Salzburg, November 07th, 2019

Dear Wolfgang Schwanghart,

We resubmit a revised version of our manuscript “The destiny of orogen-parallel streams in the Eastern Alps: the Salzach-Enns drainage system” to consider for publication in Earth Surface Dynamics. First of all, we want to thank the reviewers Adam Forte and Paul Eizenhöfer for their detailed and very constructive reviews. We appreciate their effort, which helped us to strongly improve our manuscript. We addressed all raised issues and revised our manuscript according to the reviewers’ suggestions. Both reviewers considered our manuscript as a nice contribution to Earth Surface Dynamics and we are confident that the revised version of this manuscript meets the high quality standards of this journal.
Before going into the details of the point by point reply, we would like to emphasise the main modifications of the revised manuscript.

- On suggestion of Paul Eizenhöfer, we stripped down the method section to the equations crucial for our approach. Following both reviewers, we added a further clarification concerning the selection of baselevels for the χ transformation.
- We rearranged the discussion section 4.1 to address some ambiguities pointed out by Paul Eizenhöfer. This includes the expansion of the paragraph, which shows now clearly the limitations of the used methods. Therein, we focus on implications of asymmetric drainage divides on drainage divide stability and a new strategy to narrow down large scale effects on the drainage pattern.
- In section 4.2, we now apply the discussion about general limitations more focused on our results in the Eastern Alps. We additionally added and discussed the impact of horizontal advection (Paul Eizenhöfer) and / or variation in the precipitation pattern (Adam Forte) and clearly state why we consider the observed χ gradients as indicator for mobile drainage divides.
- We clearly state that we did not perform any reconstruction of the paleo drainage pattern based on topographic information, but imitated the plan view geometry of drainage patterns based on provenance analyses of previous studies. Further, we now point out in more detail, that χ-mapping does not explicitly require information on elevation and we hence refer to changing χ anomalies across divides for different catchment geometries.

Additionally, we slightly enhanced Figure 1 on suggestion of Adam Forte and added further annotations, i.e. knee shaped bends, T-shaped junctions and wind gaps within the Eastern alpine drainage system. We further performed slight modifications to the text for enhanced clarity and style.

Thank you very much for the editorial handling.

Sincerely in behalf of all co-authors,

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Response to Adam Forte (Referee 1)

We thank Adam Forte for his detailed and constructive review. We are happy that we could take up all of his suggestions to improve our manuscript. The review does not question our methods, results or interpretation. We addressed all points in the revised version of the manuscript.

I have completed my review of 'The destiny of orogen-parallel streams in the Eastern Alps: Salzach-Enns drainage system' by Trost et al. In this contribution the authors consider the stability of drainage divides in the Eastern Alps with a variety of metrics that have been recently proposed/codified and then consider the results of this with respect to the tectonic history of the Alps and expected future evolution of the drainage network. In doing so, they present an interesting new take on how to use some of these metrics and point out some important considerations for the applicability of these metrics (especially for the Gilbert metrics) especially in places with recent histories of glacial modification. I don't have a ton of comments and most of them are largely editorial (i.e. wording and such). I have one semi major point toward the end of the paper (which I think shouldn't be too hard to deal with and I hope will help to strengthen the applicability of what they discuss beyond this particular use case). Ultimately, I think this paper will make a nice contribution to Earth Surface Dynamics. **Reply:** *We are very pleased that you find our work interesting and important. It is very nice to hear that you consider our approach as a nice contribution to Earth Surface Dynamics. In the following, we will address all suggestions line by line:*

L37 – I think you can remove 'abundantly' here. **DONE**: *We removed 'abundantly'.*

L46 – Think 'conditions' not 'conditioning' might make more sense. **DONE:** *We changed the wording in the revised version of the manuscript as suggested.*

L75 – Add direction that material was extruded to help those without a lot of familiarity with the geography of the region. **DONE:** *As suggested, we added "to the east" in the revised version of the manuscript.*

L80-83 – Might be helpful to specifically mark the location of some of the features on a figure, maybe figure 1? Or as an inset? **DONE:** *We agree that it might be useful to annotate those features. We therefore added wind gaps, knee-shaped bends and T-shaped river junctions as annotations to Figure 1.*

L203 – Good to see consideration of the choice of base level, but could you maybe elaborate on specific rationales as to those choices? I.e. is there anything special about those, e.g. is 400 m approximately the elevation of the foreland as rivers exit the mountains? Something else? **DONE:** *The lower base level is set to 400 m, representing the outflow of the main rivers to the foreland. We added this note to the method section. The increase of base level up to 1000 m follows equal steps in order to narrow down the spatial impact of tectonics and climate. We added a short paragraph to the method section and discussed the advantages of the approach in more detail in the discussion section (see section 4.1 and 4.2).*

L304-306 – Might expand this to include references that address the extent to which spatial/temporal statistics of rainfall translate into spatial/temporal statistics of runoff which is related to the question of changes in channel geometry that you highlight here. **DONE:** *Maybe it was not a good idea to start the discussion about catchment sizes and discharges here. In the revised version, we pointed out more clearly that neither climatic data at geological timescales nor the theoretical concepts (would the stream power law in terms of maximum discharge look the same?) allow for taking into account climate seriously on this level. We therefore added: "Sharp contrasts in precipitation would require (i) a sequence of decrease, recovery, and decrease in precipitations rate in east-*

west direction and (ii) an inversion of the north-south contrast along a drainage divide (WS1), both at rather small scales." to the Discussion section 4.2.

L309-310 – Which was a primary conclusion of Forte & Whipple, 2018. **DONE:** *Thank you for pointing to that. We did not intend to claim the conclusion – We added the reference.*

L331-333 – This is an interesting approach (i.e. advocating for setting the base level just down stream of the channel heads for the χ calculation to isolate what is 'being felt' by the near divide portion of the channels). What comes to mind however is wondering if that is significantly different than (1) looking at the channel steepness of the area near the headwaters (with a 'base level' a little downstream of the channel head, a χ anomaly across a divide will mainly be a reflection of a difference in channel steepness directly downstream of the channel head, I think) or (2) the Gilbert metrics at a larger accumulating area (i.e. with this high base level χ value you're kind of taking the same approach as the Gilbert metrics to focus on what's happening near the divide, but in this case you're considering an area slightly bigger than what you were with Gilbert metrics because of the choice of threshold area for defining channel heads). This is not to imply that there is anything wrong with your approach (I rather like it!), just that I think to make this a more complete contribution, it would be good to consider if these other two would be equivalent or not (I'm definitely not sure they would give you the same answers, but my initial guess would be yes). **Reply:** *Thank you for this encouraging comment! You are absolutely right that all these approaches are similar in their spirit. It is all about some kind of slope and about how to measure it in such a way that it is still related to the erosion rate (and not limited by a critical slope) and not too strongly affected by noise of the DEM (the problem of the rivers with rather low channel slopes). We even did some experiments with your idea (1) some time ago. There we started at 1 km² catchment area and moved downward by a given increase in χ and measured the elevation vs. χ slope over this range. Theoretically, maybe even the best way to measure the headwater steepness index, but we found that the results had strong variation along drainage divides, so that across divide variations were hard to interpret - we did not publish it so far. The other idea, (2), would probably still have much weight on the upper part of the hillslopes as the relief of the river profile is much lower. We would therefore guess that we do not get rid of the problem that the relief of the uppermost part of the hillslopes might not be a good proxy for the erosion rate. So we would say that the race for the best topographic proxy of erosion rate is still open.*

L434-435 – It might be better to couch this in terms of 'glacially modified' mountain ranges instead of mid-latitude as (1) while certainly latitude is going to play a big role, moisture availability and detailed local climate will also control the extent of glacial activity and (2) your observations would generally be valid anywhere glacial modification of the landscape has been significant. If you choose to make this change, I would suggest similarly changing it elsewhere in the manuscript. **DONE:** *We agree that the main issue we tried to cover with "mid-latitude mountain ranges' is the glacial overprint. As you have already mentioned, the terming "glacially modified" includes the applicability of the approach to other mountain ranges. We therefore changed "mid-latitude" to "glacially modified" throughout the revised version of the manuscript.*

Figure 2 – This doesn't really matter and is just a point of clarification, but the χ values displayed on this map seem high if a reference area of 1 was used as is implied in the text. It seems more like a value of 1e6 was probably used? Doesn't change anything, but could be a point of confusion for some (if trying to replicate what you've done). **DONE:** *Thank you for pointing to that. Unfortunately, there was a typo in the methods section. We used for our calculations, as already assumed, a reference drainage area of 1 km². We changed the value of 1 m² to the correct value of 1 km² in the revised version of the manuscript.*

Response to Paul Eizenhöfer (Referee 2)

We thank Paul Eizenhöfer for thoroughly reviewing our manuscript and his constructive comments. Almost all raised issues are minor and we implemented his suggestions in a revised version of the manuscript. Some of the issues, including two points that – according to the reviewer – require more attention, originated from the fact that we have not expressed ourselves clearly enough. We are very confident that we solved the raised issues with clearer formulations and some additional explanations in the revised version of the manuscript.

The study by Trost et al. is centred on the characterisation of drainage divides along the Salzach-Enns drainage systems in the Eastern Alps, and how the geomorphology along these systems reflect the past Alpine tectonic and climatic evolution since Early Miocene. In their approach the authors employ state-of-the art geomorphic metrics, i.e. χ stream profile analysis, swath profiling along the divides and Gilbert metrics in order to determine the potential mobility of drainage divides. Their main conclusion describes a general eastward migrating trend for the drainage divides in the Eastern Alps mainly as a result of Mid-Miocene extrusion tectonics. In this sense χ stream profile analysis indicates a rather long-term trend whereas the Gilbert metrics are partially influenced by the last glacial maximum. The geomorphic analysis is very detailed and thorough appearing overall robust to me. In this review I found rather few minor issues regarding the general approach. The study is in line with recent studies on Alpine geomorphology, e.g. Robl et al. (2017) and Winterberg and Willett (2019). Thus, its conclusions are not surprising from a fundamental note but add an important link between long-term and short-term drainage reorganisation by comparing divide mobility through χ analysis and Gilbert metrics, respectively. I am convinced the manuscript will find wider interest in the Alpine geomorphology community as well as add new constraints on effects of the eastern Alpine tectonic and climatic evolution on major rivers in the region. I am listing below some mostly minor issues and suggestions that may aid in improving the current version of the manuscript. However, this list contains also points on two topics that may require some more attention. These are concerned with general clarifications regarding processes at geologic time scales and more detailed background on the nature of Figure 7. **Reply:** *We are pleased that you think our manuscript will add new constraints on the Eastern Alpine tectonic and climatic evolution. We appreciate that you find our method and results robust and detailed. In the following, we address the comments to mostly minor shortcomings of the manuscript line by line.*

Line 14 – Perhaps also provide a rough idea on the relative time scales at which catchment geometries, headwater and hillslopes are operating. **DONE:** *Yes, but this would indeed be only a very rough idea. Thank you for this interesting but definitely not trivial comment. For large catchments, it is clear that propagation of disturbances takes millions of years, but for hillslopes it depends on the considered model which is less clear than for fluvial incision. We therefore added: "covering time scales from millions of years to the millennial scale" in our revised version.*

Line 25 – This reconstruction of the drainage network appears very prominently here in the abstract and I kept wondering throughout the manuscript how the respective Figure 7 has been produced (including the 'palaeo- stream profile analysis'). Maybe this should be improved. Further below a more detailed comment on this. **DONE:** *In the abstract, we now state more clearly that these reconstructions are based on hypotheses on the location of drainage divides. We added: "drainage network geometries" to the abstract and explained our approach in some detail later in the manuscript.*

Line 30 – I think the phrasing might be somewhat misleading since 'link' also implies that the drainage system would also somehow influence climate and tectonics (I assume this was not meant this way here). In case it is meant as such I would regard this issue as rather controversial. See discussions on this in Willett et al. (2006) or

Schlunegger et al. (2007). **DONE:** *We changed the word order to "The drainage system of a collisional orogen is inherently linked to its tectonic and climatic evolution" in order to clarify this point, although we think the former formulation did not imply that the drainage system controls climate or tectonics.*

Lines 33-36 – Perhaps add works by Miller et al. (2007) and Willet et al. (2001) since horizontal advection is being mentioned here? Also, from a structural geologist's point of view I find the description on mountain formation and orogeny a bit too simplified. There is nothing itself wrong with a simplification. However, fault activity does play an important role in this study. Thus, I would perhaps include a more solid tectonic background here considering basic principles of structural geology. **DONE/Reply:** *Adding the two references about horizontal advection makes, of course, sense. However, we do not agree that fault activity plays such an important part in this study. As mentioned in the manuscript, it is definitely important for the large-scale drainage pattern, but this pattern itself is not a subject here. Our analysis of the drainage pattern only refers to drainage divides in the large-scale pattern. In the discussion section (4.1), we pointed out that our perhaps oversimplified explanation refers to the large scales only, while fault activity becomes more and more important at smaller scales. In general, we think that the simple orogen-scale view is a good tradeoff between an explanation for readers without a background in tectonics and keeps the focus of the study.*

Lines 40-42 – A recent study by Eizenhöfer et al. (2019) discusses the impact of horizontal advection on drainage systems in convergent orogens, which might be of some general interest in this field. **DONE:** *Thank you for pointing to this very recent work, which fits well to this section. We read the study with interest and will add the respective reference. However, during the lecture of your manuscript, we felt some potential for misunderstanding. To clarify our point: With the term 'horizontal advection', we do not refer to any ramp structures (and any possible gradients in uplift rate), but rather mean the process of lateral extrusion. As we do not go into details of the tectonic evolution of the Eastern Alps, but rather look at drainage geometries, we do also not specifically include features like the Sub-Tauern Ramp.*

Lines 48-49 – It is certainly correct that previous disturbances in a drainage system are erased after a knickpoint has traversed through it, but I would add that this also involves a time component needed for a knickpoint to reach the headwaters, which is not trivial, especially in glacially influenced parts of the Alps. **DONE:** *We agree that this is indeed not trivial if $n > 1$ in the stream power law. For $n = 1$, the horizontal velocity of knickpoints is always constant in the χ representation of a river profile, regardless to the topography. For $n > 1$, flat areas, as they occur in formerly glaciated valleys, indeed cause lower velocities. However, it seems to be impossible to add serious information on this here, except for mentioning a reasonable range (0.0001 – 0.1 m/year) derived from van Heijst and Postma (2001). We therefore implemented "The velocity of knickpoint migration depends strongly on different factors such as lithology, upstream drainage area, amplitude of baselevel drop, and sediment supply (Crosby and Whipple, 2006; Loget and Van Den Driessche, 2009) and ranges between 0.001 and 0.1 m/year (e.g. van Heijst and Postma, 2001)." in our revised version.*

Lines 50-52 – I might be a bit more cautious here since horizontal advection has been mentioned and is also present in the Eastern Alps. Horizontal advection causes an asymmetry across drainage divides in the direction of advection with the geomorphic characteristics listed here. However, in most cases the divide remains immobile despite the presence of a lateral advection component (see, for example, Miller et al., 2007; Eizenhöfer et al., 2019). **DONE:** *This is in principle true. The best solution is probably to start this point from the other side. This means that migration of drainage divides is usually reflected in an asymmetric shape. We therefore changed the wording to "Across-divide gradients in erosion rate (strictly speaking, in the rate of change in surface elevation) result in the migration of the respective drainage divide, or even to discrete river piracy events. The difference in erosion rate is usually reflected in an asymmetric topography where the drainage divide migrates from the steep towards the less steep side." In turn, asymmetry may indicate an unstable drainage divide, but there may also be other reasons,* *mainly variations in precipitation or lithology or advection. The discussion why we consider these as not very likely here could is now given in more detail in the discussion part (section 4.2).*

Lines 56-58 – I am convinced that major tectonic phases do influence drainage patterns but would add some time notion to ensure that the reader understands that these drainage patterns reflect events at geologic time scales. **DONE***: We agree that it is not obvious which time scale is meant by our description. We therefore added the term "long-term" to tectonic phases, as the duration of single events also differs in duration. In this way, we aim to distinguish between long-lasting deformation and short-tectonic events.*

Line 64 – Please add a rough time information on the onset of topography information in the Alps. **DONE:** *We added "Oligocene" as time marker in the revised version of the manuscript. We also included an appropriate reference (Handy et al., 2015).*

Line 73 – I suggest being more precise with the term 'fault tectonics' since this does theoretically also involve thrusting, normal faulting and/or displacement along a décollement. I assume you refer to extrusion tectonics here. **DONE:** *In the revised version, "fault tectonics" has been changed to "extrusion tectonics" to be more precise.*

Lines 84-86 – Perhaps briefly elaborate from a more geological point of view (here or better in the next section) why sediment provenance is consistent with the drainage systems here. **Reply:** *We refer to this point in the next section*

Lines 99-100 – The exhumation of the Tauern Window and the tectonics behind this process are still debated. Since this is not a major concern in this study, I would rephrase this sentence by moving away from a causal relationship and perhaps just state a coeval occurrence. **DONE:** *We agree that the formation of the Tauern Window is still under debate and the intention of this study is the general evolution of drainage patterns in the Eastern Alps and not the Tauern Window. We therefore rephrased the sentence to:" During Early to Middle Miocene times, lateral extrusion tectonics, confined by a set of crustal scale strike-slip and associated normal faults, started and rocks at the Tauern Window were exhumed rapidly."*

Lines 104-106 – Echoing my earlier comment on sedimentary provenance, I would be a bit more precise geologically in terms of location of sources (e.g., Austroalpine units covering the Tauern Window) and indicators that were used to identify provenance. **DONE:** *We added some more detail to the location of units in the reversed version of the manuscript: "The sedimentary record consists of characteristic rocks of surrounding Austroalpine units. Later, during Middle and Late Miocene, rocks from Penninic and Subpenninic units of the rising Tauern Window, which were previously overlain by Austroalpine units, occur in the sediments of the northern foreland basin."*

Line 113 – 'recent geological past' is a fairly vague term. Please be more precise regarding timing. **DONE:** *We specified the time range to Pleistocene.*

Section 2.1 – I do not think it is required to go into such detail here regarding χ transformation and/or the derivation of channel steepness since the equations shown here do not contain any modifications and/or update on already existing literature. I would simply describe their use and theoretical background and refer to the literature in order to keep this section short and focused. **DONE:** *We streamlined the recapitulation of the theory a bit and focused it on the aspect that we need – the relationship between the slope in the χ plot and erosion rates and how this can be used in χ mapping without considering profiles explicitly. However, we learned in many discussions with colleagues, that the interpretation of the χ transform and in particular of χ mapping is challenging, so that a short recapitulation of the theory behind χ in order to point to advantages / disadvantages and pitfalls should be given.*

This goes in line with the location of section 4.1 at the beginning of the Discussion (please see also our comment below) dealing with limitations of the method.

Line 131 – In the case of n = 1 (as assumed further below to derive the ratio U over K directly, and very often used in the literature), this relation is linear. **DONE:** *This is, of course, true. Power-law relations become linear if the exponent equals 1. As nothing relies on the nonlinearity, we removed the statement about the nonlinearity within the streamlined version of the methods section.*

Line 162 – I think it would be good to show (perhaps only as supplementary material) in a simple slope/area plot that this threshold has been chosen meaningfully in excluding hillslope processes (e.g. the brake-down of a linear slope/area relationship). **DONE/Reply:** *The cutoff size of 1 km^2 is some kind of tradeoff between the amount of available data (river segments) and validity of the stream power model. Hergarten et al. (2016) investigated the effect systematically for the topography of Taiwan and found a moderate deviation in slope of about 20 % at 1 km^2 from that predicted by the stream power law, while there was still a strong correlation between slope and catchment size. The deviation may be a bit stronger for the Alps due to the lower precipitation. However, we should keep in mind that we did not consider any river profiles quantitatively. Choosing a higher cutoff value would just cut the river segments in Figs. 2 and 7 a bit, but without affecting the lower part. So nothing in the interpretation of those figures would change. Of course, it would be possible to make a slope-area plot for the considered region if required, but we are not convinced that it would really merit a supplementary figure. So we decided just to discuss it briefly (Method section): "As χ is computed in upstream direction from a given base level, the restriction to $A \geq 1\ km^2$ does not affect the χ map itself, but only removes the uppermost river segments. Such a restriction is necessary as χ increases rapidly when approaching a drainage divide and the resulting high χ values would shadow across-divide contrasts in χ. The value of 1 km^2 is a trade-off between data density and the deviation of the real erosion rate from the rate predicted by the stream power law. Hergarten et al. (2016) found a moderate deviation in slope of about 20 % at $A = 1\ km^2$ for Taiwan. As this deviation applies to both sides of the considered drainage divides, it has a minor effect on the conclusions drawn from χ mapping."*

Line 167 – Generalization of the Gilbert Metrics and applying the stream-power relation. **DONE:** *Thank you for the suggestion. We added your formulation to the revised version of the manuscript.*

Lines 178-179 – Just a minor quibble, but I would ensure that this is phrased in a way that the reader is aware that exactly across divide channel head elevation, hillslope gradient and local relief are the Gilbert Metrics. **DONE:** *We added the clarification: "channel head elevation, hillslope gradient and local relief (represented by Gilbert metrics)" for the reader.*

Line 194 – I suggest mentioning early on to which base level elevation you are referring to when discussing stream profile analyses. This is not right away clear at the beginning of this (and actually throughout) the paragraph. **DONE:** *We agree that the chosen base level is not clear. We therefore added the missing information about the base level to the method section.*

Line 203 – It needs to be clear at which base level you started (0? or something higher?). This is not trivial otherwise you would not have computed χ at different base levels). I recommend, however, to consider in your selection for the lowest base level the bedrock/alluvial transition as done by Winterberg & Willett (2019) and briefly explain why you chose this lowest base level. **DONE:** *We chose 400 m as base level and successively increased in equal steps towards the height of the channel heads. 400 m represent thereby the outflow of the main rivers to the foreland. We added a short paragraph to the method section to clarify the approach.*

Lines 270-271 – Besides climate and lithology, I would also add tectonics. **DONE:** *We will make this sentence more general: "In the simplest case with overall uniform conditions, erosion rate increases with channel steepness* *in the drainage and topographic gradient in the hillslope domain." Challenges and Complications are explained in some detail in the next section (4.1).*

Line 276 – I think the nature of this 'signal', especially its origin (i.e., climate or tectonics) needs to be more precisely elaborated. A brief description on how such 'signals' traverse through the channel up to the hillslope domain should be included. **DONE:** *Thanks, we added "expressed by an upstream migrating knick point or knick zone" to clarify the nature of the signal.*

Lines 277-279 – Are there additional references that dealt with lowering base levels due to glacial erosion (perhaps not necessarily an example from the Alps) to underline the generality of this hypothesis? **DONE:** *Thank you for pointing out the missing references. The process of glacial overdeepening is well described in many publications (e.g. Hallet et al., 1996; Whipple et al., 1999; MacGregor et al., 2000; Brocklehurst and Whipple, 2002; Montgomery, 2002; Anderson et al., 2006; Haeuselmann et al., 2007; Züst et al., 2014). We added the missing references, which includes also global examples, to enhance our point.*

Section 4.1 – This section might be better located towards the end of the manuscript (I would rather expect early on a discussion on your results followed by a description of the limitations), but this might be a matter of taste. **Reply:** *We definitely understand your concerns with the location of this section. However, due to the pitfalls and difficulties in interpreting across divide χ gradients, we made a conscious decision to clarify the use and expectations towards the χ analysis in advance of the details of our results. Overall, we think this practice helps – in this particular case – to keep the manuscript short and precise, as many clarifications are already done and discussing the results becomes straightforward.*

Lines 281-282 – From a geological point of view, I struggled with this argumentation, since mm/yr translates over geologic time scales to km/Ma, which I regard as rather significant and geologists deal with this magnitude of rates on a daily basis. Over such time period a drainage divide might have migrated over kilometre distances (Eizenhöfer et al, 2019, provides a, perhaps more theoretical, example of a drainage divide that migrates significantly over geologic time). So, determining divide migration might be challenging, but probably not 'unfeasible'. Since the scope of the study ranges over geologic time scale (starting at initial collision at ca. 30 Ma) I think this phrasing needs to be modified. **DONE:** *We agree that "feasible" is very pessimistic and we therefore changed the wording to "challenging", as suggested. However, our intention was to point to the "direct determination of divide migration rates", in which case we think "feasible" is quite fitting. We fully agree that divide migration rates in order of a mm/y result in a total divide shift of several kilometers over geologic time scales. Evidence is found in topography and the process can be modelled by employing LEMs (although this issue is not trivial). However, we do not think that there is a direct method to measure the yearly rate of divide migration in field.*

Lines 288-289 – I would elaborate in some more detail on these tectonic phases and spatial and temporal changes in uplift patterns since these are very distinct, i.e. Early Miocene collision followed by Middle Miocene extrusion tectonics. A good start are works by Frisch et al. (1998) and Kuhlemann (2007). **Reply:** *We agree on the importance of the tectonic phases. We therefore refer to the introduction (Section 1.2 Co-evolution of topography and drainage system of the Eastern Alps), where the main processes are mentioned, including the work of Frisch et al. (1998) and Kuhlemann (2007). We think a detailed description in the Discussion part potentially exceeds the scope of this work. However, as the reconstructions of the mentioned authors do neither include any information on topography nor elevation, we think that a detailed description of the tectonic processes is not necessarily helpful.*

Lines 289-290 – Please clarify whether these hillslopes are at critical slopes following glacial erosion, or potentially something else (e.g., deep mantle processes as discussed by Schlunegger & Castelltort, 2007). **DONE:** *As we are in the section about challenges and limitations, we wanted to point out that the relationship between slope and erosion rate is lost, if the slopes reach their limit of stability, so that the slope itself is no longer useful in the context* *of erosion rates and drainage divide migration. Why they are so steep does not matter much here. It is of course either glaciation or just the decrease of fluvial erosion due to decreasing catchment size, when approaching the drainage divide. We added the following to the Discussion section (4.1) of the revised manuscript: "In this context, the question may arise whether χ mapping, i.e., the consideration of χ alone without regard to differences in elevation, is as good as computing an average channel steepness from the differences in elevation and in χ values. According to Eq. (5), the slope of a χ transformed river profile is a proxy for the erosion rate at given erodibility. The χ values at the end of the rivers would be inversely proportional to this slope if they were at the same elevation everywhere. This means that both approaches are equivalent if the steepness of the hillslopes is the same at both sides of the drainage divides. Otherwise, the interpretation of χ maps is not entirely free from an influence of the hillslopes, even if the lower limit of catchment size is large enough to ensure the applicability of the stream power law. If the hillslopes at one side are steeper, the channel heads (here defined by a minimum drainage area of 1 km^2) are at a lower elevation, so that the consideration of χ alone overestimates the mean steepness of the channel. This means that χ mapping implicitly captures the steepness of the hillslopes to some degree if applied across drainage divides. With regard to the relevance of the hillslope regions for the migration of the drainage divides, this might even be seen as an advantage of χ mapping over mean channel steepness."*

Lines 293-300 – I suggest rephrasing this paragraph by focusing on and more systematically discuss the effects the three parameters (climate, tectonics and erodibility/lithology) can have on χ stream profile analysis. Here climate and tectonics are emphasised in the beginning of the paragraph while lithology appears as some 'side effect'. This issue might appear a bit nit-picky, but I would prefer to have the limitations of χ stream profile analyses clearly outlined. **DONE:** *Although the variability in erodibility due to lithology may be smaller than variations in uplift rate and precipitation, our wording should not imply that lithology is some side effect. We have recently even published a study on lithological effects controlling the shape of topographic features (Baumann et al., 2018). However, while climate and tectonics are active drivers of landscape evolution, substrate properties are a passive control. Therefore, we started describing the active part followed by the passive part. Nevertheless, we tried to state it more clearly and changed the paragraph within the section 4.1 to: "While a transient state caused by changing climatic or tectonic conditions is often considered as the most likely reason for divide asymmetry, spatial heterogeneity may in principle reproduce the same topographic characteristics, but even in a steady state (e.g. Whipple et al., 2017). In the fluvial regime, contrasts in uplift rate, lithology, and precipitation play similar parts. The crucial question in this context is whether there is a sharp topographic contrast at the drainage divide or a gradual variation. In a steady state with only vertical tectonic movement, the local steepness of the topography is related to the properties at the respective point. Thus, sharp across-divide contrasts in topography require discontinuous variations in precipitation or lithology or the existence of active faults close to the drainage divide, i.e. a sharp contrast in uplift rate. However, drainage divides do not move towards such discontinuities in general (Robl et al., 2017a), so that sharp across divide contrasts in topography due to tectonics or lithology should be rare."*

Lines 309-310 – Perhaps elaborate this 'future divide mobility' aspect a bit more? **DONE:** *The argumentation for χ to represent rather future divide migrations is shown in Forte and Whipple (2018). Thank you for pointing to the missing reference. We added the reference and additionally clarified the relation in the revised version of the manuscript.*

Lines 312-314 – This base level strategy adopted here might be strategically better placed in the methodology section. **DONE:** *As suggested, we added a short paragraph to the methods section. However, we decided to keep these two lines in the manuscript, as they demonstrate our approach to counteract some of the limitations.*

Lines 334-337 – Perhaps go even one step further: what is / could be the nature and potential origin of these signals with respect to these different amplitudes and time scales? **Reply:** *The origin of the signals is given in two examples (the development of escarpments as short wavelength – high amplitude signal; tectonic processes as large length scale low amplitude signal). We are aware that there are many more examples, but here we refer to section 4.3, were the observed (mainly high-length scale – low amplitude) signal is interpreted in terms of tectonic evolution of the Eastern Alps. Our intention here is to show the general origin of the signal. We agree, that it is rather uncommon to start the discussion section with general statements, but think that this is appropriate in the context of χ signal interpretation (see also reply to section 4.1).*

Line 343 – These simplifying assumptions (i.e., uniform climate, lithology, tectonics) should be emphasised a bit more in the limitations section. **DONE:** *We rearranged section 4.1 and added a further paragraph (see previous reply to section 4.1). We further rearranged section 4.2 to transfer the described limitations more precisely to the Eastern Alps to the following: "As discussed in the previous section, the observed asymmetry of drainage divides observed in the study region, with steep western and less steep eastern sides may in principle result from spatial heterogeneity at the drainage divides with sharp contrasts in uplift rate, substrate properties or precipitation. Furthermore over-thrusting along ramps may result in asymmetric but still stable drainage divides. Hence, divide asymmetry does not necessarily indicate divide mobility. However, there is no evidence that the drainage divides analysed here follow such lithological or tectonic structures. Sharp contrasts in precipitation would require (i) a sequence of decrease, recovery, and decrease in precipitations rate in east-west direction and (ii) an inversion of the north-south contrast along a drainage divide (WS1), both at rather small scales. Furthermore, the observed west – east asymmetry of divides is not consistent with the thrusting direction of major alpine units, which occurred roughly from south to north. In consequence, it appears unrealistic that the observed pattern is entirely controlled by climate, lithology or active faults, although some influence of climate (and also of tectonics or lithology) cannot be excluded. Summarizing, the known long-term reorganization of the drainage network (Frisch et al., 1998; Frisch et al., 2001) accompanied by changes in contributing drainage area appears to be the most likely interpretation of the observed topographic pattern and is enhanced by progressively increasing the base level for χ computation. Shifting the observational scale from presumable tectonically and climatically heterogeneous catchments to their more homogenous headwaters shows no qualitative changes in the χ pattern. The χ anomalies across the divides remain up to a baselevel of 800 m (Fig. 2, 3). Our results, therefore, suggest that drainage divides of the investigated catchments are mobile and follow a general trend. At north – south running drainage divides, tributaries feature lower χ values west of the dividing ridge and hence are steeper on average than tributaries draining towards east (Fig. 2). However, this trend in χ breaks down at some divides for a base level of 1000 m characterizing the very headwaters, only."*

Line 358 – Even though glacial erosion stopping divide migration appears trivial, is there any reference out there that would support this and could be added here? **DONE:** *Thank you for this comment. We added a reference. From a geometrical point of view, this is indeed a straightforward implication of glacial erosion. The formation of cirques with vertical cirque faces locally changes the geometry of hillslopes at the divides and temporally removes asymmetry, which may have existed prior. The impact of glacial erosion on drainage divides is discussed by (Robl et al., 2017a) and is nicely illustrated by a movie in the supplement.*

Line 363 – I suggest being more precise regarding this 'peculiar west-east directed migration', and directly implement your results (i.e., a divide migration from W to E). **DONE:** *Thank you for inviting us to be more precise. We rephrased the sentence as suggested.*

Lines 372-373 – I do not think basic background on χ stream profile analysis needs to be repeated here and should belong to the methodology section. **DONE:** *We removed the mentioned paragraph and think the relationship is sufficiently described in the methods section.*

Lines 374-377 – It is not entirely clear from the way it is phrased here whether basic background regarding χ stream profile analysis is being discussed or implications of your analyses in the Eastern Alps as a whole. Perhaps add some broad geographic location indicators? **DONE:** *Indeed, we aimed to refer to our observations from the Eastern Alps and not to a basic background. For clarification, we add the suggested locations to the revised manuscript.*

Lines 381-383 – Echoing my earlier comment on time scales, I think it is problematic to use the slow mm/yr rate of divide migration as argument for the longevity of geomorphic features (this needs to be tested) in the context of tectonic forces that operate at these time scales. **Reply:** *We fully agree that there is more work needed to test the longevity of geomorphic features. However, our aim was to work out and emphasize the difference between long-lasting continuous migration processes and sudden stream capture events, also presented by Goren et al. (2014) or (Robl et al., 2017b), which potentially work on the observed signal in our results.*

Figure 7 – There are a couple of issues I had with this figure (technically and geologically/geomorphologically). 1. How has this figure been produced? 2. Does it show some kind of 'model'? What are the model assumptions in detail? 3. How has χ been produced after changing the geometry of the drainage basins, especially that of the drainage divides? Have all elevations been the same as present-day? 4. Since Oligocene time uplift patterns and the geometry of tectonic units in the Eastern Alps have considerably changed (e.g., Frisch et al., 1998). Assuming that the drainage geometry and river courses are largely the same since then (perhaps with exception of the major strike-parallel drainage systems) and only locations of divides are changed, I find rather problematic. 5. It is very likely very challenging to accurately depict the fluvial geometry of the Eastern Alps in Early Miocene simply because numerous tectonic and climatic events (Messinian crisis, Pleistocene glaciations, Middle Miocene Optimum, significant changes of the drainage basin of the Danube far to the east, rapid Miocene exhumation of the Tauern Window, switch from convergence to extrusion-dominated tectonics, just to name a few examples) would have had a deep impact on the drainage system. Thus, Figure 7 is from my point of view an overly optimistic simplification that might be rather misleading than helpful. In applying χ analyses across the present-day Eastern Alps a number of simplifying assumptions have already been made and we somewhat already turn a blind eye to this (for good reasons), but doing the same back in geologic time, I find, is rather problematic.
Reply: *It was not our intention to reconstruct the topography of the Eastern Alps for different time steps. We would love to do that! However, uplift patterns, rates for horizontal advection, exhumation rates and so on are only very roughly constrained. It is even not clear, when the topography formation in the Eastern Alps happened and there is a vivid debate whether topographic pattern observed in the Eastern Alps relate to glacial imprint or fluvial prematurity caused by an uplift event about 5 Ma ago. Thanks to the comprehensive work of several authors (e.g. Frisch et al., 1998; Dunkl et al., 2005; Kuhlemann, 2007), there is at least some information on drainage systems and topography at certain time slice. The idea of figure 7 was just to roughly mimic the plan view geometry of drainage patterns of the Eastern Alps. As χ-mapping in contrast to χ profiling does not explicitly require information on elevation, we show changing χ anomalies across divides for different catchment geometries. We could have done this also by employing one of our landscape evolution models, but think that it is more intuitive for the reader to alter the drainage system of the Eastern Alps according to the geometries based on the restorations of Frisch et al. (1998).*
From a technical perspective, the maps were produced as described in the method section (χ mapping). The original DEM was dammed and the outflow of rivers rearranged to wind gaps, numerously described in the literature (e.g. Robl et al., 2008). A further change of the DEM is not necessary, as χ mapping, as aforementioned, does not require any information on elevation.

Lines 389-391 – Exactly these assumptions stated here I regard as problematic, and Figure 7 is probably not the best approach to simulate palaeo-drainage geometries. **Reply:** *We would agree if it was our intention to provide a serious reconstruction of the drainage pattern or even the topography at distinct times. But as discussed above, this would not only be much more complicated, but would also require much more information, which is not available. The assumption is that topography adjusted to changes in tectonics by small changes in network topology and keeps as much as possible of the valley pattern. With regard to the early work of Hergarten and Neugebauer (2001) and the recent work on river capture that has raised much attention, this concept should be a reasonable tradeoff between available information and what we can read from it.*

Lines 442 – Since Figure 7 is indeed a very rough restoration, making many in my opinion rather oversimplifying assumptions (see my comment on this above), I would be very cautious in drawing conclusions based on this figure. **DONE:** *We changed the conclusions to "Analysing catchment geometries that roughly mimic the drainage pattern…". For more details, see our previous comment.*

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The destiny of orogen-parallel streams in the Eastern Alps: the Salzach-Enns drainage system

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Abstract. The evolution of the drainage system in the Eastern Alps is inherently linked to different tectonic stages of the alpine orogeny. Crustal scale faults imposed east-directed orogen parallel flow on major rivers, whereas late orogenic surface uplift increased topographic gradients between foreland and range and hence the vulnerability of such rivers to be captured. This leads to a situation where major orogen-parallel alpine rivers such as the Salzach River or the Enns River are characterized by elongated east-west oriented catchments south of the proposed capture points, whereby almost the entire drainage area is located west of the capture point. To determine the current stability of drainage divides and to predict the potential direction of divide migration, we ~~analyzed~~analysed their geometry at catchment, headwater and hillslope scale~~.~~ covering time scales from millions of years to the millennial scale. Therefore, we employ χ mapping for different base levels, generalized swath profiles ~~along~~across drainage divides and Gilbert metrics. Our results show that almost all drainage divides are asymmetric with steeper channels west and flatter channels east of a common drainage divide. Interpreting these results, we propose that drainage divides migrate from west towards east, so that the Inn catchment grows on expense of the Salzach catchment and the Salzach catchment consumes the westernmost tributaries of the Mur and Enns catchments. While Gilbert metrics show the same trend at hillslope scale at the Salzach–Enns and Salzach–Mur drainage divide, they show no significant asymmetry at the Inn–Salzach drainage divide. As topography at the latter divide is dominated by glacial landforms such as cirques and U-shaped valleys, we interpret the missing hillslope scale asymmetry of this divide as a result of Pleistocene climate modulations, which locally obscured the large-scale signal of drainage network reorganization. We suggest that the east-directed divide migration progressively leads to symmetric catchment geometries, where eventually tributaries west and east of the capture point contribute equally to the drainage area. To test this assumption, we have reconstructed the proposed drainage network geometries for different time slices. χ mapping of these reconstructed drainage networks indicates a progressive stability of the network topology in the Eastern Alps towards the present-day situation.

1 Introduction

~~The tectonic and climatic evolution of a collisional orogen is inherently linked to its drainage system~~ (Beaumont et al., 1992; Willett, 1999; Montgomery et al., 2001; Garcia-Castellanos et al., 2003; Cederbom et al., 2004; Bishop, 2007; Roe et al., 2008; Champagnac et al., 2012; Herman et al., 2013; Robl et al., 2017a)~~.~~The drainage system of a collisional orogen is inherently linked to its tectonic and climatic evolution (Beaumont et al., 1992; Willett, 1999; Montgomery et al., 2001; Willett et al., 2001; Garcia-Castellanos et al., 2003; Cederbom et al., 2004; Bishop, 2007; Miller et al., 2007; Roe et al., 2008; Champagnac et al., 2012; Herman et al., 2013; Robl et al., 2017a). In a zone of plate convergence, crustal shortening is a primary control of the horizontal and vertical metrics of the mountain range (Houseman and England, 1986; Royden et al., 1997; Robl and Stüwe, 2005a; Robl et al., 2008b; Bartosch et al., 2017; Robl et al., 2017a). Progressive shortening leads to thickening of light, buoyant crust, which results in surface uplift and formation of high alpine topography (e.g. Molnar and Lyon-Caen, 1988). The horizontal geometry of the mountain range reflects compression in, and stretching perpendicular to the direction of plate convergence. In such a stress field, blocks of the brittle upper crust are ~~abundantly~~ advected along major strike slip fault zones ~~– a~~. This process~~, which~~ is commonly referred to as lateral extrusion (e.g. Tapponnier et al., 1982; Ratschbacher et al., 1989; Ratschbacher et al., 1991; Robl and Stüwe, 2005a; Robl and Stüwe, 2005b; Robl et al., 2008b).

As a consequence of the horizontal and vertical ~~velocity field~~motion of the crust, ~~-~~drainage systems are also advected (Clark et al., 2004; Miller and Slingerland, 2006; Stüwe et al., 2008; Castelltort et al., 2012; Kirby and Whipple, 2012; Miller et al., 2012; Fox et al., 2014; Goren et al., 2015; Yang et al., 2016; Guerit et al., 2018; Eizenhöfer et al., 2019). However, rivers are not just passive markers of crustal deformation, but also adjust their channel slopes to the contributing drainage area, uplift rate and bedrock properties until longitudinal channel profiles are graded and long-term erosion rates are in balance with uplift rates (Kooi and Beaumont, 1996; Whipple, 2001; Willett et al., 2001; Goren et al., 2014; Robl et al., 2017b)~~. Over an orogenic cycle~~. However, tectonic ~~forcing~~ and climatic ~~conditioning~~conditions are not steady over an orogenic cycle. The signal of temporal variations is routed via mobile knickpoints in channels through the entire drainage system (Wobus et al., 2006b; Kirby and Whipple, 2012; Perron and Royden, 2013; Royden and Perron, 2013; Robl et al., 2017b). Evidence for a previous tectonic phase is erased from their shapes once all knickpoints have left the drainage system at the drainage divides. The velocity of knickpoint migration depends strongly on different factors such as lithology, upstream drainage area, amplitude of baselevel drop, and sediment supply (Crosby and Whipple, 2006; Loget and Van Den Driessche, 2009) and ranges between 0.001 and 0.1 m/year (e.g. van Heijst and Postma, 2001).

~~If a drainage divide becomes thereby asymmetric, it features an across divide gradient in erosion rate and starts migrating from the steep towards the less steep side~~ (e.g. Gilbert, 1877; Robl et al., 2017a; Robl et al., 2017b; Whipple et al., 2017; Forte and Whipple, 2018)~~.~~Across-divide gradients in erosion rate (strictly speaking, in the rate of change in surface elevation) result in the migration of the respective drainage divide, or even to discrete river piracy events. The difference in erosion rate is usually reflected in an asymmetric topography where the drainage divide migrates from the steep towards the less steep side (e.g. Gilbert, 1877; Robl et al., 2017a; Robl et al., 2017b; Whipple et al., 2017; Forte and Whipple, 2018). The reorganization of the drainage system due to divide migration (continuous) and river piracy events (discrete) lasts at least one order of magnitude longer than the upstream migration of knickpoints in channels (e.g. Goren, 2016; Robl et al., 2017b). Furthermore, changes in the contributing drainage area as consequence of mobile divides ~~result in~~introduce a positive feedback, where the adaption of channel profiles to changing catchment size amplifies across divide differences in erosion rate (Willett et al., 2014). As a consequence, information on long-term major tectonic phases associated with a large~~-~~-scale reorganization of the drainage pattern persists in the drainage network topology and can be revealed from ~~analyzing~~analysing the geometric properties of the drainage system and its divides, even ~~if~~after direct evidence from channels profiles has already vanished (Willett et al., 2014; Goren et al., 2015; Yang et al., 2015; Hergarten et al., 2016; Beeson et al., 2017; Robl et al., 2017a; Robl et al., 2017b; Winterberg and Willett, 2019)~~.~~. However, it should be emphasized that the relation between drainage divide migration and topographic asymmetry is not unique. While migrating drainage divides are usually asymmetric, there are specific tectonic, lithological or climatic scenarios where asymmetric drainage divides can be stable.

In this study, we aim to decipher the morphological state of drainage divides in the Eastern Alps to (a) distinguish between mobile and immobile drainage divides and (b) constrain the potential direction of divide migration by applying a set of morphometric tools that consider divide disequilibrium at catchment, headwater and hillslope scale. Furthermore, we discuss our results in the light of proposed changes in the drainage pattern since onset of topography formation (Oligocene) in the Eastern Alps (Frisch et al., 1998; Handy et al., 2015) and explore how these changes may have affected the stability of the divides compared to the present-day situation.

1.1 The drainage system of the Eastern Alps

The drainage system of the Eastern Alps is characterized by two principal drainage divides (Robl et al., 2008a; Robl et al., 2017a) (Fig. 1). One major divide follows the main ridge of the Eastern Alps including the highest peaks and separates the Inn, Salzach and Enns catchments to the north from the Drau and Mur catchments to the south. The Danube (and eventually the Black Sea) represents the common base level of all those rivers, but their confluence is located in the Pannonian Basin hundreds of kilometers apart from the Eastern Alps. A second major drainage divide separates Alpine rivers that flow into the Adriatic Sea (e.g. Adige River) from the Mur–Drau drainage system.

~~Fault tectonics controlled the~~The configuration of the drainage systems was controlled by extrusion tectonics. Major tectonic lineaments (mainly strike-slip dominated faults, i.e. Inn Valley Fault, Salzach-Ennstal-Mariazell-Puchberg Fault (SEMP), Mur-Mürz Fault, Periadriatic Lineament (PL), Möll Valley Fault) confine a corridor of lateral extrusion, where crustal blocks were actively squeezed out to the east towards the Pannonian Basin (e.g. Ratschbacher et al., 1989; Ratschbacher et al., 1991). Almost all major streams of the Eastern Alps follow these major tectonic lineaments for several tens of kilometers (Robl et al., 2008a; Bartosch et al., 2017; Robl et al., 2017a). Hence, they flow parallel to the strike of the mountain range, instead of leaving the orogen towards north and south, following the general topographic gradient (Fig. 1).

The courses of the Salzach and Enns rivers in the north~~,~~ and the Mur and Mürz rivers in the south are characterized by knee-shaped bends and T-shaped river junctions, where rivers abruptly leave their tectonically preconditioned valleys and drain towards the forelands in the north and south, respectively (Robl et al., 2008a; Robl et al., 2017a). Such sudden river course changes in concert with the observation of wind gaps at the Salzach–Enns valleys and the Salzach–Saalach drainage divide~~,~~ (Fig. 1), as well as the provenance of sediments along the Enns valley (Dunkl et al., 2005; Neubauer, 2016) are consistent with the proposed reorganization of the Salzach and Enns drainage systems (Kuhlemann et al., 2001; Dunkl et al., 2005; Robl et al., 2008a).

~~South~~Major valleys south of the alpine main ridge~~, major valleys show~~ also show a strong tectonic control (Robl et al., 2017a). The eastern tributaries of the Adige River and the western tributaries of the Drau River ~~follow~~ roughly follow the Periadriatic Lineament (Fig. 1). The occurrence of a prominent wind gap between Adige and Drau rivers, as well as T-shaped river junctions at the tributaries of the Adige River is discussed in terms of river piracy events and an ongoing reorganization of the drainage system (Robl et al., 2017a).

1.2 Co-evolution of topography and drainage system of the Eastern Alps

Morphological observations (e.g. Robl et al., 2008a) and provenance analyses (e.g. Kuhlemann et al., 2001; Kuhlemann et al., 2002; Kuhlemann, 2007; Neubauer, 2016) give evidence for several large~~-~~-scale modifications of the Eastern Alpine drainage system. The evolution of the drainage system is inherently linked to the Late Oligocene–Early Miocene indentation (Handy et al., 2015) of the Adriatic into the European plate. At onset of indentation, the landscape of the Eastern Alps was characterized by a hilly topography (Frisch et al., 2001), which was drained by a series of northward flowing rivers (Frisch et al., 1998; Kuhlemann et al., 2006; Kuhlemann, 2007).

During Early to Middle Miocene times, lateral extrusion tectonics, confined by a set of crustal scale strike-slip and associated normal faults~~, caused rapid exhumation of~~ started and rocks at the Tauern Window~~. This process~~ were exhumed rapidly. These processes initiated a large scale reorganization of the drainage system, where faults imposed an east-directed orogen-parallel flow on major rivers (Frisch et al., 1998). This tectonic stage set the paleo-courses of the Enns, Mur and Drau Rivers (Dunkl et al., 2005; Kuhlemann et al., 2006; Kuhlemann, 2007). Evidence for a changing drainage pattern was recorded by the sedimentary pile deposited in the northern Molasse basin (Kuhlemann et al., 2006) and in inner alpine basins (Dunkl et al., 2005). The sedimentary record consists of characteristic rocks of surrounding Austroalpine units~~ and later~~. Later, during Middle and Late Miocene, ~~of~~ rocks from Penninic and Subpenninic units of the rising Tauern Window, which were previously overlain by Austroalpine units, occur in the sediments of the northern foreland basin (Frisch et al., 1998).

Provenance analyses of sediments reveal the reversal of flow directions and potential stream capture events during the Late Miocene (Kuhlemann, 2007). Frisch et al. (1998) and Dunkl et al. (2005) suggested that the initially northeast directed Mur River changed its course to the current southeast directed drainage path during the Middle Miocene (Fig. 1). The detection of wind gaps (Robl et al., 2008a) and the analysis of the sedimentary composition of intra-orogenic basins (Neubauer, 2016), suggest similar changes in the Salzach and Enns drainage systems. The abrupt increase in stream power, a few kilometers upstream, but mostly downstream of the knee-shaped river bend, (Fig. 1), and a knickpoint analysis of tributaries may indicate a stream capture event during the Pleistocene forcing a base level lowering of the Salzach River in the recent geological past (Robl et al., 2008a).

However, the drainage development since the early Pliocene is poorly constrained. In particular, the impact of the Pleistocene glaciations, resulting in flat valley floors of the trunk streams and hanging valleys with large knickpoints at tributaries (Robl et al., 2008a; Norton et al., 2010; Valla et al., 2010) altered the geometry of rivers and obscured the tectonic record of preceding tectonic events (Robl et al., 2017a).

2 Method

All topographic analyses are based on the EU-DEM (data funded under GMES, Global Monitoring for Environment and Security preparatory action 2009 on Reference Data Access by the European Commission) digital elevation model with a spatial resolution of approx. 25 m.

2.1 χ-mapping

In order to detect potentially mobile drainage divides due to across divide differences in erosion rate, we follow the approach of Willett et al. (2014) by employing the so called χ transform (Perron and Royden, 2013; Royden and Perron, 2013). This approach is based on the detachment-limited model for bedrock channel incision (Howard, 1980; Howard, 1994; Hergarten, 2002) ofwhere the formerosion rate is

$$\frac{\partial H}{\partial t} = U - E = KA^m \left(\frac{\partial H}{\partial x}\right)^n \qquad (1)$$

whereHere, H, t and x are elevation, time and the longitudinal coordinate along the river profile, increasing in the upstream direction. U and, while K represent the uplift rate andrepresents the erodibility of the bedrock. The nonlinear contribution of the channel slope $\frac{\partial H}{\partial x}$ and drainage area A to river incision is represented by the exponents m and n. The change in surface elevation at a given uplift rate U is then given by

In topographic steady state $\left(\frac{\partial H}{\partial t} = 0\right)$, Eq. (1) simplifies to

$$\frac{\partial H}{\partial x} = \left(\frac{U}{K}\right)^{\frac{1}{n}} A^{\frac{-m}{n}}$$

$$\frac{\partial H}{\partial t} = U - E \qquad (2)$$

~~If U and K are constant, we get~~

~~$$\frac{\partial H}{\partial x} \propto A^{-\theta} \qquad (3)$$~~

~~where θ = m/n is the concavity index. Then, the product~~

~~$$k_s = \frac{\partial H}{\partial x} A^{\theta} \qquad (4)$$~~

~~is constant and known as the steepness index k_s (e.g. Snyder et al., 2000; Wobus et al., 2006a), which directly represents the ratio between U and K for n = 1.~~

The~~ non-linear~~ increase of contributing drainage area (and hence discharge) with downstream distance ~~yields the~~leads to a curvature of the channel profile, which obscures the relation between topography and erosion rate and thus also the record of spatial or temporal changes in uplift rate or contributing drainage area in the geometry of the river channel. The χ transform eliminates the curvature of the river profile by transforming the longitudinal coordinate x to a new coordinate χ (Perron and Royden, 2013; Royden and Perron, 2013). The contributing drainage area can be eliminated if the transformation satisfies the condition

$$\frac{dx}{d\chi} = \left(\frac{A}{A_0}\right)^{\theta} \qquad (\text{~~5~~}3)$$

~~which~~ where $\theta = m/n$ is the concavity index. This is achieved by

$$\chi = \text{~~}\int_{x_0}^{x}\left(\frac{A}{A_0}\right)^{-\theta}\text{~~} \int \left(\frac{A}{A_0}\right)^{-\theta} dx \qquad (\text{~~6~~}4)$$

where ~~x_0 is~~the integration starts from an arbitrary given reference point~~, and~~ x_0, while A_0 is an also arbitrary reference catchment size~~.~~, which only affects the absolute scale of the χ values (A_0 = 1 ~~m²).~~km² in this study).

~~Under spatially and temporally uniform tectonic and climatic conditions, χ transformed river profiles are straight lines and their slope is constant and proportional to k_s. We calculated χ values for all channels with a contributing drainage area > 1 km² and θ = 0.5, using the numerical approach of (Hergarten et al., 2016).~~

Then the erosion rate is

$$E = K\left(\frac{\partial H}{\partial \chi}\right)^n \qquad (5)$$

Under spatially and temporally uniform tectonic and climatic conditions, χ transformed steady-state river profiles are thus straight lines. We calculated χ values for all channels with a contributing drainage area $A \geq 1$ km² and $\theta = 0.5$. As χ is computed in upstream direction from a given base level, the restriction to $A \geq 1$ km² does not affect the χ map itself, but only removes the uppermost river segments. Such a restriction is necessary as χ increases rapidly when approaching a drainage divide and the resulting high χ values would shadow across-divide contrasts in χ. The value of 1 km² is a trade-off between data density and the deviation of the real erosion rate from the rate predicted by the stream power law. Hergarten et al. (2016) found a moderate deviation in slope of about 20 % at $A = 1$ km² for Taiwan. As this deviation applies to both sides of the considered drainage divides, it has a minor effect on the conclusions drawn from χ mapping.

Major rivers of the Eastern Alps exit the mountain range to the foreland at an elevation of about 400 m. We therefore chose this elevation as the common base level ($H(x_0)$ = 400 m). In order to limit the influence of spatial heterogeneity in tectonics and climate on χ at drainage divides, we also computed χ for a series of higher base levels (600 m, 800 m and 1000 m).

The analysis of across divide differences in χ exploits the fact that channels, originating at a common drainage divide (i.e. similar channel head elevation) and sharing the same base level elevation, are steep, if χ is small (Willett et al., 2014). Hence, across divide differences in χ indicate differently steep rivers on both sides of the divide, averaged from the baselevel to the channel head. Generalizing the ideas of Gilbert (1877) and applying the stream power relation, steeper channels result in higher erosion rates, and hence, drainage divides should migrate towards the high χ catchments.

2.2 Generalized swath profiles

We employ generalized swath profiles (Hergarten et al., 2014) to explore differences in headwater relief across drainage divides. The drainage divide represents the curved baseline of the swath profile. The signed minimum distance (Euclidian distance) of every data point of the digital elevation model to the base line is computed and coordinate pairs (profile coordinate, distance) are binned. Topographic maxima and minima representing the summit domain and the drainage system, respectively, as well as mean elevation and standard deviation indicating the degree of landscape dissection are represented as function of signed distance from the drainage divide. The half width of the swath profiles is 5 km.

2.3 Gilbert metrics

To investigate the symmetry of drainage divides and potential anomalies at the hillslope scale, we determine the so called Gilbert metrics, originally proposed by Gilbert (1877) and formalized by Whipple et al. (2017). Across divide differences in channel head elevation, hillslope gradient and local relief (represented by Gilbert metrics) were computed with Divide Tools (Forte and Whipple, 2018), a collection of morphometric functions based upon TopoToolbox (Schwanghart and Scherler, 2014).

Channel heads at the transition from the hillslope to the fluvial domain are defined by a contributing drainage area threshold of 1 km². Hence, channel head elevation is the elevation at this point. The local relief is the maximum elevation (~~E_{max}~~H_{max}) within a circular window minus the elevation of the channel head. We chose the default window size with a radius of 0.5 km (Forte and Whipple, 2018), which encloses the nearby ridge lines, but does not reach far beyond. The slope gradient is the average topographic gradient between the channel head and the highest point within the ~~analyzed~~analysed window. These metrics are averaged (arithmetic averaging) at each side of the watershed. Δ-values (e.g. $\Delta_{Elevation}$) represent the difference of averaged metrics of the two sides of the drainage divide. Eventually, Δ-values are normalized to a range from -1 to 1, so that every deviation from 0 evidences for an asymmetric drainage divide. Following the nomenclature of Forte and Whipple (2018), we refer to these metrics as Gilbert metrics.

3 Results

By applying a set of standard morphometric analyses, we discovered several distinctly asymmetric drainage divides. We found divide asymmetry considering information from entire catchments, headwaters, and even hillslopes.

3.1 χ-mapping: across divide differences at catchment scale

As already described by Robl et al. (2017a) and Winterberg and Willett (2019), we also found distinct χ anomalies at the divides of the Salzach catchment and the Inn and Adige (WS 1) catchments in the west, the Saalach (WS 2) catchment in the north, and the Enns (WS 3) and Mur (WS 4) catchments in the east (Figs. 1, 2a-d). Across divide differences in χ between the Salzach catchment and the Drau catchment in the south are small. As a clear trend, all streams at the western side of roughly north-south trending drainage divides feature significantly lower χ values than adjacent streams east of the divides. We observe this trend at WS 1, where tributaries of the eastern Salzach River show significantly higher χ values than tributaries of the western Inn River. Similar anomalies in χ occur at WS 3 and WS 4, where the tributaries of the Enns and Mur Rivers feature higher χ values than tributaries of the Salzach River. At WS 2, separating the Salzach from the Saalach catchment, higher χ values are observed north of the divide within the Saalach catchment.

A stepwise increase of the baselevel from 400 m (Fig. 2a) to 600 m (Fig. 2b) and 800 m (Fig. 2c), and tantamount a shift of the starting point of the χ computation towards the headwaters, changes the absolute χ values, but does not change the observed across divide gradients in χ. However, starting the χ integration at the very headwaters of the investigated catchments by setting a baselevel of 1000 m (Fig. 2d), several across divide χ gradients disappear or are even reverted, as observed at WS 1. There, and in contrast to lower base levels, tributaries of the Inn River feature higher χ values than tributaries of the Salzach River. The rivers on both sides of WS 2 and WS 3 show similar χ values. However, the distinct χ anomaly observed at WS 4 still remains. All tributaries of the Mur show higher χ values than tributaries across the divides to the Drau, Salzach and Enns catchments. Beyond that, the analysis shows that χ gradients across the Mur and Enns drainage divides increase with increasing baselevels.

For a baselevel of 400 m, absolute values of χ, extracted at the channel heads on both sides of the investigated drainage divide, reflect the described across divide χ gradients quantitatively (Fig. 3). At the westernmost drainage divide of the Salzach catchment, the distribution of χ ranges between 3190 m and 6740 m in the Inn / Adige catchment and between 5810 m and 8890 m in the Salzach catchment. Mean values in χ are 4887 m at the Inn / Adige side and 7525 m at the Salzach side of the drainage divide. The χ gradient indicates that the average steepness of the channels is higher at the Inn / Adige side than at the Salzach side of the divide. At the eastern drainage divides of the Salzach catchment, the Salzach – Enns and the Salzach – Mur divide, the χ distribution of the Salzach ranges between 2670 m and 6530 m, while channel heads at the Enns and Mur catchment feature χ values between 4410 m and 9100 m. Mean values in χ are 4267 m and 5443 m at the Salzach catchment, and 6360 m and 8093 m at the Enns and Mur catchments. The χ gradients indicate higher average channel steepness at the Salzach side of the divides. Across divide gradients at the northern Salzach – Saalach divide are distinctly smaller than those at the western and eastern Salzach watersheds. The χ distribution ranges between 3670 m and 6220 m at the Salzach side and between 3390 m and 8130 m at the Saalach side. Mean χ is slightly shifted towards higher values at the Saalach (5834 m) relative to the Salzach side (4829 m). This, however, is caused by the long tail of the skewed right χ distribution of the Saalach catchment.

3.2 Swath profiles: across divide differences at headwater scale

The four curved swath profiles ~~following~~perpendicular to the watershed segments WS1 – WS4 indicate a series of distinct across divide differences in the headwater relief (Figs. 1, 4). At first glance, WS 1 appears to be roughly symmetric with a steady decrease in mean (~~E_{mean}~~H_{mean}) and minimum elevation (~~E_{min}~~H_{min}) with increasing distance from the divide. Up to a distance of 2 km, the drop in ~~E_{mean}~~H_{mean} is larger at the Inn side of the divide. At a distance of 5 km, ~~E_{min}~~H_{min} is slightly lower at the Salzach side in comparison to the Inn side. At this distance, the swath corridor already reached the trunk valley of the Salzach drainage system, but reached only a small tributary of the Inn River at the other side of the divide. Overall, the relief (~~$E_{max} – E_{min}$~~$H_{max} – H_{min}$) is larger at the Inn than at the Salzach side of the divide. The Saalach – Salzach drainage divide (Fig. 4, WS2) shows a strong asymmetry in ~~E_{mean}~~H_{mean} and relief, but no spatial trend in ~~E_{min}~~H_{min}. The latter is bound up with the fact that the drainage divide exhibits a wind gap, which connects the valley floors of the Salzach and Saalach rivers without a significant drop in valley floor elevation (Fig. 1). In contrast, the eastern divides of the Salzach catchment show a strong asymmetry (Fig. 4, WS3, 4). The drop in ~~E_{min}~~H_{min} and ~~E_{mean}~~H_{mean} with increasing distance from the divides is distinctly more pronounced at the Salzach side than at the Enns and Mur sides of the drainage divide. In consequence, high gradients in ~~E_{min}~~H_{min} and ~~E_{mean}~~H_{mean} form towards west, and gentle gradients arise towards east.

3.3 Gilbert ~~Metrics~~metrics: across divide differences at ~~hillslopes~~hillslope scale

The Gilbert metrics suggested by Forte and Whipple (2018) comprise three measures characterizing the local differences at drainage divides (i.e. channel head elevation, mean upstream relief, mean upstream gradient). Overall, a strong divide asymmetry at hillslope scale is only observed at the Salzach – Mur drainage divide (Fig. 5).

At the westernmost drainage divide of the Salzach catchment, elevations at channel heads (Fig 5, WS 1) lie in the range between 1100 m and 2600 m. At the Salzach basin, channel head elevations show ~~an~~a unimodal distribution with a mean value of 2044 m, while the distribution at the Inn / Adige basin is bimodal and has a mean value of 1977 m. Overall differences are small, but indicate a slight shift towards lower channel head elevations at the Inn / Adige side of the drainage divide. The upstream relief ranges between 200 m and 660 m and is uniformly distributed within the Salzach, but skewed-left distributed in the Adige catchment. Mean values of upstream relief are similar in the Salzach and Inn / Adige catchment with 386 m and 382 m, respectively. Analogous to the upstream relief, upstream gradient is uniformly and skewed-left distributed in the Salzach and Inn / Adige catchments, respectively. Values for upstream gradient are in the range of 0.2 and 0.8, with mean values of 0.45 for the Salzach and 0.44 for the Inn / Adige catchments. Beside outliers, upstream relief and upstream gradient appears slightly larger in the Inn / Adige catchment than in the Salzach catchment.

At the Salzach~~–~~ – Saalach drainage divide, differences in all Gilbert metrics are small. Elevation at channel heads (Fig 5, WS 2) ranges between 740 m to 1750 m with mean values of 1424 m and 1370 m at the Salzach and Saalach side of the divide. The upstream relief and the upstream gradient range between 250 m and 760 m, and between 0.35 and 1.1 in the Salzach and Saalach catchment, respectively.

While the eastern drainage divide, separating the Salzach from the Enns and the Mur catchments, features consistently large anomalies in χ, Gilbert metrics representing the hillslope scale indicate a largely symmetric Salzach – Enns, and a distinctly asymmetric Salzach – Mur drainage divide. Channel head elevation of the Salzach – Enns divide (Fig. 5, WS 3) ranges between 840 m and 2200 m, with mean values of 1206 m and 1296 m at the Salzach and Enns side of the divide. The lower channel head elevation is also reflected by a slightly higher mean upstream relief and mean upstream gradient in the Salzach, in comparison to the Enns catchment. Mean values are 351 m and 0.42 for the Salzach, and 343 m and 0.4 for the Enns catchment. The divide between Salzach and Mur catchments is characterized by the largest across divide differences in all Gilbert metrics (Fig. 5, WS 4). Elevation at channel head lies between 1350 m and 2220 m. On average, channel head elevation is distinctly lower in the Salzach catchment (1747 m) than in the Mur catchment (1982 m). Lower channel head elevations result in a larger mean upstream relief and higher upstream gradient for the Salzach (425 m, 0.5), in comparison to the Mur catchment (375 m, 0.42).

4 Discussion

Gilbert (1877) already recognized that cross-divide differences in erosion rate result in mobile watersheds, whereby catchments featuring higher erosion rates grow on expense of adjacent catchments with lower erosion rates. ~~Given~~In the simplest case with overall uniform ~~climate and lithology~~conditions, erosion rate increases with channel steepness in the drainage and topographic gradient in the hillslope domain. Hence, divide asymmetry evidences for drainage divide migration from the steep towards the less steep side (Gilbert, 1877; Willett et al., 2014; Robl et al., 2017b; Forte and Whipple, 2018). Asymmetry at drainage divides may occur at catchment, headwater and hillslope scale, but may not necessarily be observed at all these magnitudes. For example, an increase or decrease in drainage area due to a river capture event may cause a χ anomaly at the drainage divide, which predicts drainage divide mobility. However, if the signal – expressed by an upstream migrating knick point or knick zone – has not yet reached the divide, the divide may still be symmetric at the hillslope scale indicating divide stability at that time. Glacially controlled base level lowering (e.g. Hallet et al., 1996; Whipple et al., 1999; MacGregor et al., 2000; Brocklehurst and Whipple, 2002; Montgomery, 2002; Anderson et al., 2006; Haeuselmann et al., 2007; Züst et al., 2014) with an increase in local relief at the north facing side of divides may cause a strong asymmetry at hillslope scale, but will not result in an anomaly in χ maps, as long as the drainage network topology remains unchanged.

4.1 Challenges and limitations interpreting drainage divide asymmetries

A direct determination of present-day divide migration rates is ~~unfeasible,~~challenging as migration rates are in the range of millimeters per year (Goren et al., 2014) and major river capture events are rarely observed (Brocard et al., 2012; Yanites et al., 2013). In concert with sediment provenance (Frisch et al., 1998; Kuhlemann, 2007) and erosion rates based on cosmogenic nuclides (e.g. Dixon et al., 2016), topographic metrics serve as proxy for drainage divide mobility. ~~In particular,~~

Due to the superposition of climatic, tectonic and lithological signals in ~~mid-latitude~~tectonically active, glacially modified mountain ranges~~ such as the Eastern Alps, gradients in erosion rate reflect rather a transient landscape state due to glacial–interglacial periods, than across divide differences resulting from the reorganization of the drainage system. However~~, the interpretation of topographic metrics ~~derived from tectonically active, mid-latitude mountain ranges such as the Eastern Alps~~in terms of stable versus mobile drainage divides is not unique and paved with some pitfalls. ~~The~~ For example, the topography of the Eastern Alps ~~resulted from~~reflects different tectonic phases ~~and hence spatial~~with a spatiotemporally diverse vertical and ~~temporal changes in the~~horizontal crustal velocity field controlling uplift ~~pattern~~rates and horizontal advection (i.e. lateral extrusion) (Ratschbacher et al., 1989; Ratschbacher et al., 1991; Robl et al., 2008b; Bartosch et al., 2017)~~. Furthermore, hillslopes are abundantly at a critical slope angle affected by numerous landslides (Kühni and Pfiffner, 2001) and show in some regions a strong glacial imprint~~, changing climatic conditions governing peculiarity and even rates of erosional surface processes (e.g. Herman et al., 2013; Dixon et al., 2016), and substrate properties limiting the steepness of landforms as expression of the long-term tectono-metamorphic evolution of the mountain range (Schmidt and Montgomery, 1995; Kühni and Pfiffner, 2001; Schmid et al., 2004; Robl et al., 2015). In particular the strong glacial imprint altered topographic metrics and affected exhumation and erosion rates (e.g. Dixon et al., 2016; Fox et al., 2016), whereby the turnover time from glacial to fluvial landscape characteristics is controlled by lithology (Robl et al., 2015) and uplift rate (Prasicek et al., 2015). Then gradients in erosion rate reflect rather a transient landscape state due to glacial–interglacial periods than across divide differences resulting from the reorganization of the drainage system.

Across divide differences in χ may indicate spatial or temporal variations of climate (e.g. precipitation) or tectonics (e.g. uplift rate) (e.g. Whipple et al., 2013), but may also reflect the long term reorganization of the drainage network accompanied by changes in contributing drainage area (Goren et al., 2014; Willett et al., 2014; Robl et al., 2017b). Contrasts in bedrock erodibility may also result in differently steep channels despite uniform erosion rates. Even if channel steepness and erosion rate differ across drainage divides, divides may still be stable if differently steep channels result from spatial variations in uplift rate. Alternative formulations of the χ transform, considering spatial variation in uplift rate (Willett et al., 2014) and erosion rate (Robl et al., 2017a) have been presented, but information on the long term uplift / erosion pattern is sparse in the Eastern Alps. The curvature of channel profiles removed by the χ transform is introduced by the non-linear increase of discharge in downstream direction. However, instead of discharge (or peak discharge) contributing drainage area as proxy for discharge in rivers is employed by the detachment limited version of the stream power equation, which in its original form neglects spatial climatic variations, such as orographic precipitation. Yang et al. (2016) considered precipitation computing χ, but again long term precipitation rates are not well constrained and the control of precipitation on the geometry of river channels is still debated (e.g. Burbank et al., 2003; Dadson et al., 2003; Molnar, 2003; Reiners et al., 2003; Wobus et al., 2003; Hodges et al., 2004). Beyond methodical issues, the vertical distance between channel head and base level divided by χ is the average steepness of the channel, but provides no explicit information on the steepness of the dividing ridge itself. Consequently, a low increase in χ at the lower channel reach may result in a steep channel on average, and small χ values even at the channel heads. This, however, means that χ anomalies at drainage divides may indicate potential divide mobility in the future, rather than currently mobile divides. Without doubt, many factors and processes may lead to an amplification or emergence of across divide gradients in χ and complicate the interpretation of χ in terms of divide stability (Whipple et al., 2017; Forte and Whipple, 2018). As a strategy to counteract some of these pitfalls, a series of χ maps with progressively raised base levels narrows down the impact of spatial heterogeneity in tectonics and climate from catchment to headwater scale. This allows statements on the position of the disturbance within the drainage system and potential divide mobility in the far and in the near future.

While a transient state caused by changing climatic or tectonic conditions is often considered as the most likely reason for divide asymmetry, spatial heterogeneity may in principle reproduce the same topographic characteristics, but even in a steady state (e.g. Whipple et al., 2017). In the fluvial regime, contrasts in uplift rate, lithology, and precipitation play similar parts. The crucial question in this context is whether there is a sharp topographic contrast at the drainage divide or a gradual variation. In a steady state with only vertical tectonic movement, the local steepness of the topography is related to the properties at the respective point. Thus, sharp across-divide contrasts in topography require discontinuous variations in precipitation or lithology or the existence of active faults close to the drainage divide, i.e. a sharp contrast in uplift rate. However, drainage divides do not move towards such discontinuities in general (Robl et al., 2017b), so that sharp across divide contrasts in topography due to tectonics or lithology should be rare. This is, however, not necessarily true if horizontal advection is involved. Then a divide that is stable in an absolute frame is mobile in the moving system and thus asymmetric with a sharp contrast. The conditions for the development of such stable divides were investigated in detail by Eizenhöfer et al. (2019) by computing the crustal velocity governed by over-thrusting at a flat-ramp-flat geometry and modelling the response of the drainage system. Beyond this, contrasts in precipitation are another candidate for the origin of sharp asymmetries at drainage divides because the pattern of precipitation is influenced by the topography, although the control of precipitation on the geometry of river channels is still debated (e.g. Burbank et al., 2003; Dadson et al., 2003; Molnar, 2003; Reiners et al., 2003; Wobus et al., 2003; Hodges et al., 2004).

Concerning the question whether the across divide asymmetry of the topography is sharp or rather gradual, the analysis of stream profiles has only limited benefits as the stream power law does not capture the hillslopes. This limitation also affects all analyses based on the χ transform. The vertical distance between channel head and base level divided by χ is the average steepness of the channel, but provides no explicit information on the steepness of the dividing ridge itself. Consequently, a low increase in χ at the lower channel reach may result in a steep channel on average, and small χ values even at the channel heads. Even if a stable divide can be excluded by other arguments, this implies that χ anomalies at drainage divides may indicate potential divide mobility in the future, rather than currently mobile divides (Forte and Whipple, 2018). Without doubt, many factors and processes may lead to an amplification or emergence of across divide gradients in χ and complicate the interpretation of χ in terms of divide stability (Whipple et al., 2017; Forte and Whipple, 2018). As a strategy to counteract some of these pitfalls, a series of χ maps with progressively raised base levels narrows down the impact of spatial heterogeneity in tectonics and climate from catchment to headwater scale. This allows statements on the position of the disturbance within the drainage system and potential divide mobility in the far and in the near future.

In this context, the question may arise whether χ mapping, i.e., the consideration of χ alone without regard to differences in elevation, is as good as computing an average channel steepness from the differences in elevation and in χ values. According to Eq. (5), the slope of a χ transformed river profile is a proxy for the erosion rate at given erodibility. The χ values at the end of the rivers would be inversely proportional to this slope if they were at the same elevation everywhere. This means that both approaches are equivalent if the steepness of the hillslopes is the same at both sides of the drainage divides. Otherwise, the interpretation of χ maps is not entirely free from an influence of the hillslopes, even if the lower limit of catchment size is large enough to ensure the applicability of the stream power law. If the hillslopes at one side are steeper, the channel heads (here defined by a minimum drainage area of 1 km²) are at a lower elevation, so that the consideration of χ alone overestimates the mean steepness of the channel. This means that χ mapping implicitly captures the steepness of the hillslopes to some degree if applied across drainage divides. With regard to the relevance of the hillslope regions for the migration of the drainage divides, this might even be seen as an advantage of χ mapping over mean channel steepness.

The Gilbert metrics, a set of local topographic measures, characterize hillslopes at both sides of the investigated divide (Forte and Whipple, 2018) and hence the (a) symmetry of the divide itself. In contrast to χ mapping, there are no far field effects and significant asymmetry of the dividing ridge should correspond in principle to across divide gradients in erosion rate and divide mobility. However, in active, ~~mid-latitude~~glacially modified mountain ranges, several factors and processes make the interpretation of these metrics challenging. Landslide-controlled threshold hillslopes emerge, where incision rates in the drainage system are high (Montgomery et al., 2001). Then the relationship between topographic gradient and hillslope erosion rate breaks down, and dividing ridges become symmetric although they feature across divide gradients in erosion rate and migrate. For the European Alps, an average limiting slope stability angle of 25° is reported (Schmidt and Montgomery, 1995; Kühni and Pfiffner, 2001), so that most of the divides in the study area are prone to landsliding. However, in particular within the formerly glaciated realm of the Alps, many of the non-soil mantled hillslopes are distinctly steeper and still feature glacial landscape characteristics (Robl et al., 2015). There, local metrics such as relief, gradient or channel head elevation rather indicate the impact of the last glaciations on topography than long-term trends in drainage network reorganization. Glacial overprint does not primarily affect the first order drainage networks, but has a strong impact on local relief (e.g. Brocklehurst and Whipple, 2002; van der Beek and Bourbon, 2008; Norton et al., 2010; Salcher et al., 2014). Aspect-controlled differences in relief formation due to glacial erosion (e.g. north versus south facing mountain flanks) result in local, reversible compensating motions of the divides (Robl et al., 2017a) that may counteract the regional trend during the ~~turn overtime~~turnover time from glacial to fluvial landscapes. Hence, such local disturbances cover large~~-~~-scale and long~~-~~-lasting changes in the drainage network topology. Generalized swath profiles and χ maps with a base level at the headwaters may bridge the gap between catchment and hillslope scale and assist detecting local peculiarities as described above.

Summarizing, the major advantage of Gilbert metrics lies in the analysis of short wavelength – high amplitude signals, e.g. the development of escarpments (e.g. Tucker and Slingerland, 1994). In contrast, the reorganization of drainage patterns forced by tectonic processes represents a ~~high~~large length scale – low amplitude signal taking place in millions of years (Robl et al., 2015), which can be targeted ~~best~~ by the calculation of χ maps. Headwater processes and the position of the erosional signal can be addressed by varying the base level for the χ transformation and the extraction of generalized swath profiles. We hereinafter discuss the ~~mobility~~behaviour of the drainage divides in consideration of the described pitfalls.

4.2 Mobility of Drainage Divides in the Eastern Alps

~~Our results imply that drainage divides of the investigated catchments are mobile and follow a general trend: at north – south running drainage divides, tributaries feature lower χ values west of the dividing ridge and hence are steeper on average than tributaries draining towards east (Fig. 2). Given uniform tectonic, climatic and lithological conditions, steeper channels are characterized by higher erosion rates (e.g. Howard, 1994), so that the observed morphological divide asymmetry at the Salzach – Enns, Salzach – Mur and Inn – Salzach watersheds may result in erosion rate gradients across the divides. However, uniform tectonic and climatic conditions and substrate properties on the scale of major drainage systems cannot be assumed in a tectonically active mountain range, such as the Eastern Alps. This means that the observed χ pattern may not necessarily indicate migrating divides, but may result from spatial variations on climate (e.g. precipitation, Yang et al., 2016) and tectonics (e.g. uplift rate, Willett et al., 2014). However, progressively increasing the base level for χ computation and shifting the observational scale from presumable tectonically and climatically heterogeneous catchments to their more homogenous headwaters shows no qualitative changes in the χ pattern. The χ anomalies across the divides remain up to a baselevel of 800~~

~~m (Fig. 2, 3) and indicate that divides are mobile. However, this trend in χ breaks down at some divides for a base level of 1000 m characterizing the very headwaters, only.~~

As discussed in the previous section, the observed asymmetry of drainage divides observed in the study region, with steep western and less steep eastern sides may in principle result from spatial heterogeneity at the drainage divides with sharp contrasts in uplift rate, substrate properties or precipitation. Furthermore over-thrusting along ramps may result in asymmetric but still stable drainage divides. Hence, divide asymmetry does not necessarily indicate divide mobility. However, there is no evidence that the drainage divides analysed here follow such lithological or tectonic structures. Sharp contrasts in precipitation would require (i) a sequence of decrease, recovery, and decrease in precipitations rate in east-west direction and (ii) an inversion of the north-south contrast along a drainage divide (WS1), both at rather small scales. Furthermore, the observed west – east asymmetry of divides is not consistent with the thrusting direction of major alpine units, which occurred roughly from south to north. In consequence, it appears unrealistic that the observed pattern is entirely controlled by climate, lithology or active faults, although some influence of climate (and also of tectonics or lithology) cannot be excluded. Summarizing, the known long-term reorganization of the drainage network (Frisch et al., 1998; Frisch et al., 2001) accompanied by changes in contributing drainage area appears to be the most likely interpretation of the observed topographic pattern and is enhanced by progressively increasing the base level for χ computation. Shifting the observational scale from presumable tectonically and climatically heterogeneous catchments to their more homogenous headwaters shows no qualitative changes in the χ pattern. The χ anomalies across the divides remain up to a baselevel of 800 m (Fig. 2, 3). Our results, therefore, suggest that drainage divides of the investigated catchments are mobile and follow a general trend. At north – south running drainage divides, tributaries feature lower χ values west of the dividing ridge and hence are steeper on average than tributaries draining towards east (Fig. 2). However, this trend in χ breaks down at some divides for a base level of 1000 m characterizing the very headwaters, only.

Gilbert metrics characterizing divides at hillslope scale are consistent with the χ pattern at the Salzach – Enns and Salzach – Mur drainage ~~divide~~divides and indicate that these divides are currently mobile. However, and in contrast to the χ pattern (up to a base level of 800 m), they indicate divide stability at the Inn – Salzach drainage divide (Figs. 2, 3). In particular at the latter divide, glacial landforms such as cirques and U-shaped valleys are abundant and we interpret the missing hillslope scale asymmetry of this divide as a result of glacial erosion, which temporally stops divide migration~~.~~ (Robl et al., 2017b). However, Robl et al. (2017a) showed that the impact of variable glacial erosion across divides is small and reversible. We suggest that the topographic signal of cold climate processes, primarily acting during the Pleistocene, locally obscures the large-scale signal of drainage network reorganizations in many parts of the Eastern Alps and in general limits the applicability of Gilbert metrics in glacially shaped mountain ranges.

~~The peculiar west – east directed~~We suggest that the proposed drainage divide migration ~~of drainage divides~~from west to east is inherently linked to the plan view geometry of the Salzach and Enns catchments south of the Northern Calcareous Alps (Figs. 1, 2, 6). In this domain, the main stem of the Salzach and Enns still follows the SEMP, which is one the major tectonic lineaments of the Eastern Alps (Wang and Neubauer, 1998). It has been proposed that during the Mid-Miocene, Salzach and Enns formed a common catchment with an east-directed flow path (e.g. Neubauer, 2016), but were separated by major river piracy events due headward eroding south – north draining rivers (Kuhlemann et al., 2001; Dunkl et al., 2005; Robl et al., 2008a). As a consequence, the major portion of the Salzach and Enns drainage areas are located west of their capture points and by reversing the flow direction only to a minor amount east of the capture points. This is consistent with the current asymmetry of the catchments, with a large western and a small eastern sub-catchment and explains the observed across divide gradients in χ. Long east-directed channel segments in concert with distinctly elongated catchments result in a slow decrease in catchment size in upstream direction. ~~Hence, χ, which is the measure for upstream flow length after channel length profile linearization (c transform, Perron and Royden, 2013; Royden and Perron, 2013),~~Hence, χ accumulates to large χ values at the western and low χ values at the eastern drainage divides. Integrating from a common base level up to the same channel head elevation, large and small χ values on different sides of a common divide (Inn / Salzach, Salzach / Enns and Salzach / Mur divides) are the expression of a low and high average channel steepness of long west–east and short east–west draining channel segments, respectively. This, however, implies that observed χ anomalies at the investigated drainage divides are the consequence of the Early to Mid-Miocene lateral extrusion tectonics (Ratschbacher et al., 1989; Ratschbacher et al., 1991), where the activity of crustal scale faults imposed non-ideal flow-direction to major rivers~~.~~ (Robl et al., 2008b; Robl et al., 2017a). The indicated drainage network reorganization from orogen-parallel to orogen-perpendicular flow is a long-lasting process. While river piracy events cause a sudden large-scale modification of the drainage network, drainage divide migration and flow direction reversal is a slow continuous process at rates of few millimeters per year (Goren et al., 2014), which explains the longevity of morphological disequilibrium after changes in the tectonic forcing.

4.3 Stability of divides for different evolutionary states

Based on provenance analyses and geomorphological studies, it has been proposed that different tectonic phases have triggered a repeated reorganization of the drainage system since the onset of topography formation in the Eastern Alps (Frisch et al., 2000; Kuhlemann et al., 2001; Dunkl et al., 2005; Kuhlemann, 2007; Keil and Neubauer, 2009; Neubauer, 2016). As the position of past drainage divides is not well constrained, we test if and how different catchment geometries, roughly mimicking the catchment geometry suggested for different phases of the drainage evolution, affect the stability of drainage divides (Fig. 7). We focus on the plan view geometry of catchments only and do not consider potential topographic (e.g. uplift of the Northern Calcareous Alps) or base level ~~changes (e.g. inversion of the northern foreland basin, the Molasse basin).~~ (e.g. inversion of the northern foreland basin, the Molasse basin) changes. In order to create the proposed drainage patterns for different time slices, we dammed valleys and forced rivers to drain across prominent wind gaps (see Fig. 1 for wind gaps), which changes the large scale system of rivers but leaves the small scale network topology unaffected. As the χ computation considers the network topology only and does not require further topographic information, it is not a problem here that the topography of the Eastern Alps during the evolution is not well constrained.

For the period of lateral extrusion during the Early to Mid-Miocene, it was suggested that the Salzach and Enns formed a common drainage system (Paleo-Enns) with an orogen-parallel flow path following the SEMP fault from west to east (Fig. 7a) (Frisch et al., 1998). Compared to the present-day drainage pattern (Fig. 7d), the elongated catchment with its long main stem and numerous short tributaries contributing drainage area from south and north~~ cause~~, causes very high χ values at the eastern domain of the drainage system. In particular, the Inn – Paleo-Enns drainage divide is characterized by high across divide gradients in χ, but even the southern drainage divide between Paleo-Enns and Drau indicates a strong χ anomaly. This suggests that the Early to Mid-Miocene situation, with elongated catchments featuring hundreds of kilometers of orogen-parallel flow, were prone to river piracy events and the migration of drainage divides.

The timing of the following drainage network reorganization is not well ~~constrained~~known. However, streams originating south of the SEMP fault and draining towards the northern foreland basin eroded headwards and captured the eastward draining Paleo-Enns (Salzach – Enns) drainage system (Frisch et al., 1998). Currently, two rivers, the Salzach and the Enns, follow the SEMP for more than 100 km each, but abruptly change their course in a knee-shaped bend towards north~~.~~ (Fig. 1). These sudden changes in flow direction most likely indicate capture points. In addition, a suspicious wind gap separating the Saalach from the Salzach valley with a vertical drop of only a few meters (Fig. 1) may indicate that the Paleo-Enns was once captured by the Saalach River, but redirected again potentially during the Pleistocene glaciations (Robl et al., 2008a) (Fig. 7b, c).

Although not yet constrained by provenance studies, a potential capture of the Paleo-Enns drainage system by the Saalach River would stabilize the westernmost drainage divide (Inn – Saalach divide). This is indicated by a decrease of the across divide χ gradient similar to the present situation (Fig. 7d). However, in this scenario, the western drainage divide of the Enns catchment shows a distinct across divide χ gradient with high χ values at the Paleo-Enns and low χ values at the Saalach side of the divide, which would result in a progressive flow direction reversal of the upper Enns River.

It is still debated ~~when~~at which time the orogen-parallel Paleo-Enns River was captured by the south–north draining Salzach River (Fig. 7c). A Pleistocene, glacial-induced activation of the northward directed drainage outflow and blocking the passage at the Saalach – Salzach ~~windgap~~wind gap is discussed (Robl et al., 2008a). ~~However, a~~A similar event recently happened in Yukon, Canada due to climate warming and glacial retreat (Headley, 2017; Shugar et al., 2017). Assuming a Pleistocene capture event due to waxing or waning of glaciers, the origin of the Salzach (similar to the nearby Lammer River) must have inevitable been located south of the NCA. Beyond others, one argument for such a scenario is the small amount of flow reversal of the former Enns River east of the capture point. However, the concurrent drainage through Saalach and Salzach valley would lead to the disappearance of the χ gradient across the Saalach and Salzach watershed (Fig. 7c). The watershed separating Salzach from Enns basin complies with the present-day location of the watershed (Fig. 7c, d) and the χ distribution shows a similar χ anomaly indicating an eastward drainage divide migration as proposed for the present-day situation.

5 Conclusion

The tectonic evolution of the Eastern Alps caused a repeated reorganization of the drainage network since onset of topography formation in the Late Oligocene / Early Miocene. We applied various morphometric methods to constrain the potential mobility of drainage divides on catchment, headwater and hillslope scale. Based on our analysis, we came to the following conclusions.

- Almost all drainage divides of the investigated domain are asymmetric at catchment, headwater, and even hillslope scale, which evidences for drainage divide mobility, where the steeper side of the divide migrates towards the less steep side of the divide.
- It turned out that the western side of the considered drainage divides is in general steeper than the eastern side, so that the general direction of divide migration is west towards east. This implies that the Inn catchment grows on expense of the Salzach catchment and the Salzach catchment consumes tributaries of the Enns and Mur catchments.
- At some divides, metrics characterizing hillslopes (Gilbert metrics) are not consistent with those characterizing larger scales. We found that glacial imprint locally obscures large-scale signals of drainage network reorganization. Hence, the applicability of the classical Gilbert metrics in ~~mid-latitude~~glacially modified mountain ranges such as the Eastern Alps is limited.
- The~~ reason for the~~ general drainage migration trend from west towards east is probably caused by the geometry of catchments, which dates back to the period of lateral extrusion in the Early to Mid-Miocene. The activity of major faults north and south of the central axis of ~~eastern~~the Eastern Alps imposed non-ideal, orogen-parallel flow directions to major rivers. Subsequent capture events restored orogen-perpendicular flow, but relics of the lateral extrusion period remained: elongated catchments west of the capture point, with an about 100 km long east-draining main stem and short tributaries draining south–north and north–south.
- ~~A rough restoration of~~Analysing catchment geometries that roughly mimic the drainage ~~networks~~pattern from Early to Mid-Miocene towards the present situation shows that anomalies in χ at the divides decreased, indicating that divide stability increased over time. Currently, large across divide gradients in average channel steepness (and hence erosion rate) occur mostly at north~~–~~–south running watersheds (i.e. Inn – Salzach, Salzach – Enns, Salzach – Mur), where tributaries with short and long flow lengths from channel heads to the base level meet at the divides. However, as continuous divide migration is slow and major capture events at these divides are not expected, we suggest that the observed disequilibrium is long-lasting.

Timing of river piracy events and rates of drainage divide migration are still not well constrained. There is great need for additional provenance studies of river sediments, and dating river terraces and cave sediments.

Data availability

The EU-DEM (data funded under GMES, Global Monitoring for Environment and Security preparatory action 2009 on Reference Data Access by the European Commission) is available from the European Environment Agency.

Author contribution

GT and JR conceived the study. SH and JR developed the algorithms for χ mapping and the calculation of generalized swath profiles. GT performed the geomorphological analyses. FN contributed to the understanding of the tectonic evolution of the study area. All authors contributed to the final form of the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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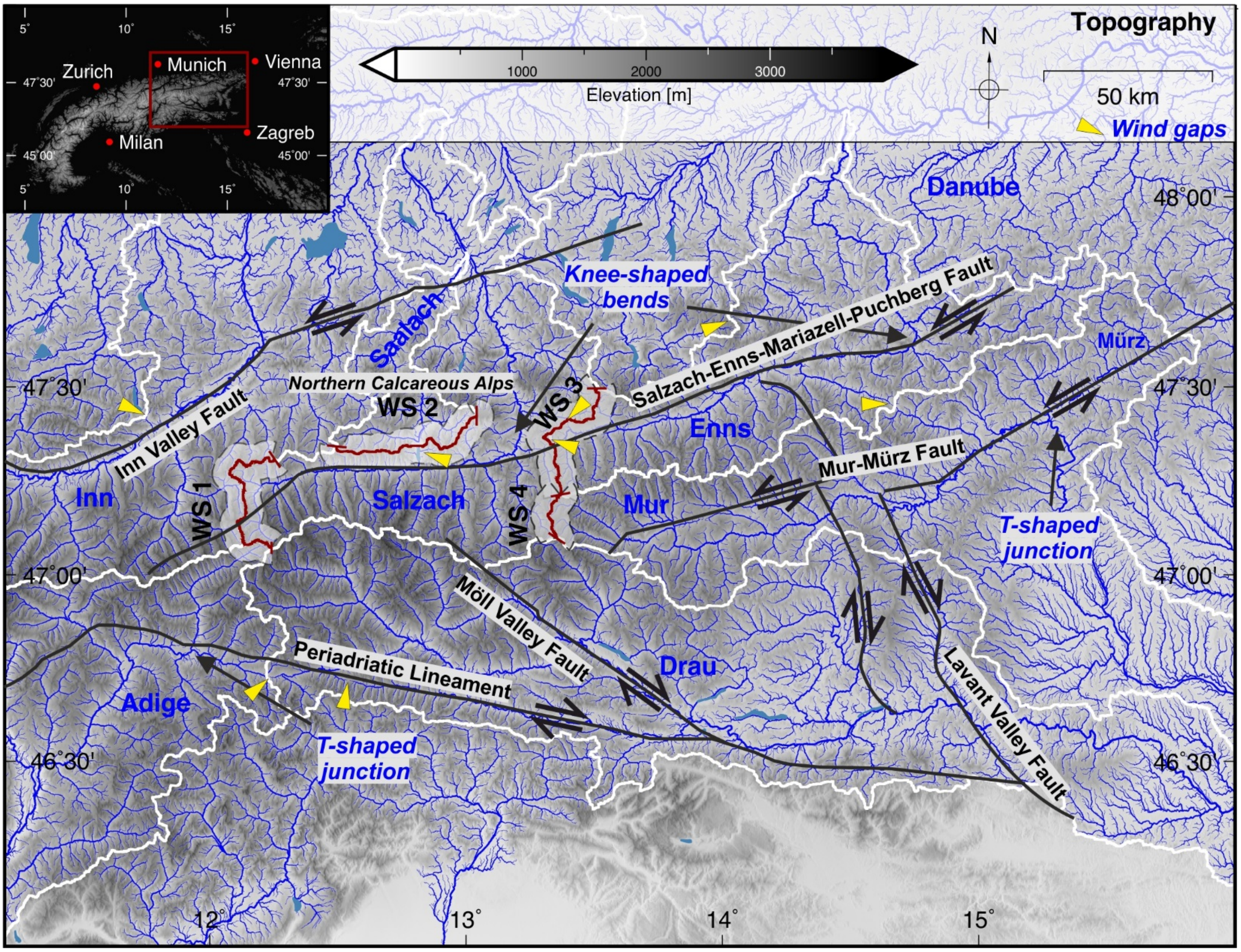

Figure 1. Topographic map of the study area and the drainage pattern of the Eastern Alps. The inset shows the position of the study within the European Alps. Blue lines indicate the drainage pattern, whereby the line width is proportional to $\log_{10}$ of the contributing drainage area. Drainage divides are shown by thick white lines. Major faults are indicated by solid black lines and the direction of motion is shown by ~~arrow~~arrows. The red line and the grey hull indicate the course of the swath profiles shown on Figure 3. Yellow triangles illustrate the occurrence of prominent wind gaps.

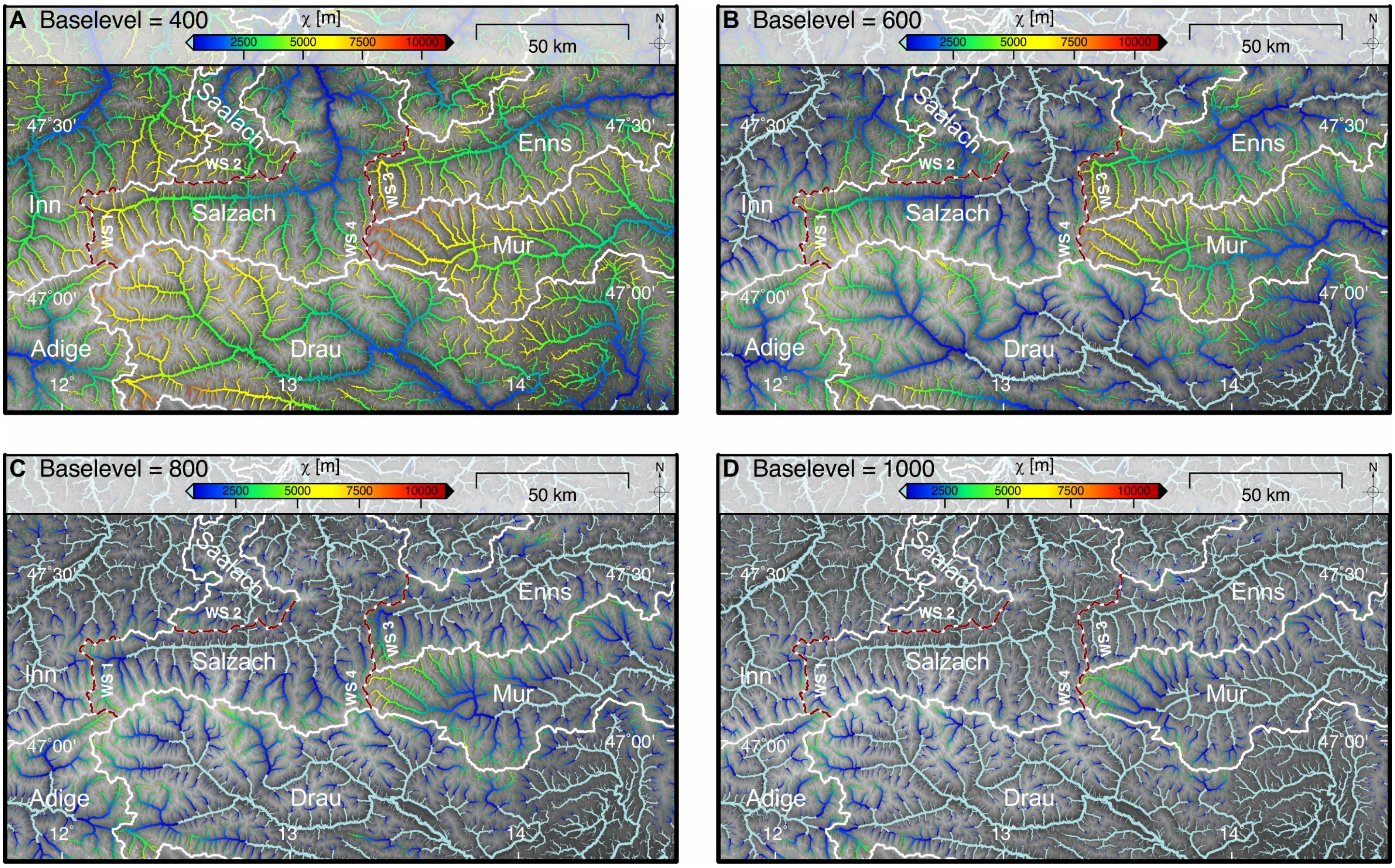

Figure 2. Drainage pattern of the Eastern Alps calculated for increasing baselevels and color-coded for χ. All streams with a contributing drainage area larger than 1 km² are shown. The line width of the channels is proportional to $\log_{10}$(drainage area). White lines and annotations represent the major drainage divides. (A) Baselevel set to 400 m of elevation. (B) Baselevel set to 600 m of elevation. (C) Baselevel set to 800 m of elevation. (D) Baselevel set to 1000 m of elevation.

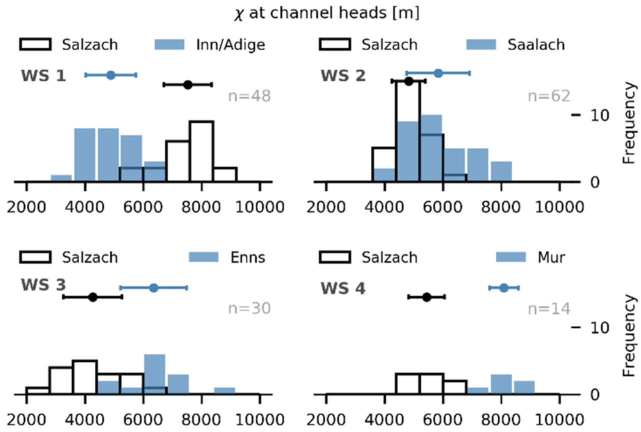

Figure 3. ~~χ values measured at channel heads (Forte and Whipple, 2018)~~ **χ values measured at channel heads of the investigated catchments. Histograms with a black outline represent the Salzach drainage basin. Histograms with a blue filling represent the adjacent Inn/Adige (WS 1), Saalach (WS 2), Enns (WS 3) and Mur (WS 4) drainage basins~~.~~ with n as the total number of data points. Data are divided in 10 equally-spaced bins. Error bars indicate the standard deviation and filled circles are the mean values of the dataset.** ~~n is the total number of data points.~~

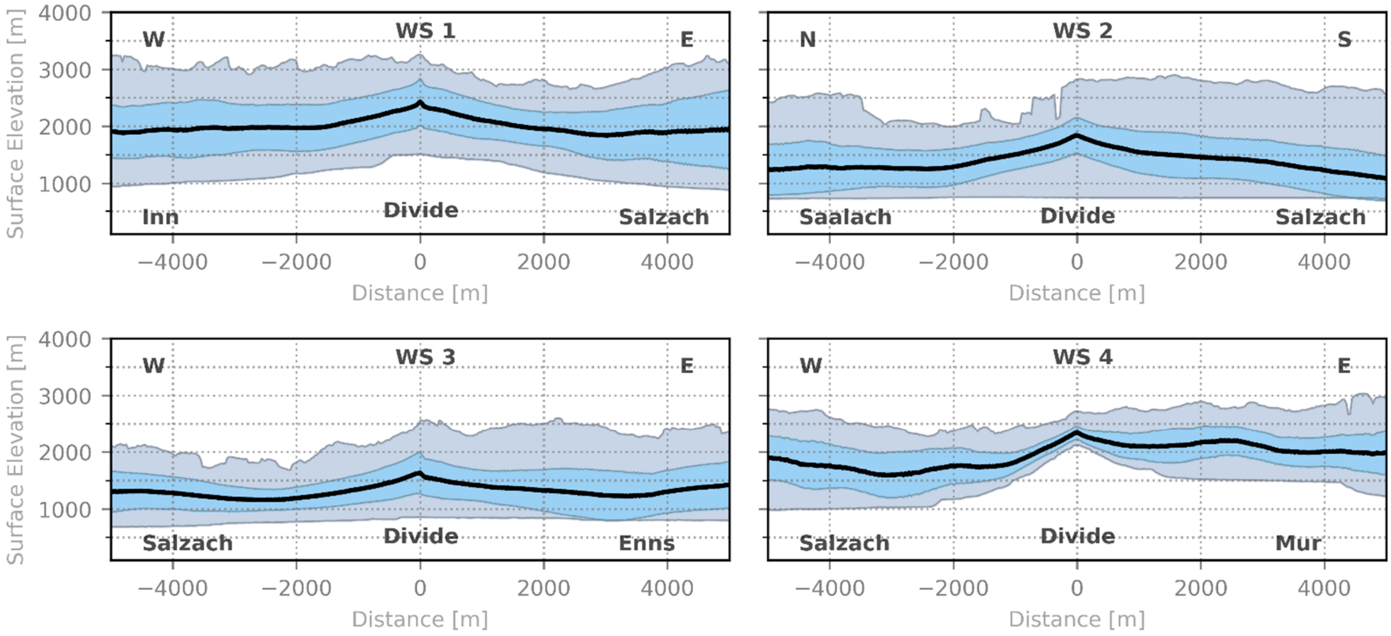

Figure 4. Generalized swath profiles ~~(Hergarten et al., 2014) along the profile lines shown in Figure 1.~~<u>(Hergarten et al., 2014) across the profile lines (drainage divides) shown in Figure 1.</u> The profiles have a half-width of 5 km to each side of the profile line (drainage divide). The black line indicates the mean elevation. The hull of the blue area is the standard deviation and the hull of the grey area the extreme values within the swath segments.

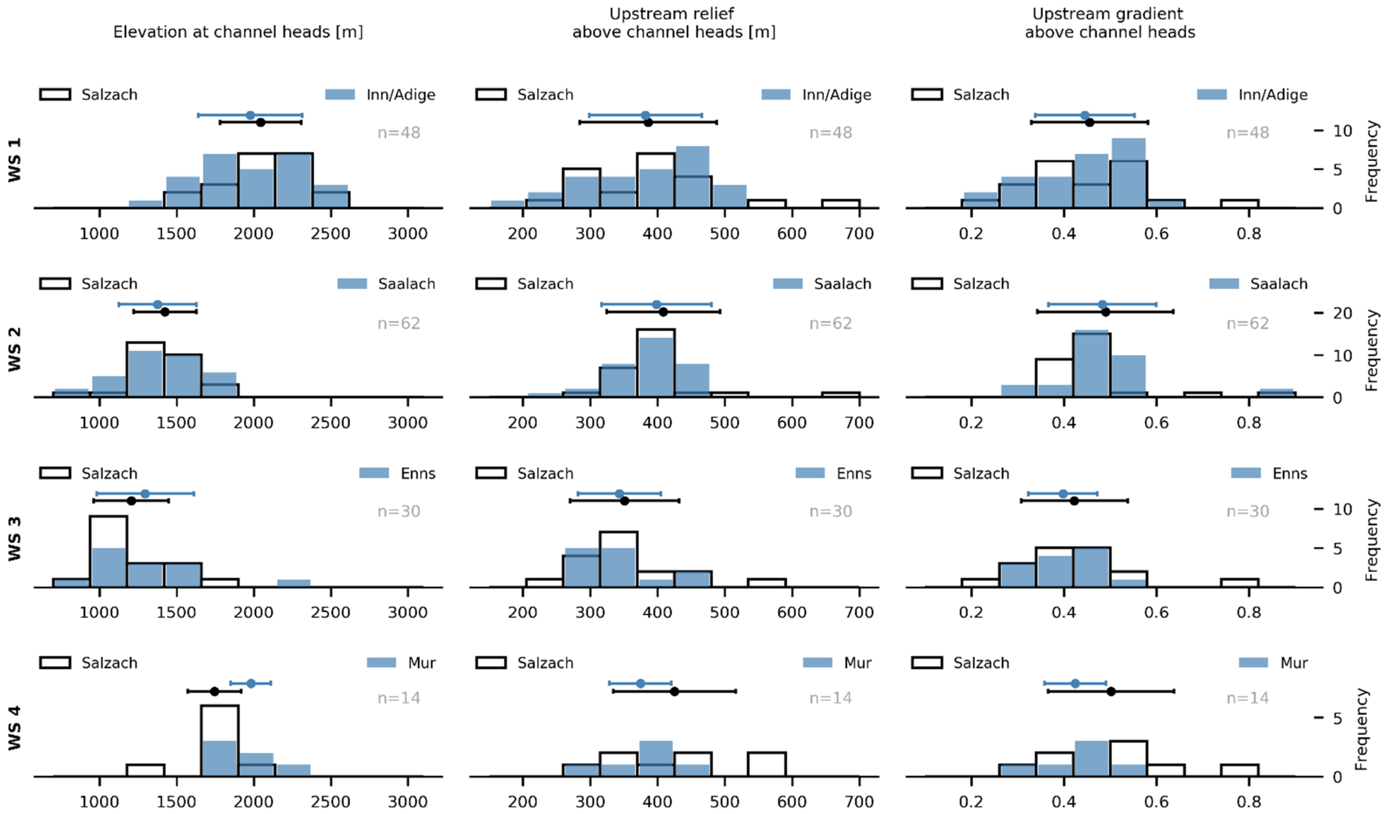

Figure 5. Gilbert metric histograms (Forte and Whipple, 2018) for the investigated watersheds of the study area. Histograms with a blue filling represent the adjacent Inn/Adige (WS 1), Saalach (WS 2), Enns (WS 3) and Mur (WS 4) drainage basins~~.~~ with n as the total number of data points. Data are divided in 10 equally-spaced bins. Error bars indicate the standard deviation and filled circles are the mean values of the dataset. ~~n is the total number of data points.~~

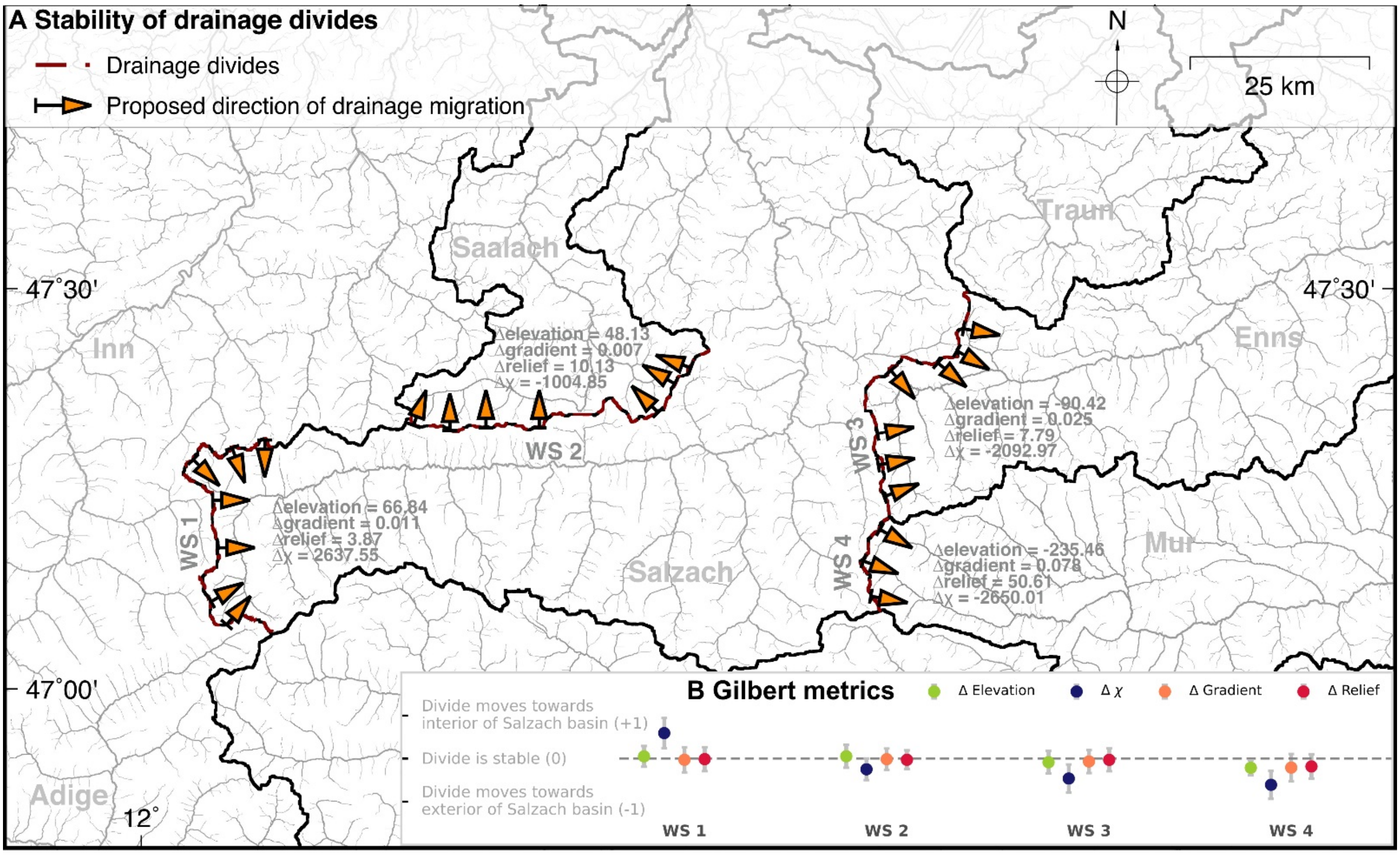

Figure 6. Proposed direction of drainage migration of the main drainage divides of the study area. (A) The major drainage basins are annotated. Orange arrows indicate the proposed migration direction of divides based on ~~χ.~~ χ. Gilbert metrics for each investigated catchment are shown. Positive ΔElevation and ~~Δχ~~ Δχ values as well as negative ΔRelief and ΔGradient indicate migration towards the Salzach drainage basin. (B) Normalized ~~Δplot~~ Δ plot of Gilbert metrics. Negative values of ΔRelief and ΔGradient are standardized to positive values such that all positive values indicate a migration towards the Salzach basin. Error bar and filled circles indicate 1 – standard deviation and mean values, respectively.

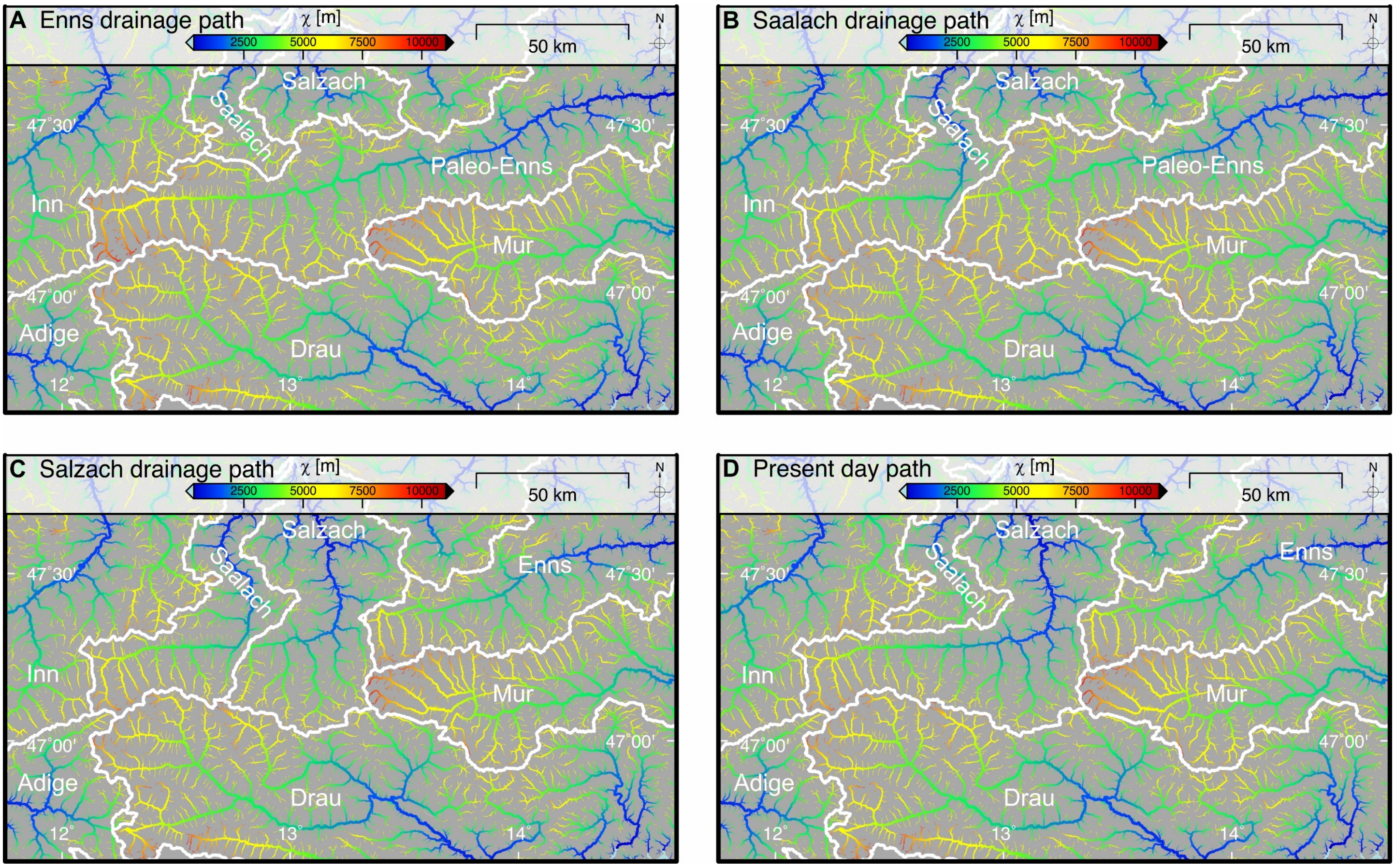

Figure 7. ~~χ~~χ colored drainage pattern of reconstructed paleo drainage geometries of the Eastern Alps. All streams with a contributing drainage area larger than 1 km^2 are shown and the line width of the channels is proportional to log$_{10}$(drainage area). The baselevel for ~~χ~~χ computation is set to 400 m. White lines and annotations represent the major drainage divides. (A) Enns drainage path ~~-~~– drainage scenario assuming an elongated Enns catchment representing the Mid-Miocene situation as ~~suggest~~suggested by Frisch et al. (1998). (B) Saalach drainage path ~~-~~– drainage scenario assuming that the Saalach captured the westernmost part of the Paleo-Enns catchment. (C) Salzach drainage path ~~-~~– drainage scenario assuming that both Saalach and Salzach took over parts of the Paleo-Enns catchment as suggested by Robl et al. (2008a). (D) Present day drainage ~~path~~pattern for comparison.