Author response to comments of Reviewer 2 on "*Interactive comment on* "Contrasting exhumation histories and relief development within the Three Rivers Region (Southeast Tibet)" *by* Xiong Ou et al. "

We thank reviewer Massimiliano Zattin for his constructive and helpful comments. Below, we respond to the reviewer's line-by-line comments (response indented, line numbers in red mark the modifications in revised manuscript).

Line by line comments:

Lines 52-54. The age range for this rapid exhumation event is very large (from 20 and 60 Ma). I do not think that it is possible to talk about a single "phase" as more than one could have been taken place in a single region.

> The phrase will be changed to "Other thermochronologic studies have also provided evidence for earlier phases of rapid exhumation, the timing of which varies regionally between 30 – 20 Ma in the Longmenshan (Wang et al., 2012; Tan et al., 2014), to 40 – 30 Ma in the Yalong thrust belt (Zhang et al., 2016) and ~60 – ~40 Ma in the BaimaXueshan massif (Liu-Zeng et al., 2018). The latter has been linked to uplift of the Southeast Tibetan plateau, consistent with paleo-elevation data implying that the plateau has been close to its present-day elevation since the Late Eocene - Oligocene (Hoke et al., 2014; Li et al., 2015; Wu et al., 2018)." (line 56-60)

Lines 75-78. As it is written here, it is not clear if the role of tectonics in the exhumation of Kawagebo is derived from literature or is one of the output of this work. I would better specify which are the goals of the paper.

> Replumaz et al. 2020 have shown that exhumation was so rapid in the Kawagebo that it implies tectonic forcing. They speculate a local fault underlying the Kawagebo massif, which has not been observed in the field. In our study, by using the same data, we explore this hypothesis and could constrain the geometry of this fault. It is one of the specific goals of this paper to determine the geometry of the fault along the Mekong, but also to examine the influence of Mekong incision on exhumation, by doing more complex modeling of published data using Pecube.
>
> This will be clarified by adding: "The Kawagebo massif is thought to have been rapidly exhumed recently (<10 Ma) due to motion on a local thrust fault in a restraining bend between two regional-scale strike-slip faults (Replumaz et al., 2020, Fig. 1b, 1c)" (line 80-82)

Figure 1. Separation of AFT and AHe ages in two separate maps is good in terms of readability but it forces to move from one figure to the other to have a complete picture of exhumation ages. Is it not possible to merge all the ages in a single map?

> We separate AFT from AHe ages because they do not convey the same information: the AHe map shows more clearly the Miocene rapid exhumation phase where AHe ages are <15 Ma, while the AFT map shows very clearly the relict surfaces where AFT ages are >50 Ma. Furthermore, a map with both AFT and AHe ages is shown in the new figure 9 (previous figure 7).

Line 85 (caption of figure 1). Why grey outlines? I see only black lines around these surfaces.

> It was grey lines on Figure 1b to show the same relict surfaces as in Figure 1c. But we made them black as in Figure 1c and will modify the legend as: "Black outlines delimit low-relief relict surfaces with relief <600 m, as mapped by Clark et al. (2006)." (line 93)

Line 103. The name "AilaoShan fault" is not in the map. Moreover, the "Red River" marks a fault and not a river.

The name “Ailaoshan fault” will be replaced by “Ailaoshan-Red River shear zone” and it will be added in Figure 1a, together with “Red River”. To be clearer, we will modify as following: “From the late Eocene to the early Miocene, the dominant driver of deformation in SE Tibet was the extrusion of the Indochina block along the left-lateral AilaoShan-Red River shear zone following the Red River (Fig. 1a), subsequently inverted along the right-lateral Red River fault since ~5-10 Ma (Leloup et al., 1995, 2001; Replumaz et al., 2001; Fyhn and Phach, 2015) (Fig. 1b).” (line 114-117)

Line 107. This sentence is not related to the previous one as they deal with very different topics. So, why "in contrast"?

The timing of the uplift of the plateau is not well constrained when comparing to the timing of the extrusion.

To be clearer, we will modify line 107 as follow: “Compared to the timing of extrusion, no clear estimation for the timing of plateau uplift in the Three Rivers Region has been obtained.” (line 119-120)

Lines 108-111. This sentence is not well connected to the previous ones. In general, this paragraph appears as a collage of sentences with no clear relationships between them.

This paragraph presents the deformation history since Late-Eocene, focusing on the most important studies who show significant uplift phases in different zones across or near the Three Rivers Region. In the discussion part, we compare them with our modelling results, showing that none of these phases has been recorded as exhumation phases by the thermochronology dataset.

To be clearer, this paragraph will now read: “Rapid sediment filling of the Jianchuan basin (Fig. 1b), located downstream of the Three Rivers Region, around 37-35 Ma demonstrates significant erosion and suggests uplift in the source region just predating extrusion (Gourbet et al., 2017). The Jianchuan basin subsequently experienced significant exhumation along thrust faults between ~28 and 20 Ma (Cao et al., 2019), suggesting regional uplift at that time.” (line 120-123)

Line 112. How can a shear zone join a river? Furthermore, the AilaoShan-Red River shear zone is not marked in the map of figure 2a.

The Ailaoshan-Red River shear zone is prolongated along a Jurassic red-wine colored clastic formation, which is intensively sheared and roughly follows the Mekong river, as shown and discussed in Replumaz et al. (2020).

We will re-write the sentence as following: “the AilaoShan-Red River shear zone is prolongated along a distinctive and intensively sheared Jurassic red-wine coloured clastic formation, following the Mekong River”. (line 124-125)

We will mark the ASRRSZ on Figure 1a, 2a. (as shown in the answer to the comment of Figure 2a below)

Lines 116-118. The only Eocene deposits visible in map of fig. 2A are located east of the city of Deqing. Is it just a matter of scale? In the text you describe “several thrusts affecting Eocene basins”.

There are, indeed, only 3 Eocene basins on the map of Figure 2a. Other Eocene basins located further to the north or south of the Three Rivers Region could not be shown; the most emblematic one is the Jianchuan basin (Fig. 1), located south of the map of Figure 2, and also affected by thrusts (Cao et al 2019).

Figure 2A. There is a thin red line in the top of the map, nearly parallel to the Yangtze river, that is probably not correctly drawn. In the legend, check the word “Eocene”. The colors of Triassic Yidun and Qiangtang formations are very similar

All those will be corrected in figure 2A.

Line 153. “. . .of the onset of this rapid exhumation phase”. Are you referring to the 8 Ma or 1.5 Ma step?

We are referring to the exhumation since 8 Ma here. The sentence will be changed to “Quantitative time-temperature inversion of the Kawagebo ages suggests rapid exhumation since at least 8 Ma, with no clear estimate of the onset timing, and followed by an acceleration after ~1.5 Ma (Replumaz et al., 2020).” (line 162-164)

Lines 155-156. Which structure? The stepover? Actually it is defined by faults and I see that these faults have been mapped and here described.

This structure refers to the local thrust fault in a restraining stepover between two dextral faults. The sentence will be changed to “However, this local thrust fault, inferred to be related to reactivation of regional north-south trending thrusts, has not been documented in the field.” (line 166-167)

Line 158. What do you mean with "collision period"? Tectonics here was changing through time so, for example, the Eocene is marked by extensional basins.

Collision, in the context of the Tibetan Plateau, refers to the Indian-Eurasian continent collision, which is ongoing since ~55 Ma and continuously set the fundamental tectonic regime for SE Tibet, even though local-scale extension is recorded during the Eocene.

The sentence will be changed to “Therefore, additional work is needed in this region to resolve the exhumation history of the low-relief mean-elevation BaimaXueshan and the high-relief high-elevation Kawagebo massifs during the India-Asia collision period, in order to distinguish the effects of regional plateau uplift, incision of the Mekong River, and uplift along local tectonic structures.” (line 167-169)

Lines 186-187. The second part of the sentence is not very clear. Can you better explain the meaning of "transition times"?

Transition time is a term used in Pecube modeling to represent the timing between two exhumation phases.

A phrase will be added to explain this concept: “Different transition times mark the timing of exhumation or topographic changes between any two different phases.” (line 189-190)

Table 1. It is not clear if the references are related to the left or the right parameters. Or both?

In this table, parameters without references are default values from Pecube, but to avoid confusion, we will add Braun et al. (2012) and Chen et al. (2014) as reference for them.

Lines 222-223. This conclusion is referred to the steady-state scenarios only? Or is it more general?

Yes, this only refers to those steady-state scenarios with three thermochronometers. The models with three thermochronometers and different exhumation phases are designed to decipher the exhumation history since 110 Ma, trying to reveal the important exhumation phases regionally observed during India-Asia collision. But, surprisingly, none of these regional tectonic events has been recorded in our modelled exhumation history. That’s why we conclude that BaimaXueshan only experienced a single rapid exhumation phase since ~7 Ma.

Lines 230-232. I agree on the focus on AHe and AFT but... what happens if you exclude the ZHe data also in the previous scenarios? Such a change in the input data could have relevant effects on the outputs?

The ZHe ages in BaimaXueshan are all >75 Ma, showing that those samples must have been exhumed at a very slow rate before the recent rapid exhumation phase (<7 Ma). They therefore do not influence much the young exhumation phase deduced from AFT and AHe ages.
We will modify the sentence to clarify that: "We finally tested a plateau scenario, including both regional rock uplift and incision, fitting only the AHe and AFT ages younger than 22 Ma to concentrate on the Neogene history, considering that the steady-state models, including the old ZHe ages, adequately predict the early history." (line 236-238)

Lines 289-290. Why since 10 Ma?

We choose to start our modelling at 10 Ma, because the maximum ZHe age, considering the error bar, is ~9 Ma, and allowing a predicted age slightly older than it, as observed for the Baimaxueshan (Fig. 3b).

Line 299. Given the dipping angle, I would not use the term "thrust" for this fault.

Indeed, in this tectonic scenario with a simple planar fault (one-segment), the dipping angle is 85°, we will change it to reverse fault in this paragraph. (line 287-290)

Figure 5. I am a bit confused... Each arrow yields a color which should be related to an exhumation rate... but is this figure associated to a specific time? In fact, here you write about the presence of different exhumation phases.

In Pecube, the velocity field over a fault is constant during one phase of exhumation, so Figure 5 is valid between 1.5 and 0 Ma. This will be clarified in the legend of Figure 5 as following: "The arrows show velocity field generated by movement along the fault, during the rapid exhumation phase, since 1.5 Ma;" (line 318-319)

Lines 345-350. I am not sure that this sentence is correct as your model is starting at 22 Ma. All the events cited here are occurring mostly before 22 Ma.

This part discusses the steady-state scenario including three thermochronometers since 110 Ma, where deformation phases before 7 Ma could not be revealed in exhumation history of BaimaXueshan. The modelling of Neogene history since 22 Ma is discussed in the following paragraph.

Modification will be made to clarify it in the beginning of this paragraph: "For the BaimaXueshan massif, east of the Mekong River, our best-fit model, exploring the exhumation history since 110 Ma, shows rapid regional exhumation at a rate of 0.42 km/Myr since ~7 Ma, succeeding a phase of slow regional exhumation at a rate of 0.04 km/Myr before that." (line 331-333)

Line 352. So the paragraph above is related to the models starting before 22 Ma? This is not very clear. But, if this is true, why are you discussing the models starting before 22 Ma if you write that these are not resolving well the dataset?

One of our first conclusion is that the uplift phases before 7 Ma during the India-Asia collision is not expressed by the exhumation history of the BaimaXueshan massif. The age reconstruction shows that this model resolves relatively well the overall dataset covering a 110 Ma history. The Neogene history with young AHe and AFT ages since 22 Ma is dedicated to explore the recent exhumation and Mekong river incision.

Line 368. This is not the definition of "relict surface" or, better, its definition should not be related to time of collision (Clark et al. do not give any definition like that).

Clark et al. (2005) defined relict surfaces as "remnants of a paleo-landscape that was formed at low elevation and subsequently uplifted" implying low exhumation rate during the collision. Our compilation of thermochronological ages and our modelling results lead us to add the age constraint (AFT >50 Ma) to define a low-relief surface as a relict surface. A surface with younger AFT ages should have experienced significant exhumation during the collision, such as the Baimaxueshan.

We will add a precision to the text: "We conclude that a relict surface *sensu-stricto*, i.e., remnant of a paleo-landscape that was barely affected by exhumation during India-Asia collision (Clark et al., 2005), should show AHe ages older than 50 Ma, and that not all low-relief surfaces in southeast Tibet can be classified as a relict surface." (line 361-364)

Lines 385-386. Actually there are not so many data between the Parlung fault and the Longmucuo-Shuanghu suture and young ages are widespread also more to the south and to the north.

Many existing studies focus on the Eastern Himalayan Syntaxis or neighbouring regions, but ages are more or less well spread over the entire region. To first order, our correlation between an elevation contour of 5000 m and the rapid uplift phase since at least 10 Ma in and around the EHS, marked by AHe ages <15 Ma and AFT ages <50 Ma, is valid. Most young ages to the northeast of the suture are either due to supplementary local tectonic exhumation, such as close to the Litang fault, or strong river incision, with AHe ages <15 Ma along the Yangtze River.

Line 388. Define the acronymn EHS.

EHS stands for Eastern Himalayan Syntaxis, as defined in line 11.

Lines 390-391. An extrapolation of the present-day velocity field to 10 Ma ago can be chancy. On the other hand, if your results are coherent with the present-day velocity field, you can infer that plate kinematics has not changed since then.

There is no extrapolation of the present-day velocity field, which is measured on very different time scale from our modelling. We just use the GPS data to show the present velocity field related to the ongoing indentation of India on a much wider scale across Tibet than our modelling.

Line 395. Not sure about the use of "far-field" as this area is along the border of EHS.

We remove the word far-field, and modify the sentence as: "Moderate uplift along those thrusts could be due to the distance from the EHS, with a west-to-east gradient of decreasing exhumation and erosion rates across the Three Rivers Region (Yang et al., 2016)." (line 395-397)

Line 413. What do you mean with "since 10 Ma at river level"?

Both the amount of tectonically controlled exhumation and the amount of river incision are spatially variable; the former is controlled by the modelled geometry of the fault and the latter depends on the modern elevation. In order to clarify this, the phrase will be changed as follows: "The average topographic lowering due to river incision at the elevation of the samples is ~2 km, accounting for ~25% of the total exhumation of the massif (Fig. 7)." (line 414-415)

Lines 424-426. Your model is clearly designed to verify the amount of tectonic exhumation along a thrust and the results to confirm that this model is working well. Furthermore, no acceleration of exhumation since 1.6 Ma is occurring in the BaimaXueshan massif. As a whole, these data seem to

indicate that glacial erosion, if present, was of minor importance. This is an interesting outcome that could be emphasized.

It's true that the recent acceleration of exhumation since 1.6 Ma of Kawagebo massif is not modelled in BaimaXueshan massif. But as discussed in line 369-379, we could not exclude the potential role of glaciation in the exhumation of BaimaXueshan, as numerous cirques, moraines and U-shaped valleys are observed across the massif. And until now, unfortunately, we could not quantify the contribution of glacial erosion on exhumation due to the limit of Pecube of not being able to model the glaciation processes.

Line 442. What do you mean with "postulated crustal geometries of fault"? Are you referring to the "black" faults or the active ones?

This refers to the active faults in red and will be clarified as follows: "Also shown are the crustal geometries of faults (in red) active in the last 10 Myr." (line 438)

Lines 454-456. Once again I would stress the fact that data and your modelling focus on the "young" (i.e. Neogene) part of the history. So I am not very sure that you can affirm that tectonic events were negligible before 10 Ma

The steady-state scenario of three thermochronometers since 110 Ma only resolves a rapid exhumation phase since 7 Ma, showing that the regional deformation phases, such as large scale motion on shear zones (34-17 Ma) and Eocene basin filling (37-35 Ma), have not been expressed in the exhumation history of BaimaXueshan.

This is our first conclusion in the discussion part, some modification will be made to clarify it: "For the BaimaXueshan massif, east of the Mekong River, our best-fit model, exploring the exhumation history since 110 Ma, shows rapid regional exhumation at a rate of 0.42 km/Myr since ~7 Ma, succeeding a phase of slow regional exhumation at a rate of 0.04 km/Myr before 7 Ma." (line 331-333)

Line 456. Can you put a number? Otherwise the meaning of "moderate" is ambiguous.

Yes, 0.25 km/My of exhumation will be added. (line 463)

Line 460. I would emphasize also the inferred acceleration at 1.5 Ma and the exhumation rates that jump to values higher than 1 km/Ma (one order of magnitude).

Yes, this will be added as following: "Total tectonically driven exhumation since ~10 Ma at a rate of 0.45 km/my, with an acceleration to 1.86 km/My since 1.6 Ma, is estimated to be 6.1 km, with incision of the Mekong River contributing only ~25% of the total exhumation." (line 467-469)