward into the Alpine foreland. In the non-detached part of the North Alpine foreland, thrusting of the proximal Molasse occurred. Far-field stress transferred into the foreland, induced the reactivation of Paleozoic structures (Egli et al., 2016). In the western North Alpine foreland, large-scale strain partitioning occurred when deformation propagated 50-90 km to the north forming the Jura FTB, while at the same time imbricates of Subalpine Molasse were thrusted northward (e.g. Becker, 2000; Burkhard, 1990; Burkhard and Sommaruga, 1998; von Hagke et al., 2012).

However, it has also been reported that the proximal foreland basin east of the easternmost ECM, i.e., the Aar Massif, has been subject to post-12 Ma thrusting and horizontal shortening (Figs. 6a and 6b; Ortner et al., 2015). Our AHe age data from the Subalpine Molasse (Figs. 3, 4, and 5) fit with AHe ages farther east (von Hagke et al., 2012, 2014b) and chronicle a period of thrusting and exhumation of the Subalpine Molasse between 12 Ma and 4 Ma (Fig. 6a). This occurred ~~coeval~~coevally with the main deformation phase in the Jura FTB, which lasted from ca. 12-4 Ma (e.g. Becker, 2000). Similar ages constrained from geological and seismic interpretation, and observations of growth strata in the youngest preserved sediments have been reported for the Subalpine Molasse between Lake Constance and Salzburg (Fig. 6a; Ortner et al., 2015). ~~Based on stratigraphic data, Haus (1935) inferred already in 1935 that~~ Late Miocene thrusting in the Subalpine Molasse of Central Switzerland ~~was subject to major thrusting in late Miocene times.~~has also been inferred from stratigraphic data (Haus, 1935). Since the youngest AHe ages are ~~associated with~~recorded from the internal tectonic slices of the Subalpine Molasse (Figs. 3, 4, and 5), we can infer the occurrence of break-back thrusting, a characteristic feature, which has been confirmed so far along the Subalpine Molasse between Bern and Salzburg based on thermochronological data and cross section restorations (von Hagke et al., 2012, 2014b; Ortner et al., 2015; Schuller et al., 2015), but has been locally argued for as early as the 1930s (Haus, 1935, 1937). The break-back thrusts are supposedly younger than the development of the frontal triangle zone, which formed the active northern deformation front from ca. 20-12 Ma (von Hagke et al., 2014b; Ortner et al., 2015). Furthermore, our AHe ages from the Plateau Molasse record a partially exhumed PRZ (Figs. 3, 4, and 5) and thus corroborate the occurrence of substantial exhumation of the flat-lying Plateau and Foreland Molasse (Cederbom et al., 2011; Genser et al., 2007; Gusterhuber et al., 2012; von Hagke et al., 2012; Zweigel et al., 1998), indicating a large wavelength exhumation signal across the entire basin. ~~Because the tectonically driven exhumation signal between 12 Ma and 4 Ma is not unique to the forelands of the ECMs and late Miocene shortening estimates in the North Alpine foreland do not correlate spatially with the high-uplift domains of the ECMs (Fig. 6), we suggest that although kinematically linked, the late Miocene foreland deformation is not a consequence of uplift and exhumation of the ECMs.~~

Although foreland deformation is kinematically linked to the late phase of thrust-dominated exhumation of the ECMs (‘horizontal tectonics’; Herwegh et al., 2017, 2020), the occurrence of late Miocene thrusting in the foreland is not restricted to the areas in front of the ECMs, and the along-strike variation in horizontal shortening does not seem to reflect the different levels of exhumed basement blocks (i.e. ECMs) in the hinterland (Fig. 6). Based on the observations of a continuous down-going European slab in combination with the extent of the Subalpine Molasse, we suggest that late Miocene thrusting is a large wavelength feature which occurs along the entire northern Central Alps encompassing both the ECMs and the foreland (i.e. Subalpine Molasse and Jura FTB; Fig. 8c). This follows an early to mid-Miocene stage, which was characterized by the sub-vertical extrusion of the eastern ECMs and a stationary deformation front in the Subalpine Molasse. Hence, along the northern Central Alps, the mid-late Miocene boundary marks the transition from an inferred buoyancy-driven regime with the sub-vertical rise of the eastern ECMs (‘vertical tectonics’; Herwegh et al., 2017, 2020) to a large-scale thrust-dominated regime (‘horizontal tectonics’), thereafter.

5.2.2 Possible link to geodynamic processes beneath the core of the Central Alps

~~During mid- to late Miocene times, the Central Alps underwent a major change from dominantly vertical to horizontal tectonics. This is also witnessed by the supersession of the vertical extrusion of the ECMs by north-directed thrusting along shallow SE-dipping shear zones (Fig. 8c; Herwegh et al., 2017, in press). In the western North Alpine foreland, large-scale strain partitioning occurred when deformation propagated 50-90 km to the north into the Jura FTB (Becker, 2000) while at the same time the Subalpine Molasse experienced break-back thrusting and thrust reactivation along the entire segment of the Alps between Lake Geneva and Salzburg (Figs. 6a and 8c). The occurrence of late Miocene thrusting has also been reported for the foreland of the Western Alps (Schwartz et al., 2017). In the Southern Alps, deformation propagated ca. 50 km southward between ca. 15 Ma and 7 Ma (Schmid et al., 1996; Schönborn, 1992).~~

~~This rapid change from pre-12 Ma vertical tectonics in the core of the Alps (Herwegh et al., 2017; Hurford, 1986; Schmid et al., 1996~~This transition from pre-12 Ma buoyancy-driven ‘vertical tectonics’ (Herwegh et al., 2017, 2020), with the triangle zone in the Subalpine Molasse acting as a stationary deformation front from ca. 20-12 Ma (von Hagke et al., 2014b; Ortner et al., 2015), to post-12 Ma ~~orogen~~large-scale ‘horizontal ~~tectonics, accompanied by orogen-perpendicular growth of the Alps,~~tectonics’ cannot be explained by a classical model of continent-continent collision and continuous foreland propagation of the orogenic wedge. In the following, we discuss the observed exhumation pattern along the Subalpine Molasse (Fig. 6a) in the context of the post-35 Ma tectonic evolution of the Central Alpine orogeny as proposed by Kissling and Schlunegger (2018) and Schlunegger and Kissling (2015~~)~~), and we argue for a deep-driver ~~to control~~controlling the large-wavelength thrusting in the North Alpine foreland and the proposed transition from ~~dominantly vertical~~buoyancy-driven ‘vertical’ to ‘horizontal ~~tectonics, associated with widespread tectonic activity in the foreland and a period of orogenic widening~~tectonics’ thereafter.

During the Alpine orogeny, convergence rates between the Adriatic and European continental plates decreased when the positively buoyant European continental crust started to enter the subduction zone ca. 35 My ago (Fig. 8b; Handy et al., 2010; Schmid et al., 1996) and when ~~delamination and~~ wedging of European continental crust was initiated (Schmid et al., 1996). Large slab pull forces exerted by the negatively buoyant oceanic lithospheric slab induced extensional forces within the subducting plate, which led to necking and possibly eventually to slab breakoff (Davies and von Blanckenburg, 1995). ~~Subsequent slab unloading caused strong uplift and backthrusting along the Insubric Line (Berger et al., 2011; Hurford, 1986; Schmid et al., 1996).~~ According to Kissling (2008) and Kissling and Schlunegger (2018), the ~~delaminated and thus~~ dense European mantle slab, which was still attached to the foreland plate but delaminated (i.e. separated) from the crust, continued to roll back, with the consequence ~~of~~that the slab ~~steepening~~steepened and ~~northward migration of~~that the locus of crustal delamination migrated northward. This forced new crustal material to enter the subduction system and to become stacked to the Alpine edifice ~~as evidenced by~~in the ~~emplacement~~form of ~~the~~crystalline and sedimentary nappes (e.g. Helvetic nappes ~~(Fig. 8c~~), or alternatively it was accreted to the crustal root through the basal accretion of mid-crustal material (Fry et al., 2010). Ongoing ~~slab~~ roll-back subduction and an associated increase in the lower ~~plate~~plate's flexure ~~resulted~~is probably reflected in ~~a~~the northward propagation of the northern margin of the Central Alps' Molasse Basin until ca. 20-18 Ma (Fig. 8a).

Thereafter, plate convergence rates seemed to decrease noticeably (Fig. 8b; Handy et al., 2010; Schmid et al., 1996). At this stage, pro-wedge widening of the Molasse Basin came to a relative halt~~.~~ (Fig. 8a). In the Central Alps, the proximal part of the basin kept subsiding by additional 2-3 km (~~Fig. 8a;~~ Burkhard and Sommaruga, 1998; Schlunegger and Kissling, 2015), while the distal realm became subject to erosion (Kuhlemann and Kempf, 2002). This phase was also associated with the period of buoyancy-driven differential vertical ~~tectonics~~uplift of the ~~ECMs,~~Aar Massif (and probably also the Mont Blanc and Aiguilles Rouges Massifs), i.e. ~~their~~its rise along steeply dipping reverse shear zones between ca. 20 Ma and 12 Ma (Herwegh et al., 2017, 2020; Wehrens et al., 2017), while the northern deformation front remained stationary in the Subalpine Molasse (Fig. 8c; Burkhard and Sommaruga, 1998; von Hagke et al., 2014b; Ortner et al., 2015). East of Munich, however, the Molasse Basin experienced, at this time, a period of uniform subsidence and even a short-lived phase of uplift (ca. 17-16 Ma) as evidenced by horizontal to 5° westward tilting strata of post-20 My old Molasse sediments (Gusterhuber et al., 2012; Zweigel et al., 1998). ~~This~~The latter was attributed to ~~a decrease in surface loads in the orogen in response to~~eastward-directed lateral extrusion ~~(i.e. escape tectonics) and a corresponding lowering of the Eastern Alps' topography~~of crustal blocks (Gusterhuber et al., 2012~~; ~~). It also correlates with the observed westward increasing gradient of crustal thickening associated with an eastward decrease of the Eastern Alps' average elevation (Rosenberg et al., 2018). Alternatively, Handy et al. (2015) explained this signal as a result of deep crustal unloading due to a proposed slab tear and a corresponding subduction polarity reversal beneath the Eastern Alps. These observations imply that important along-strike changes and a large-scale geodynamic (Hetényi et al., 2018b; Kissling et al., 2006; Lippitsch et al., 2003; Mitterbauer et al., 2011) and tectonic (e.g. Handy et al., 2015;

Ratschbacher et al., 1991; Rosenberg et al., 2018) decoupling between the Central and the Eastern Alps and their Molasse Basins have been established by the end of mid-Miocene times.

This is also mirrored by the along-strike ~~changes~~pattern in ~~the~~ late Miocene cumulative horizontal shortening in the North Alpine foreland, which ~~decreases~~, without fully considering the possibly large uncertainties of shortening estimation in the Subalpine Molasse, seems to decrease from >30 km near Lake Geneva, to ca. 20 km near Lake Constance~~, and finally~~ . A rapid decrease from ca. 18 km to <1 km ~~near~~ over a lateral distance of just ca. 120 km is finally recorded between ca. 10.5° E and Salzburg (Fig. 6). East of Salzburg at the front of the Eastern Alps, zero late Miocene shortening is recorded in the proximal Molasse~~.~~ (Beidinger and Decker, 2014; Hinsch, 2013; Ortner et al., 2015). This pattern has been attributed to an increasing transfer of shortening towards the internal parts of the orogen (i.e. the Tauern Window) and to the out-of-section removal of crust through lateral extrusion in the Eastern Alps (Ortner et al., 2006, 2015). While such upper crustal processes may certainly mask the signal of late Miocene foreland deformation, the latter may also reflect the response to the change of a geodynamic driving force operating at a larger scale, situated at deeper crustal levels, and encompassing the entire Central Alps until as far east as 12.8° E (near Salzburg; Fig. 9). The attached European lithospheric slab beneath the Central Alps presents here a possible candidate for driving the observed large wavelength signal of late Miocene foreland deformation (Fig. 9). This hypothesis is based on the following main observations and considerations: (i) The along-strike extent of late Miocene thrusting in the foreland correlates spatially remarkably well with the proposed extent of the steeply south-dipping Central Alpine European slab imaged by seismic tomography (Fig. ~~9).~~9; Kästle et al., 2020; Lippitsch et al., 2003; Zhao et al., 2016). (ii) The large spatial wavelength of tectonically driven exhumation of the ~~tectonic signal, which at least in the~~ Subalpine Molasse, which has been attributed to distinct thrusting events between ~~Lake Thun and Lake Constance seems to occur in the form of individual tectonic pulses, likely excludes more local~~ca. 12-4 Ma, can be viewed as an upper crustal ~~phenomena as possible drivers and points towards bigger players such as plate tectonics or slab dynamics.~~expression of a lithospheric-scale tectonic driver acting at that wavelength. (iii) The proposed segmentation of the deep structure of the Central and Eastern Alps (~~i.e. slab detachment and subduction polarity reversal;~~ Handy et al., 2015; Hetényi et al., 2018b; Kästle et al., ~~2019~~2020; Kissling et al., 2006; Lippitsch et al., 2003; Mitterbauer et al., 2011; Schmid et al., 2004), which is expected to have induced a geodynamic and tectonic reorganization along the Alpine chain by the end of mid-Miocene times could explain the subsequent late Miocene tectonism, which was restricted to the foreland of the Central Alps until ca. Salzburg and which was thus decoupled from the Eastern Alps. The corresponding ~~change~~transition in the macro-tectonic regime of the northern Central Alps from ~~dominantly vertical~~buoyancy-driven 'vertical' to large-scale 'horizontal ~~tectonics~~tectonics' may reflect decreasing rates of European slab rollback and a late phase of post-collisional indentation of Adria as recently proposed by Herwegh et al. (2017~~) and Kissling and Schlunegger (2018~~; 2020).

5.2.3 The exceptional position of the Bavarian Subalpine Molasse

The configuration of the lithospheric mantle slabs is inherently different beneath the Central and the Eastern Alps (Kästle et al., 2020; Kissling et al., 2006; Kissling and Schlunegger, 2018; Lippitsch et al., 2003; Mitterbauer et al., 2011; Zhao et al., 2016). At the lithospheric scale, a polarity reversal between the European slab and the Adriatic slab has been conjectured beneath the western Tauern Window (Lippitsch et al., 2003). However, this model is currently debated as new geophysical data indicate that at depth the southward dipping European slab extends from the Central Alps until east of the Giudicarie and Brenner Faults (Kästle et al., ~~2019~~2020) and possibly as far east as 12.5° E, i.e. the central Tauern Window (Figs. 1 and 9; Qorbani et al., 2015). ~~Although the~~Based on tomographic results from the AlpArray intiative, Hetényi et al. (2018b) propose that at ca. 13° E a northward-dipping slab of the Adriatic plate is present. All these studies show that the deep structure remains very uncertain and debated since tomographic data have been interpreted in different ways regarding the slab geometries at depth (Hetényi et al., 2018b; Kästle et al., ~~2019~~2020; Lippitsch et al., 2003; Mitterbauer et al., 2011; Zhao et al., 2016~~), most of them~~). However, they all concur on the observation that between the deep velocity anomalies of the Central and the Eastern Alps a major discontinuity is present east of the Giudicarie and Brenner Faults (see also Handy et al., 2015). This correlates with the eastward termination of the late Miocene Subalpine Molasse near Salzburg (Fig. 9). Hence, the geophysical data place the link between the deep structure and deformation of the Subalpine Molasse between Lake Constance and Salzburg in a Central Alpine rather than an Eastern Alpine context.

While at the mantle scale, a segmentation of the slab structure is observed at ca. 12.5° E (Fig. 9), an along-strike segmentation at crustal levels occurs further west (at the Brenner Fault). East of the Brenner Fault (Figs. 1 and 9), the post-collisional evolution of the Eastern Alps is characterized by the northward indentation of the Dolomite indenter and the related eastward lateral extrusion of crustal blocks (Ratschbacher et al., 1991). At the larger scale, this was possibly facilitated by slab retreat beneath the Carpathians and the associated rifting in the Pannonian Basin (Peresson and Decker, 1997). The main phase of lateral extrusion occurred in early and mid-Miocene times (Frisch et al., 1998; Ratschbacher et al., 1991), possibly extending into the late Miocene (Ortner et al., 2015). These processes were additionally associated with the collisional exhumation of the Tauern Window and normal faulting along its bounding low-angle normal faults (see Rosenberg et al., 2018). In this respect, the Bavarian Subalpine Molasse is particularly interesting, since it extends over this transition area (Fig. 9). In this transient position, the tectonics of this segment of the Subalpine Molasse between Lake Constance and Salzburg was probably affected by the deep-seated dynamics of the Central Alpine European slab, while at the same time ~~tectonic processes related to slab dynamics were possibly~~being also masked by the aforementioned upper crustal processes of Eastern Alpine tectonics (e.g. lateral extrusion).

For resolving the influence of deep-seated processes on the tectonics of the Subalpine Molasse and the foreland basin in general, the present-day slab geometries underneath the entire Alps must be resolved at higher resolution. Furthermore, the time-evolution of the slabs must be constrained with a focus on if, when, and how a potential subduction polarity reversal occurred in the Eastern Alps. These studies should be supported by source-to-sink analyses linking the stratigraphy of the foreland to hinterland processes. New thermochronological data from the Bavarian Subalpine and Foreland (i.e. undeformed) Molasse will be essential. Furthermore, we expect that ongoing seismo-tomographic investigations will disclose further details to constrain the deep-seated driving mechanisms (Hetényi et al., ~~2018~~2018a).

6 Conclusions

In this paper, we presented new low-temperature thermochronological age data from the Subalpine Molasse of the Central European Alps. By comparing our results to published age and stratigraphic data along-strike the Alps from Lake Geneva to Salzburg we conclude that:

- (U-Th-Sm)/He ages along the Subalpine Molasse of the Central Alps ~~are consistently~~record thrust-related exhumation between 12-4 Ma ~~and can be assigned to~~with at least two ~~tectonic pulses~~thrusting events associated with it at ca. 10 and 6 Ma.
- The pattern of strain ~~release~~accommodation is strongly conditioned by the local-scale mechanical stratigraphy, since the locus of deformation depends on the distribution of mechanically weak (sand- and mudstones) and strong (conglomerates) lithologies. Accordingly, a general widening of the foreland thrust-belt (i.e. tectonic salients) and en-bloc deformation of large conglomerate bodies occurs at the locations where the stratigraphy is conglomerate dominated, i.e. at the site of former megafan dispersal systems depositing large and km-thick conglomerate sequences into the foreland. Conversely, tectonic recesses and a more distributed deformation pattern developed where the mechanical stratigraphy is dominated by sand- and mudstone deposits.
- ~~Despite the~~The along-strike highly non-cylindrical hinterland ~~exhumation history and~~ architecture~~,~~ and the variability of the sites of exhumation of the former basement of the European margin has no apparent imprint on the distribution of late Miocene ~~tectonic signal~~shortening recorded in the Subalpine Molasse ~~is remarkably constant along-strike the Alps, from Lake Geneva to Salzburg~~and the Jura fold-and-thrust belt.

Hence, we observe that the deformation style during late Miocene thrusting of the Subalpine Molasse is masked by local variations in the stratigraphic architecture. However, ~~the overall tectonic signal~~in terms of timing and kinematics, thrust-related shortening, though decreasing in intensity from the west to the east, is consistent ~~in terms of timing and kinematics~~ along-strike ~~the part~~in those parts of the Alps which ~~correlates~~correlate with the lateral (i.e. along-strike) extent of the Central Alpine lithospheric mantle slab at depth. ~~Large-wavelength~~ Thus, we may interpret late Miocene large-wavelength thrusting ~~may thus be interpreted~~ as an upper crustal signal resulting from changes of this lithospheric driving force. The latter possibly leads to a ~~prominent~~ change in the macro-tectonic regime in this sector of the Alpine orogen at ca. 12 Ma, from ~~dominantly vertical~~buoyancy-driven ‘vertical’ to ~~horizontal~~thrusting-dominated ‘horizontal’ tectonics.

In summary, although we lack the required data to precisely determine the geodynamic processes responsible for the late phase of shortening in the Molasse, we are able to constrain the timing of this event to 12-4 Ma. In addition, this work shows that low-temperature thermochronological data yield an improved understanding of the chronology of orogenic processes where the late orogenic stage of a mountain belt may be characterized by a complex pattern of strain release conditioned by site-specific stratigraphic and thus lithological conditions at the local scale, and by ~~a change from vertical to horizontal tectonics at the larger scale including the entire Central Alps~~widespread tectonism possibly resulting from changes in deep seated driving forces.

~~**Appendix A: Apatite separation and picking**~~

~~To release the apatite crystals from the rock samples, we used the electrodynamic disaggregation technique (selFrag). This method exposes the rock specimen to a high voltage pulse and fractures it along its grain boundaries. As opposed to separation using a jaw crusher, this method is less time consuming and the rock is disintegrated along the grain boundaries (Giese et al., 2010). This ensures individual grains are less prone to damaging during processing.~~

~~To prepare the samples for electrodynamic disaggregation, they had to be crushed into fist-sized pieces by hand using a hammer. This was necessary due to the limiting dimensions of the processing vessel of the selFrag. For releasing the individual grains, we applied a frequency of 3 Hz and electric potentials of 130-150 kV, depending on the hardness of the rock. For every sample, the electrode distance was incrementally reduced in 5 mm steps from a maximum of 40 mm to a minimum of 15 mm. Per step, a minimum of 20 pulses was applied to ensure full release of the individual grains. It has been shown that the influence of diffusive loss of ^{4}He due to the plasma channel hitting the apatite crystal is negligible, and (U-Th-Sm)/He (AHe) ages from samples separated with electrodynamic disaggregation are indistinguishable from AHe ages measured on apatites released with mechanical techniques (Giese et al., 2010).~~

~~Apatite crystals were concentrated using standard rock separation techniques. First, the grain size fraction of 64-250 µm, which is suitable for AHe dating, was separated using disposable sieving meshes. To remove magnetic minerals from the sieved sample fraction, we used a Frantz magnetic separator at 0.5 A and 1.2 A. To concentrate apatite from the remaining grains, we used lithium-based tungstate ($\rho = 2.81$ g cm^{-3}) as heavy liquid for density separation of the heavy minerals. On average, we had to process ca. 100 g of sample material to acquire enough heavy minerals. The heavy mineral fraction has been thoroughly rinsed with deionized water and then dried at 30°C.~~

~~Apatites have been hand-picked under a binocular and checked for inclusions and imperfections under an optical microscope with cross-polarized light. Wherever possible, we selected euhedral, intact, and inclusion free grains with a minimum width of 60 µm. However, as the grains are detrital, partly grains with rough surfaces or tiny fluid inclusions had to be picked. This may result in larger error bars or even grain ages that do not yield a geologically meaningful age. These ages were excluded (see section 3.2 and Table 1).~~

Data availability

The research data is enclosed in this paper and can be freely accessed.

Author contribution

SM designed the study with support from MH, FS, and CvH. FS and MH assisted SM during sampling in the field. SM carried out mineral separation and picked the apatite crystals. ID carried out the helium extraction and the ICP-MS measurements at University of Göttingen. CvH and ID assisted in analyzing and interpreting the apatite (U-Th-Sm)/He ages. SM prepared the manuscript, with contributions from all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

We thank Judith Dunkl (Göttingen) for assisting in the selection of apatite crystals, Pierre Valla (Bern) for discussions on the AHe ages and the thermal models, and Edi Kissling (Zurich) for his insights on lithospheric scale processes. The manuscript has greatly benefited by detailed and constructive comments by Claudio Rosenberg (Paris), Giovanni Luca Cardello (Rome) Hugo Ortner (Innsbruck) and Nicola Levi (Vienna). Additional information of the data can be found in the supplementary material. The study was funded by the Swiss Geological Survey of the Federal Office of Topography (swisstopo) as part of the GeoMol CH project. We acknowledge the use of the Move Software Suite (used for Fig. 5) granted by ~~Midland Valley's Academic Software Initiative~~Petroleum Experts Limited.

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Table 1 Apatite (U-Th-Sm)/He dating results

Sample	He vol. [ncc][a]	1σ [%]	U mass [ng]	1σ [%]	Th mass [ng]	1σ [%]	Sm mass [ng]	1σ [%]	Ft[b]	Raw age [Ma]	Corrected age [Ma]	2σ [Ma][c]	Average age [Ma][d]	2 std. error [Ma][e]	Excluded age[f]
SM-1 a1	0.02	3.77	0.01	5.64	0.07	2.56	0.34	7.06	0.60	5.5	9.0	1.4			
SM-1 a2	0.08	2.09	0.04	2.66	0.21	2.45	0.98	6.92	0.72	7.2	10.0	1.0			
SM-1 a4	0.07	2.43	0.03	3.18	0.15	2.47	0.66	6.84	0.74	8.5	11.5	1.2			
SM-1 a5	0.03	3.70	0.02	4.97	0.07	2.56	0.40	7.15	0.69	6.2	9.0	1.2			
SM-1 a6	0.08	2.09	0.03	2.52	0.15	2.45	0.55	3.47	0.68	9.4	13.9	1.5			
SM-1 a7	0.05	2.67	0.02	3.25	0.14	2.46	0.92	3.64	0.79	6.9	8.8	0.8			
SM-1 a8	0.04	3.24	0.03	2.65	0.02	2.82	0.23	3.34	0.64	8.1	12.6	1.7	10.7	0.8	
SM-4 a1	0.03	3.13	0.02	3.08	0.01	2.48	0.03	3.70	0.66	10.5	15.9	2.1			e
SM-4 a2	0.06	2.51	0.06	2.03	0.10	2.42	0.37	3.70	0.61	5.9	9.6	1.2			
SM-4 a3	0.01	4.81	0.02	3.79	0.05	2.49	0.56	3.70	0.59	3.0	5.0	0.8			e
SM-4 a4	0.06	2.64	0.05	2.20	0.06	2.45	0.51	3.70	0.61	6.6	10.8	1.4			
SM-4 a5	0.02	4.31	0.02	3.99	0.03	2.54	0.34	3.70	0.55	5.0	9.2	1.5			
SM-4 a6	0.08	2.21	0.07	2.01	0.02	2.64	0.38	3.70	0.66	8.6	13.1	1.5	10.7	0.9	
SM-5 a1	0.05	2.79	0.04	2.52	0.13	2.46	0.90	3.70	0.62	4.7	7.5	1.0			
SM-5 a2	0.10	2.11	0.15	1.86	0.09	2.43	0.66	3.70	0.66	4.6	7.0	0.8			
SM-5 a3	0.02	4.42	0.02	4.25	0.06	2.57	0.25	3.70	0.74	4.3	5.8	0.7			
SM-5 a4	0.01	5.90	0.01	6.10	0.09	2.50	0.22	3.70	0.62	2.2	3.6	0.6			e
SM-5 a5	0.04	3.02	0.04	2.35	0.15	2.46	1.00	3.70	0.65	3.7	5.6	0.7			
SM-5 a6	0.20	1.51	0.13	1.88	0.08	2.44	0.54	3.70	0.63	11.3	18.1	2.2	6.5	0.5	e
SM-6 a1	0.05	2.66	0.05	2.20	0.10	2.43	0.83	3.70	0.61	6.0	9.8	1.3			
SM-6 a2	0.07	2.20	0.07	2.04	0.12	2.47	1.30	3.70	0.82	5.6	6.8	0.5			
SM-6 a3	0.04	2.90	0.04	2.29	0.08	2.44	0.77	3.70	0.61	4.8	7.8	1.1			
SM-6 a4	0.00	9.84	0.00	43.45	0.01	2.77	1.05	3.70	0.59	0.8	1.3	0.4			e
SM-6 a5	0.14	1.72	0.13	1.87	0.02	2.68	0.51	3.70	0.64	7.9	12.3	1.4	9.2	1.2	
SM-7 a1	0.01	7.55	0.01	5.93	0.03	2.67	0.34	4.55	0.54	2.1	3.9	0.8			e
SM-7 a2	0.03	3.57	0.02	3.57	0.02	2.88	0.43	3.21	0.69	7.9	11.5	1.5			
SM-7 a3	0.15	1.66	0.07	2.00	0.07	2.52	0.31	4.06	0.62	13.5	21.7	2.7			
SM-7 a4	0.02	4.43	0.02	4.16	0.04	2.62	0.31	3.52	0.57	5.1	9.0	1.5			
SM-7 a5	0.05	2.85	0.03	2.82	0.05	2.58	0.41	3.81	0.54	8.4	15.7	2.4			
SM-7 a6	0.02	4.37	0.02	3.98	0.05	2.45	0.57	3.70	0.71	3.7	5.2	0.7			e
SM-7 a7	0.02	4.28	0.01	6.31	0.04	2.65	0.60	3.70	0.65	6.1	9.5	1.4			
SM-7 a8	0.24	1.48	0.13	1.87	0.11	2.42	0.57	3.70	0.73	12.3	16.9	1.6			
SM-7 a9	0.00	8.62	0.00	28.40	0.03	2.69	0.30	3.70	0.55	2.4	4.3	1.1			e
SM-8 a1	0.02	3.67	0.02	3.39	0.06	2.54	0.56	4.01	0.77	4.4	5.7	0.6			
SM-8 a2	0.02	3.68	0.03	3.02	0.03	2.67	0.43	4.57	0.70	4.7	6.8	0.8			
SM-8 a3	0.12	1.93	0.03	2.61	0.08	2.50	0.56	3.86	0.77	18.5	24.0	2.1			e
SM-8 a4	0.02	3.88	0.02	3.25	0.06	2.55	0.53	3.32	0.80	4.5	5.6	0.6	6.0	0.4	
SM-11 a1	0.05	2.53	0.05	2.14	0.11	2.42	0.47	4.56	0.78	5.5	7.0	0.6			
SM-11 a2	0.02	4.35	0.02	3.89	0.06	2.45	0.34	3.42	0.73	5.3	7.2	0.9			
SM-11 a3	0.02	4.04	0.02	4.02	0.07	2.43	0.52	3.68	0.75	4.1	5.6	0.7			
SM-11 a4	0.02	4.77	0.02	3.77	0.06	2.44	0.30	4.20	0.57	3.8	6.6	1.1			
SM-11 a5	0.05	2.52	0.04	2.35	0.04	2.49	0.26	4.54	0.67	9.2	13.6	1.6	6.6	0.4	e
SM-12 a1	0.04	3.00	0.04	2.22	0.06	2.44	0.40	3.80	0.51	5.5	10.7	1.7			
SM-12 a2	0.26	1.50	0.15	1.84	0.01	2.72	0.46	4.13	0.69	13.4	19.4	2.0			e
SM-12 a3	0.02	3.63	0.03	2.85	0.03	2.51	0.36	3.46	0.74	5.4	7.3	0.8			
SM-12 a4	0.22	1.50	0.19	1.83	0.18	2.41	0.46	4.07	0.82	7.8	9.6	0.7	9.2	1.0	
SM-13 a1	0.06	2.27	0.07	1.99	0.02	2.84	0.59	3.13	0.61	6.1	10.0	1.3			

Sample	He vol. [ncc][a]	1σ [%]	U mass [ng]	1σ [%]	Th mass [ng]	1σ [%]	Sm mass [ng]	1σ [%]	Ft[b]	Raw age [Ma]	Corrected age [Ma]	2σ [Ma][c]	Average age [Ma][d]	2 std. error [Ma][e]	Excluded age[f]
SM-13 a2	0.04	2.93	0.03	2.54	0.04	2.67	0.39	3.93	0.68	6.6	9.7	1.2			
SM-13 a3	0.06	2.59	0.07	2.05	0.01	3.46	0.35	4.68	0.74	6.8	9.1	0.9			
SM-13 a4	0.02	4.51	0.02	2.96	0.02	2.71	0.31	4.28	0.63	4.3	6.9	1.0			
SM-13 a5	0.01	6.37	0.01	5.91	0.01	2.82	0.34	3.96	0.76	3.2	4.2	0.7	8.9	0.7	e
SM-14 a1	0.06	2.60	0.03	2.71	0.06	2.44	0.55	3.70	0.68	8.9	13.0	1.5			e
SM-14 a2	0.03	3.33	0.02	3.21	0.07	2.44	0.39	3.70	0.56	6.4	11.4	1.7			
SM-14 a3	0.05	2.66	0.03	2.70	0.10	2.48	0.32	3.70	0.59	6.8	11.4	1.6			
SM-14 a4	0.02	4.41	0.02	3.66	0.05	2.62	1.11	3.70	0.61	3.4	5.7	0.9			e
SM-14 a5	0.04	3.07	0.02	3.59	0.07	2.53	0.41	3.70	0.73	7.1	9.7	1.1			
SM-14 a6	0.07	2.25	0.05	2.10	0.09	2.43	2.20	3.70	0.79	6.5	8.3	0.7	10.8	0.6	e
SM-15 a1	0.04	2.72	0.04	2.44	0.18	2.41	2.39	3.70	0.71	3.5	5.0	0.5			
SM-15 a2	0.11	1.82	0.05	2.33	0.12	2.42	0.39	3.70	0.66	12.2	18.4	2.1			e
SM-15 a3	0.04	2.92	0.04	2.60	0.17	2.41	0.82	3.70	0.64	3.7	5.8	0.7			
SM-15 a4	0.46	1.26	0.16	1.85	0.77	2.41	0.62	3.70	0.76	11.1	14.5	1.2			e
SM-15 a5	0.03	3.24	0.03	2.87	0.08	2.50	0.51	3.70	0.61	4.0	6.5	0.9			
SM-15 a6	0.08	2.13	0.07	2.16	0.17	2.42	2.56	3.70	0.69	4.8	7.0	0.8	6.1	0.4	
SM-16 a1	0.27	1.33	0.09	1.96	0.09	2.43	3.15	3.70	0.71	16.6	23.5	2.3			
SM-16 a2	0.90	1.01	0.36	1.82	0.28	2.41	1.98	3.70	0.73	16.9	23.2	2.1			
SM-16 a3	0.25	1.56	0.12	1.87	0.18	2.41	0.37	3.70	0.72	12.5	17.3	1.6			e
SM-16 a4	0.01	6.40	0.01	7.86	0.06	2.46	0.28	3.70	0.75	3.3	4.3	0.7			e
SM-16 a5	0.14	1.77	0.18	1.84	0.03	2.52	1.03	3.70	0.76	6.0	7.9	0.7			
SM-16 a7	0.04	3.25	0.09	1.90	0.07	2.44	0.55	3.70	0.69	3.1	4.4	0.5			e

[a]Amount of helium is given in nano-cubic-cm in standard temperature and pressure.

[b]Ejection correction (Ft): correction factor for alpha-ejection (Farley et al., 1996; Hourigan et al., 2005).

[c]Uncertaintiy of the single grain age is given as 2 sigma in % (or in Ma) and it includs both the analytical uncertainty and the estimated uncertainty of the Ft.

[d]Average ages for totally reset samples were calculated as the unweighted arithmetic mean.

[g]Uncertainty of the sample average age is 2 standard error, as (SD)/(n)1/2; where SD=standard deviation of the age replicates and n=number of age determinations.

[f]Ages with a substantial first He re-extract (>4%) and/or a total analytical error of >10% have been excluded. Outliers on the [He]–P plot have also been excluded (Vermeesch, 2008).

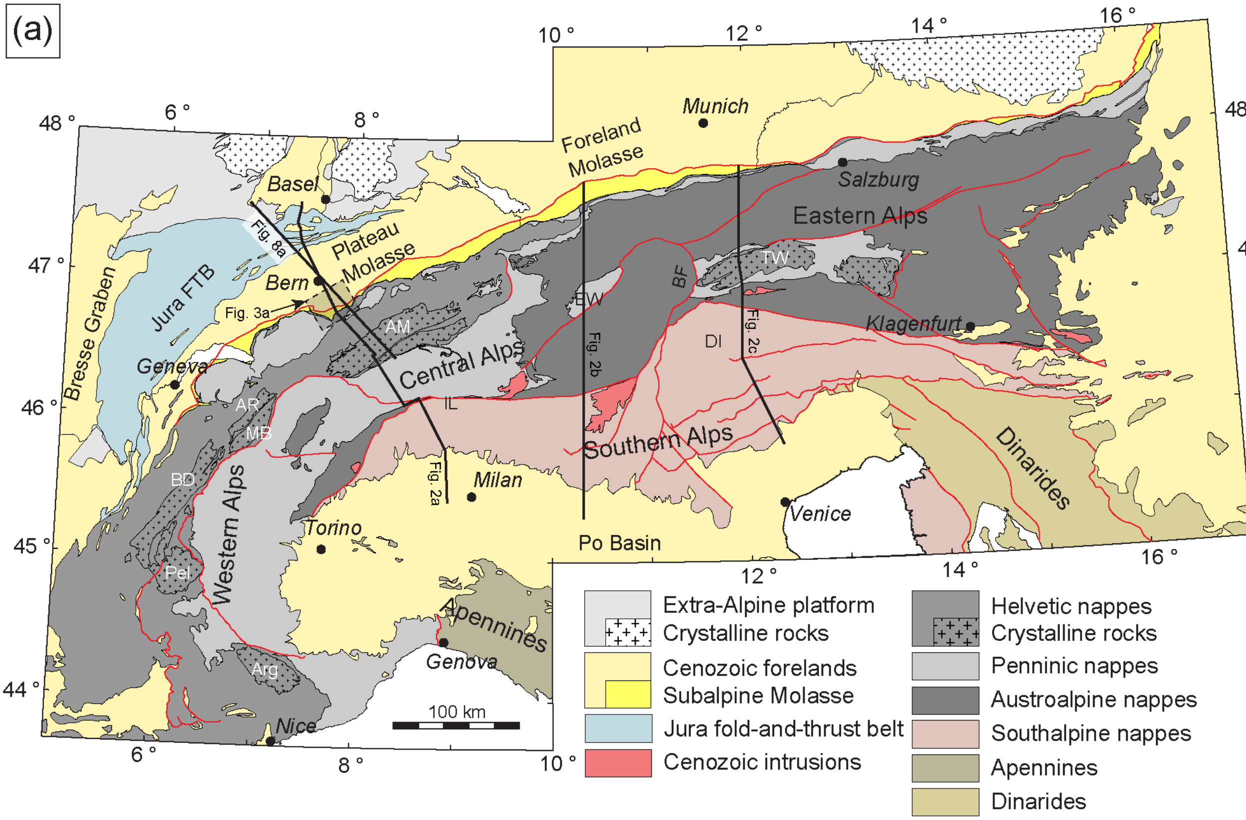

Fig. 1 (a) Tectonic map of the European Alps and its foreland basins (adapted from Schmid et al., 2004). Traces of the cross-sections in Fig. 2 and Fig. 8a are given as bold black lines. The sample area south of Bern (Fig. 3a) is denoted by a dashed rectangle. AM, Aar Massif; AR, Aiguilles-Rouges Massif; BD, Belledonne Massif; BF, Brenner Fault; DI, Dolomite indenter; EW, Engadine Window; FTB, fold-and-thrust belt; IL, Insubric Line; MB, Mont-Blanc Massif; Pel, Pelvoux Massif; TW, Tauern Window

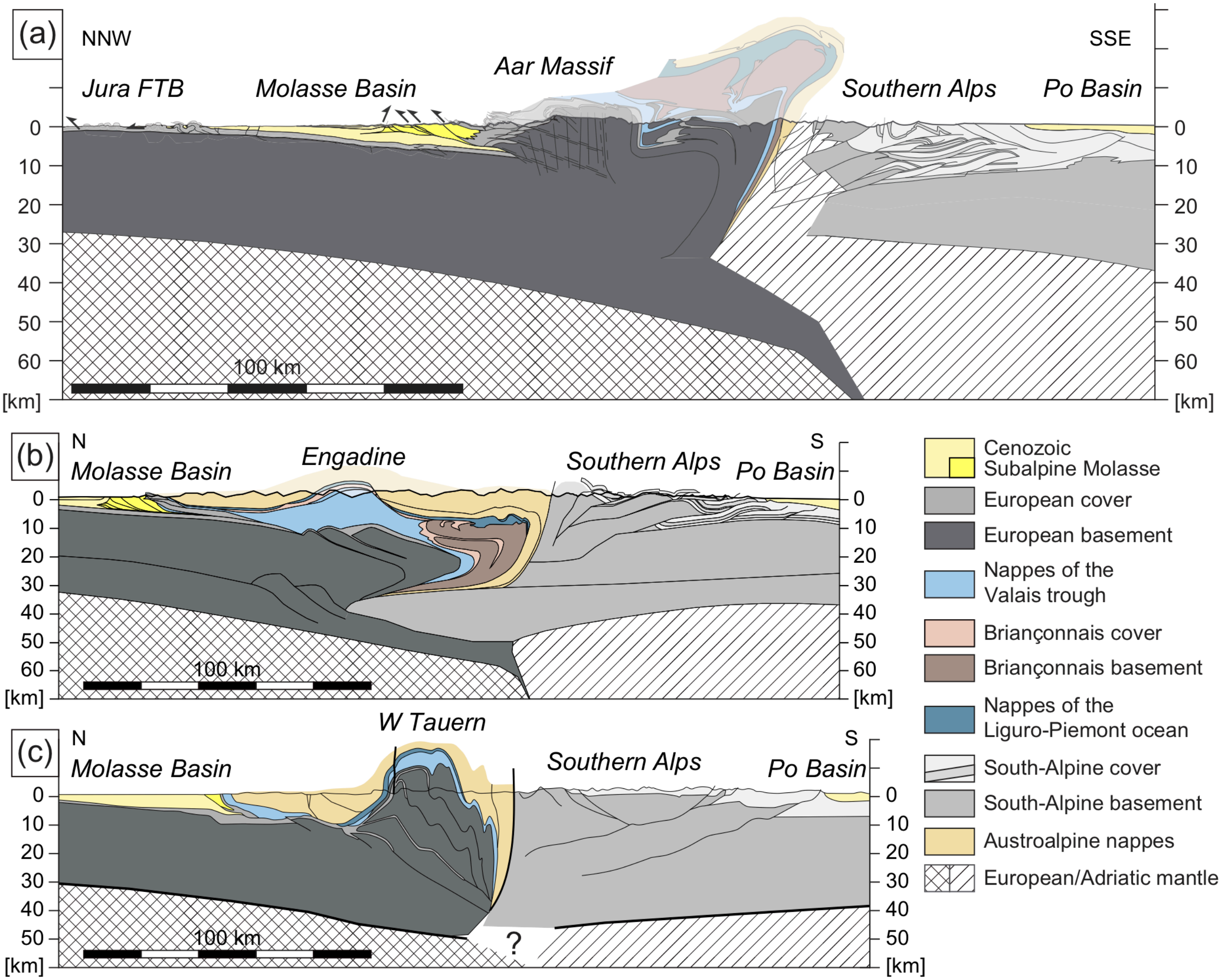

Fig. 2 Cross-sections through the Alps. (a) Jura - Plateau Molasse - Aar Massif (compiled from Buxtorf, 1916; Herwegh et al., 2017; Mock and Herwegh, 2017; Pfiffner, 2009; Rosenberg and Kissling, 2013). (b) Engadine Window (adapted from Rosenberg et al., 2015). (c) Western Tauern Window (adapted from Rosenberg et al., 2015).

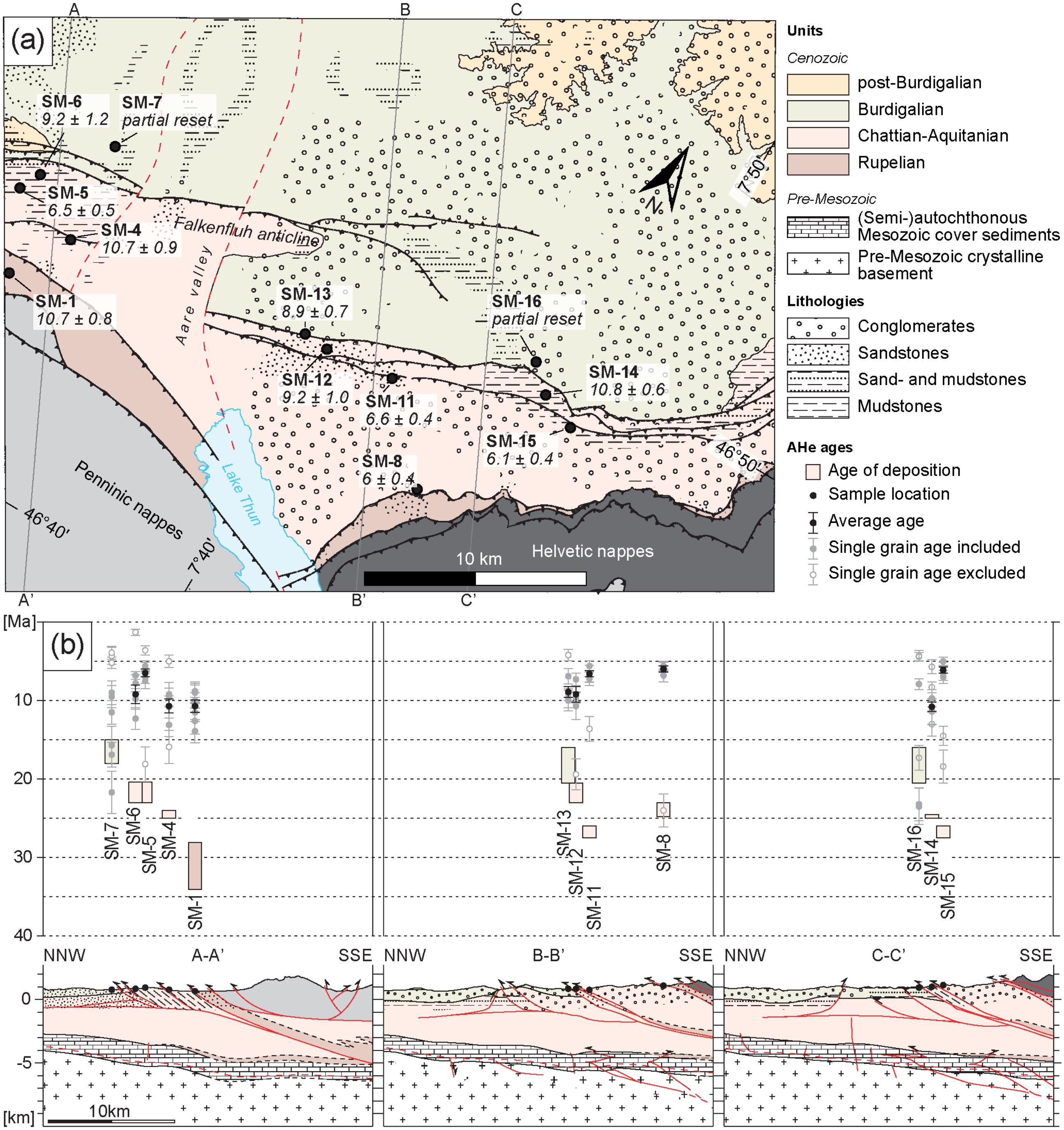

Fig. 3 (a) Litho-tectonic map of the Lake Thun area showing sample locations and corresponding average apatite (U-Th-Sm)/He (AHe) ages. Traces of cross-sections A-A', B-B', and C-C' in Fig. 3b are given as black lines. The location of the sampling area is shown as a dashed rectangle in Fig. 1. Note the arrow indicating north. (b) Cross-sections through the sampling area west (A-A') and east of the Aare valley (B-B' and C-C'), showing single grain and average AHe ages

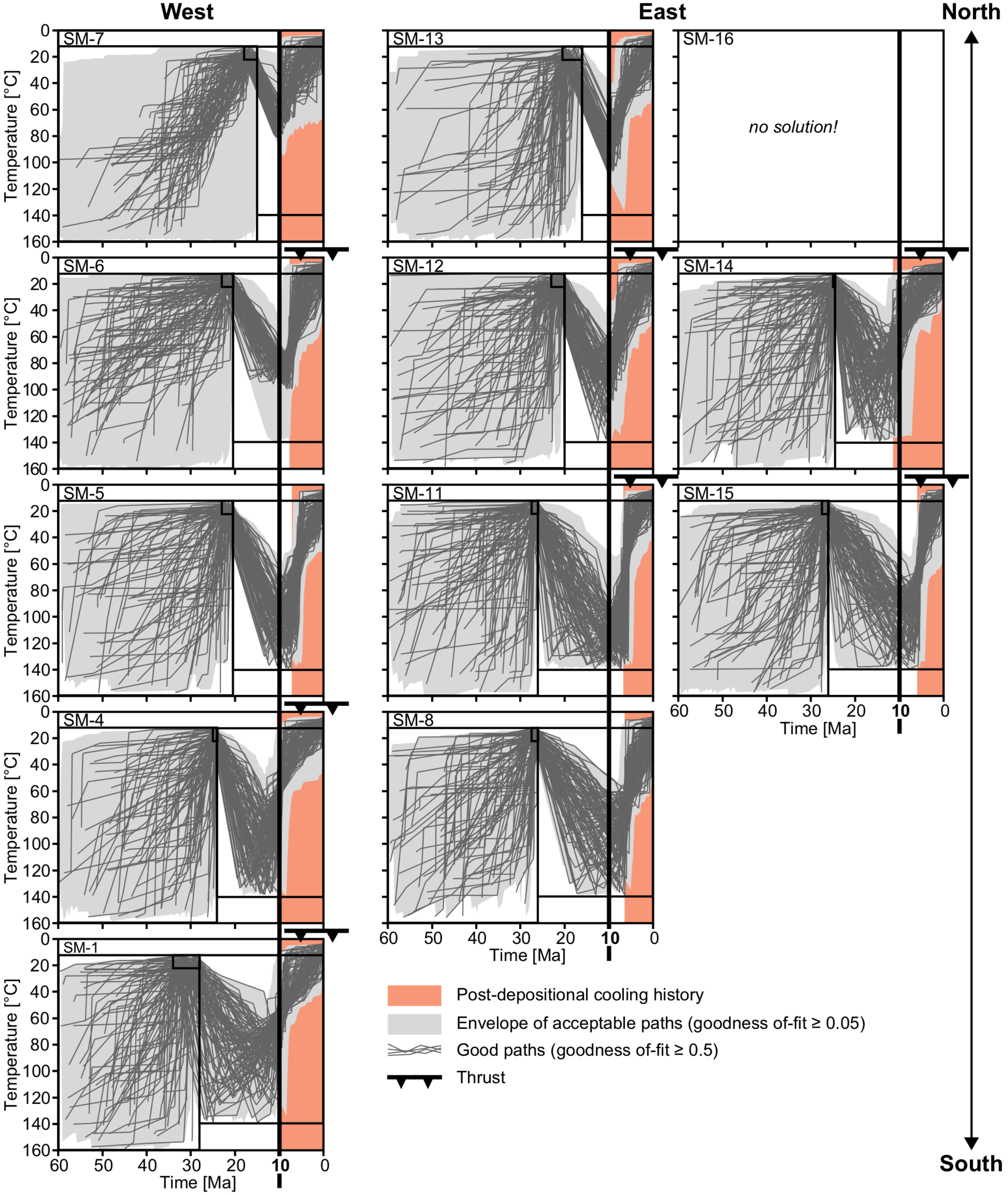
West
East
North
South
SM-7
SM-13
SM-16
no solution!
SM-6
SM-12
SM-14
SM-5
SM-11
SM-15
SM-4
SM-8
SM-1
Temperature [°C]
Time [Ma]
Post-depositional cooling history
Envelope of acceptable paths (goodness of-fit ≥ 0.05)
Good paths (goodness of-fit ≥ 0.5)
Thrust

Fig. 4 Thermal evolution of samples. The results from inverse modeling of apatite (U-Th-Sm)/He (AHe) ages with the HeFTy software (Ketcham, 2005) show the time-temperature history of the samples discussed in the text. Modeling constraints are shown as black boxes. The bold black lines at 10 Ma serve as a visual time reference. The thermal histories for the different samples are aligned from north to south and from east to west according to their sample location

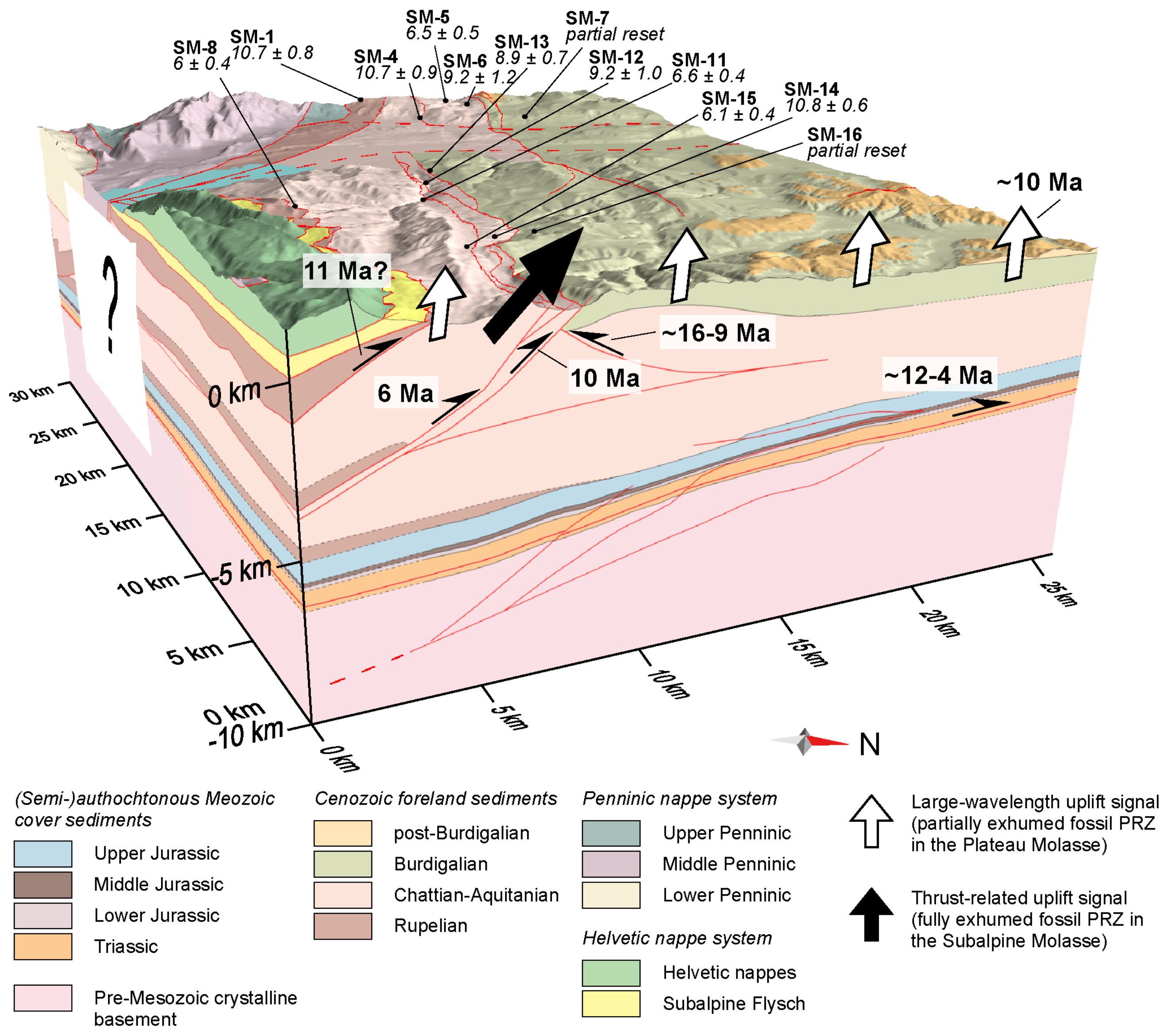

Fig. 5 Block model of with sample locations and corresponding average (U-Th-Sm)/He ages. The construction of the block model is based on surface (Beck, 1945; Haus, 1937; Jordi, 2012; Rutsch, 1947; Schlunegger et al., 1993, 1997) and subsurface (2D seismic interpretation; Mock and Herwegh, 2017) geological information. PRZ, partial retention zone

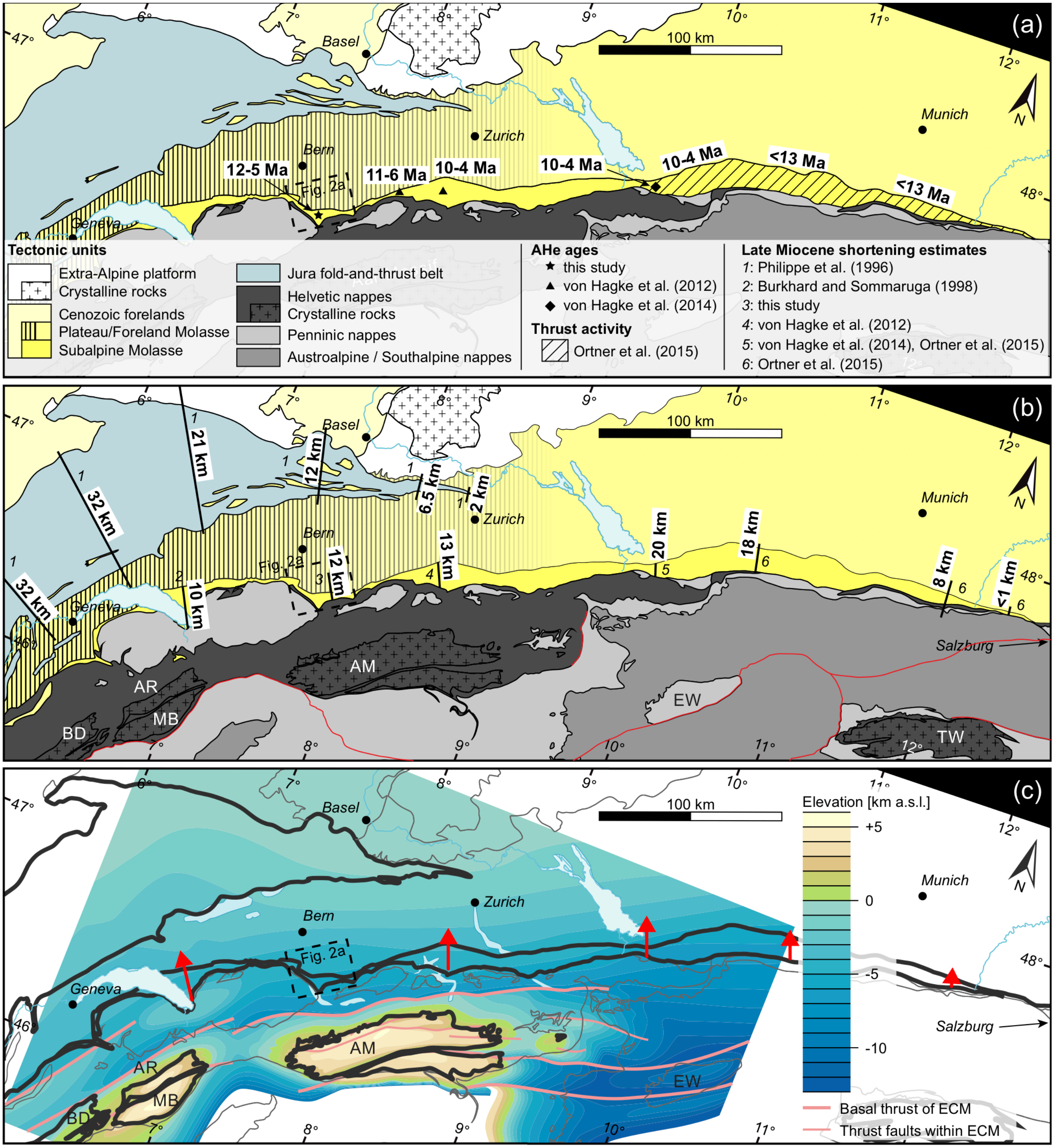
(a)
Basel
Zurich
Bern
Geneva
Munich
100 km
N
Fig. 2a
12-5 Ma
11-6 Ma
10-4 Ma
10-4 Ma
10-4 Ma
<13 Ma
<13 Ma
Tectonic units
Extra-Alpine platform
Crystalline rocks
Cenozoic forelands
Plateau/Foreland Molasse
Subalpine Molasse
Jura fold-and-thrust belt
Helvetic nappes
Crystalline rocks
Penninic nappes
Austroalpine / Southalpine nappes
AHe ages
this study
von Hagke et al. (2012)
von Hagke et al. (2014)
Thrust activity
Ortner et al. (2015)
Late Miocene shortening estimates
1: Philippe et al. (1996)
2: Burkhard and Sommaruga (1998)
3: this study
4: von Hagke et al. (2012)
5: von Hagke et al. (2014), Ortner et al. (2015)
6: Ortner et al. (2015)
(b)
32 km
32 km
21 km
12 km
6.5 km
2 km
10 km
12 km
13 km
20 km
18 km
8 km
<1 km
Salzburg
AR
MB
BD
AM
EW
TW
(c)
Elevation [km a.s.l.]
+5
0
-5
-10
Basal thrust of ECM
Thrust faults within ECM

Fig. 6 Along-strike variations in late Miocene deformation of the North Alpine foreland between Lake Geneva and Salzburg. (a) Tectonic map (modified from Schmid et al., 2004) and activity of thrusting in the Subalpine Molasse deduced from AHe ages and geological interpretation. (b) Tectonic map (modified from Schmid et al., 2004) and estimated amount of late Miocene shortening in the North Alpine foreland (i.e., Subalpine Molasse, and Jura FTB). Estimates from the Subalpine Molasse record minimum shortening. (c) Top basement map of the Central Alps (modified from Pfiffner, 2011) showing the highly non-cylindrical hinterland architecture with the high relief domains of the External Crystalline Massifs (ECMs). Red arrows indicate the constant late Miocene deformation signal with a slight decrease in horizontal shortening recorded in the North Alpine foreland. AM, Aar Massif; AR, Aiguilles-Rouges Massif; BD, Belledonne Massif; EW, Engadine Window; MB, Mont-Blanc Massif; TW, Tauern Window

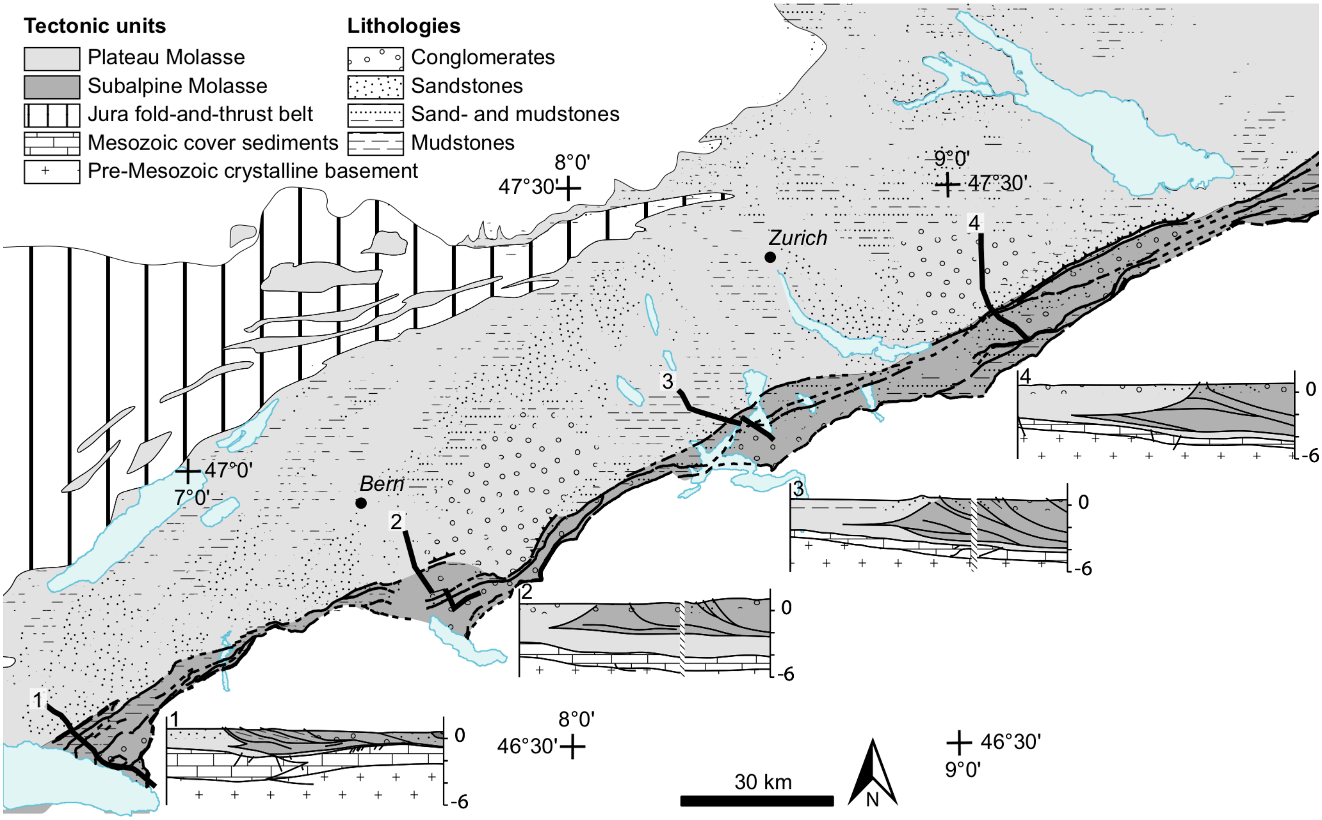

Fig. 7 Litho-tectonic map of the Swiss Molasse Basin (modified from Landesgeologie, 2005). Cross-sections 1-4 are based on 2D seismic interpretation (cross-section 2, Mock and Herwegh, 2017; cross-sections 1, 3, and 4, Sommaruga et al., 2012)

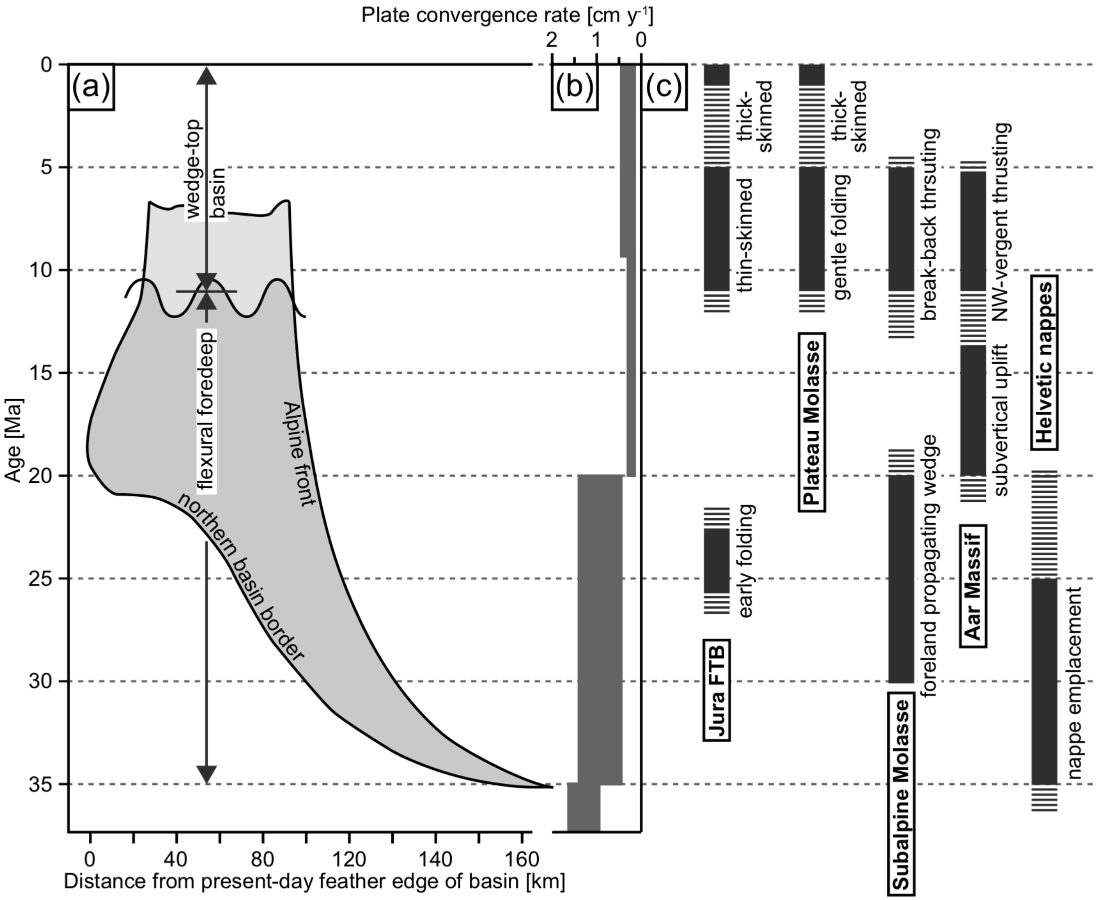

Fig. 8 Oligocene to present-day evolution of the northern Central Alps. (a) Temporal evolution of the Molasse Basin architecture (adapted from Schlunegger and Kissling, 2015). The location of the section is given in Fig. 1. (b) Rates of plate convergence between Adria and Europe (Handy et al., 2010; Schmid et al., 1996). (c) Tectonic evolution of the major tectonic units of the northern Central Alps. FTB, fold-and-thrust belt

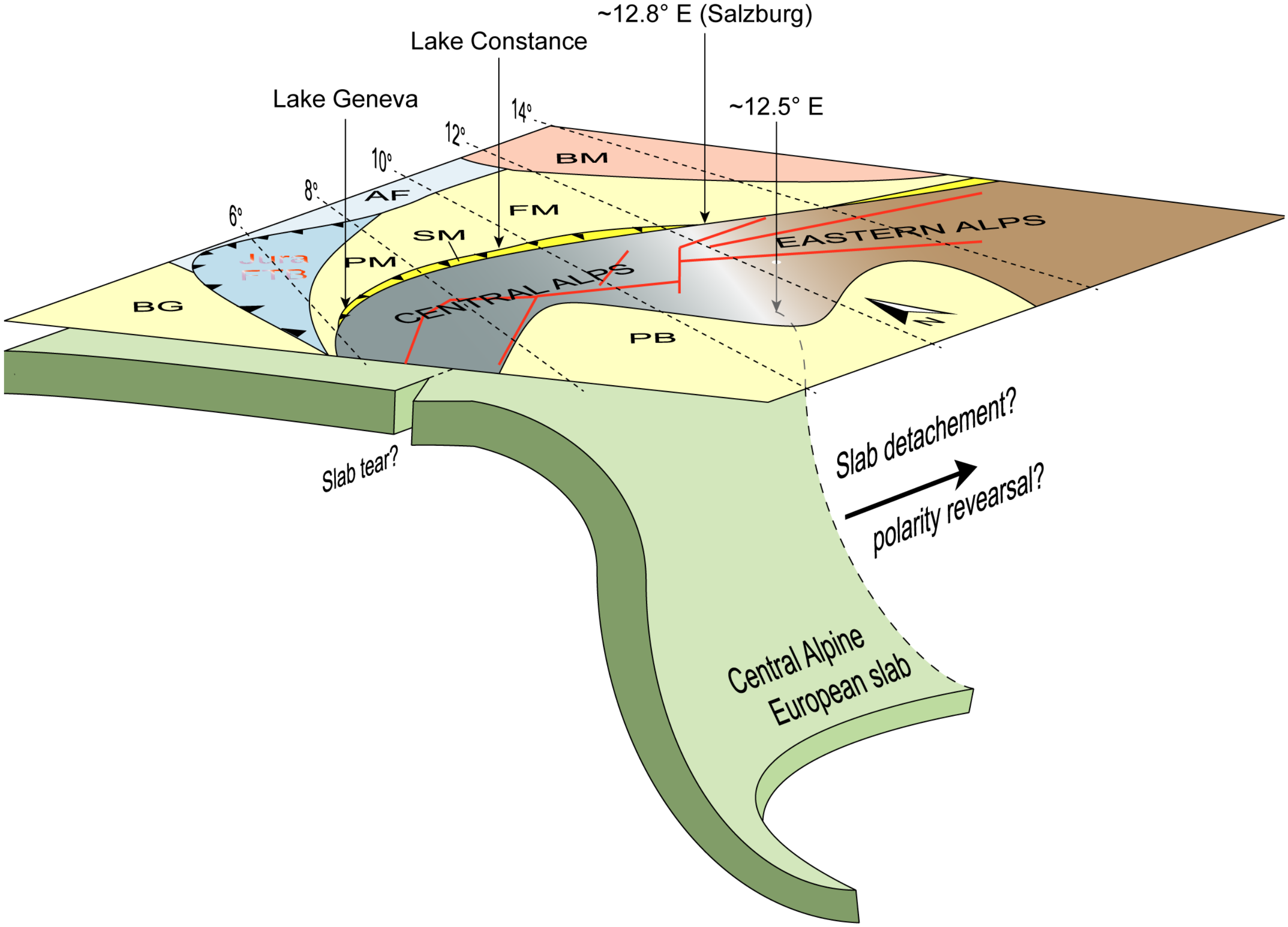

Fig. 9 Schematic 3D representation of the structure of the Central Alpine European slab and its spatial correlation with the eastward termination of the late Miocene Subalpine Molasse near Salzburg. PM, Plateau Molasse; FM, Foreland Molasse; SM, Subalpine Molasse; PB, Po Basin; TW, Tauern Window; BF, Brenner Fault; FTB, Fold-and-thrust belt; BG, Bresse Graben; AF, autochthonous foreland; BM, Bohemian Massif.