<u>Response to reviewer and public comments</u>

esurf-2016-29 Manuscript

"Glaciation's topographic control on Holocene erosion at the eastern edge of the Alps

By Jean L. Dixon, F. von Blanckenburg, Kurt Stüwe, and Marcus Christl

<u>Pierre Valla – Reviewer 1</u>

Thank you to Pierre Valla for his complete and insightful review. Below we detail how we address the reviewer's comments.

This is a very interesting, well-written and presented manuscript. The authors have really well introduced their work with a comprehensive review of the literature and presentation of the open questions concerning the late evolution of the European Alps. They propose new detrital 10Be-derived erosion rates that nicely complement previous observations in the Eastern Alps and have performed a detailed topographic analysis to discuss their dataset and the spatial variability of catchment-wide erosion rates over the entire European Alps. As such this study represents in my opinion a valuable contribution and will have potential of great interest for the community. I have some questions and suggestions, mainly to better clarify some of the results and their interpretation, and have outlined them in a set of general and specific comments below.

We thank the reviewer for this assessment of the manuscript.

General Comment 1: Structure: the present manuscript is overall well-structured, with clear "Introduction" and "Approach" sections. However, the merged section 3 "Results and Discussion" is sometimes quite difficult to follow between the different sub- sections. I would suggest the authors to separate the results from the discussion which may be easier to follow for the readers.

We have separated the results and discussion into two sections in our revision. We believe this edited structure helps improve the logical flow of the manuscript.

General Comment 2 - 10Be-derived basin erosion rates: the new results for 26 basins presented by the authors are really interesting and nicely complement previous investigations of Holocene erosion rates across the European Alps. However, I would recommend the authors to provide more discussion about the possible bias in calculated erosion rates from local complexities and the resulting implications for their story. I have listed some detailed questions below, especially concerning the integration times, snow-cover correction, the sediment grainsize, the approach for floodplains and non-quartz bearing areas. . . Moreover, some discussion about the (previously) glaciated catchments would be helpful for ESurf readers concerning the re-mobilization of morainic/glaciogenic material, or the glacial perturbation on 10Be concentrations which might be non-negligible for slowly-eroding terrains (e.g. Glotzbach et

al., 2014 Terra Nova). Finally, the compilation of existing 10Be-derived basin erosion rates from the literature is very interesting and nicely put the new dataset into a broader context. I am wondering if 10Be-derived basin erosion rates have been directly taken from published papers, or if the authors have recalculated the erosion rates with a uniform/updated production rate? If not, maybe discuss also this point and potential implications.

The reviewer points out several important points that we clarify in the revised manuscript. We made several assumptions regarding erosion rates in the glaciated basins that we now better address.

A) Glacial perturbation on ^{10}Be concentrations

The reviewer is correct that the glacial history of several of our catchments may influence cosmogenically derived erosion rates in ways we do not address. Firstly, glacial perturbations may result in non-trivial differences between erosion rates calculated assuming either steady or non-steady state 10Be concentrations, especially in slowly eroding terrain (e.g., Glotzbach et al., 2014). We now compare erosion rates derived from steady state assumptions to those derived using non-steady state calculations from Lal 2001. In the case of our glaciated catchments, with erosion rates between 170-230 mm/ky, assuming 10Be concentrations have reached steady state may result in the overestimation of erosion rates by 9%. This assumption results in a non-trivial, but still relatively small bias to calculated erosion rates considering our glaciated basins erode roughly a factor of two times faster than non-glaciated basins, and up to a factor of five times faster than background erosion rates near 40 mm/ky. We address this assumption and bias in the revised manuscript, and additionally reference Glotzbach et al. (2014), Wittmann et al. (2007) and Norton et al. (2010) who have previously addressed this issue.

The reviewer also requests that we address other impacts of glaciation on ^{10}Be signals, such as the re-mobilization of glaciogenic material. Though we do not have data that speak directly to this issue, we expand our discussion of results in the revised manuscript to more broadly discuss the varied complications that arise using ^{10}Be concentrations in previously glaciated terrain. Wittmann et al. (2007) and Delunel et al. (2014) suggest glaciogenic sediment may contain inherited ^{10}Be concentrations if glaciers have incompletely zeroed surface concentrations via shallow erosion or if glacial advance overrode soils and later incorporated them into glacially eroded sediments. In this case, ^{10}Be concentrations may instead underestimate erosion rates, though this effect should be the largest in currently glaciated or recently glaciated catchments. Furthermore, Wittmann et al. (2016) measured ^{10}Be concentrations upstream and downstream of several glacial features that may influence sediment storage: deep lakes formed during glacial retreat and large moraine amphitheaters). These authors found negligible effects of sediment storage on ^{10}Be concentrations.

B) Compilation of erosion rates

In the submitted manuscript, figure 7 shows erosion rates previously published across the Alpine range. In this original compilation, we did not recalculate erosion rates using a uniform or updated production rate. Our intent was to show the range and variability of erosion rates, and not to publish a comprehensive compilation of erosion rates. However, considering that differences in assumed production rates between published studies may alter the data shown in this figure, in our revised manuscript we recalculate erosion rates to a consistent sea level, high latitude production rate of 4 at/g/yr, regardless of the original scaling factors used. This rescaling of published erosion rates to a consistent production rate does not significantly alter this figure, nor change interpretation of the

data across the Alps. However, it does increase the usefulness of our compilation and improve comparison of rates across disparate studies.

General Comment 3- Topographic metrics: the authors provide a detailed topographic analysis of the studied catchments with a special attention on mean basin slopes and slope distributions within the basins. I would suggest to also report other metrics, such as hypsometry or local relief to strengthen their message (see also specific comments below).

We have added measurements of mean local relief into the manuscript, and the data is now provided in table 2.

Finally, the authors discussed in some sections the role of fluvial incision and river response to potential perturbations, but this would be better illustrated with some river profiles shown as a new figure. This will clearly help readers to evaluate the degree of disequilibrium in river profiles, and potential differences between regions/massifs or glaciated vs. non-glaciated catchments.

We choose to focus our analyses on hillslope processes within catchments rather than fluvial. The manuscripts by Legrain et al. (2015) and Robl et al. (2008) have previously presented and discussed detailed river profiles across our study region of the Austrian Alps. However, our figure 6 does provide accumulation area scaling of local slope gradients and allows us to compare how hillslope gradients and channel slopes both vary across our catchments.

Specific comments, by line number: - Page 1, lines 26 and 27: "poor topographic indicators of controls" (l.26) contradicts with the end of the next sentence "its topographic legacy" (l.27). Maybe rephrase the sentence on line 26 (which also appears in contradiction with the manuscript's title).

This text has been deleted.

Page 2, lines 14-15: "suggest that glacial forcings are the dominant control on land- scape evolution in mountain belts". This sentence reads vague and quite general, maybe rephrase to precise in which mountain belts (mid- and high-latitudes?) and over which timescales (Plio-Quaternary?).

This sentence now specifically references "modern mid- and high-latitude mountain belts".

Page 2, line 26: "have been invoked as principle drivers of erosion and uplift". Maybe cite also there Fox et al. 2015 (Geology).

Citation added.

Page 2, line 28: "post-glacial erosion may explain rates of uplift in the region via isostasy". Please clarify the timescales over which this correlation is valid, i.e. Holocene for erosion rates from Wittmann et al. (2007) and historical/modern for uplift rates (leveling data from Schlatter et al., 2005).

This section now explicitly notes that Wittman compared millennial-scale erosion rates to modern rates of uplift.

Page 2, line 29: "youthful tectonic features such as river knickpoints". Please rephrase, river knickpoints can have several origins and as rightly stated after ("correlated with previous glacial cover. . .") these are not tectonic markers.

We have removed the interpretation of 'youthful tectonic features' and simply note that Norton et al (2010) correlated knickpoints to glacial extent.

Page 3, line 8: "erosion rates". Please specify the timescale "post-LGM/Holocene" for these erosion rates.

Changed.

Page 3, lines 13-14: Please indicate the massifs, basins and other important locations on Figure 1 for clarity.

We have labeled more locations in the figure for context.

Page 3, line 17: "that has uplifted some 300 m above sea level in the last 7 Ma". Please add a reference here if possible.

Reference added to Legrain et al., 2014.

Page 3, line 18: "Massifs" corrected by "massifs".

Corrected

Page 3, line 27: "This timing coincides with inversion and uplift of the Styrian and. . .". Please clarify which timing is considered here. Is it 4 Ma (l.27), 7 Ma (l.17) or 10 Ma (l.16)?

This passage immediately follows the sentence referencing the initiation of incision at 4 Ma. We have clarified this point by changing this text to read, 'The timing of incision…'.

Page 4, line 9: "250-500 um size fraction". In Table 1, some sample sizes are higher (500-800 um). Are they replicates? Please clarify, and maybe also discuss potential implications when comparing the resulting erosion rates for different grainsizes.

Our ^{10}Be analyses were run on the find sand (250-500 um) size fraction. However, three samples were sieved at both 250-500 um and 500-800 um size fractions to check for grain size dependence of ^{10}Be analyses. We clarify this in the text.

Page 4, line 25: "elevation-snow depth relationships previously determined in the Swiss Alps". I am not sure to what extent the data from Auer (2003) in the Swiss Alps can be extrapolated to the Austrian/Slovenian Alps (this extrapolation might depends on the local precipitations and moisture patterns). How comparable are the two climatic settings? Please discuss this extrapolation and the potential implications for calculated erosion rates.

Snow shielding, calculated here, represents an 8% correction to production rates, and therefore is a non-trivial calculation. We recognize that elevation-snow depth relationships determined across the Swiss Alps may not universally apply to our study region in Austria and Slovenia, nor do they likely reflect snow conditions across the millennial timescales over which cosmogenic ^{10}Be integrates.

However, they do provide best-available constraints for snow shielding. This is now clarified in the text, and table 2 provides our data for snow-shielding so the reader can assess the magnitude of this correction.

Page 4, line 26: "we set production rates equal to zero in parts of drainage basins with carbonate terrains". These areas should be excluded from the calculations (since they do not contribute quartz) and not set to zero-production, otherwise this would introduce a bias in the catchment-wide erosion rates. Please correct or clarify. Also, how did the authors consider low-gradient areas such as floodplains (figure 1) in their calculations? Are they included in the integrated 10Be erosion rate calculations? Please clarify.

Thank you for pointing out this unclear text. Carbonate terrain are excluded from calculations, and this is clarified now in the text. We did not specifically consider floodplains in our calculations, and all quartz-bearing portions of the catchment are included in 10Be calculations and topographic metrics. Floodplains do not make up significant portions of our basins, primarily because even though catchment size is typically over 50 km^2, the majority of our catchments are hilly to mountainous. Interestingly, glaciated catchments may contain high altitude, low gradient areas such as cirque valleys. If these portions of the landscape did not deliver sediment, perhaps because trapped in cirque lakes, then they should also be removed from calculating production rates. Hence catchment-wide production rates would decrease, and so would denudation rates. This could result in erosion rates in glacially conditioned catchments to be lower than calculated. We now discuss this complication in section 3.3.

Page 5, line 14. The (previously) glacial setting for these catchments may imply potential biases in the 10Be concentrations and thus in the calculated erosion rates, with input from morainic/glaciogenic material (e.g. Delunel et al., 2014 ESPL) or the impact of former glaciation (Glotzbach et al., 2014 Terra Nova). I would suggest the authors to discuss these points further and to what extent they may perturb the inferred catchment-wide erosion rates.

Please see our response to General Comment 2 above.

Page 5, line 21: "Measured erosion rates also generally increase with increasing mean basin elevation". Can the authors provide a figure for this correlation?

This text is now removed; however, elevation data is provided in Table 2.

Page 5, line 22: "Measured erosion rates also generally increase with [. . .] slope". Looking at Figure 2b, we can also see two clusters: 1) non-glaciated basins with no correlation between slope and erosion, and 2) (previously) glaciated basins where there seem to be an inverse correlation between slope and erosion. Please consider discussing this potential alternative observation.

We now explicitly address this point in the second paragraph of section 4.1.

Page 5, line 28: "We note that both erosion rates and catchment mean slope correlate with the proportion of the catchment that exceeds 35° (Fig. 2b)". This is not shown on figure 2b, or maybe I missed something. Please correct or clarify.

This line mistakenly referenced a figure we had removed prior to submission. As stated on the response to Page 5, line 21, we have expanded Figure 3 to add this plot.

Page 6, lines 9-14: "therefore likely reflect this erosional response to river incision and tectonic processes across the range". In the previous section (3.1, lines 11-12), the spatial variability in erosion rates was suggested to reflect lithological variations. Please clarify. –

The previous section was describing the catchments, not attributing controls on erosion rates. However, we have better clarified this text by indicating that Legrain found "Higher rates in the Styrian Basin compared to uplands of Koralpe, therefore likely reflect this erosional response to river incision and tectonic processes across the range, rather than lithologic differences."

Page 6, line 25: "We segmenting". Please correct.

Corrected

Page 7, line 1: "consistent with characteristic glacial and non-glacial slope-elevation curves predicted by Robl et al. (2015)." This specific slope distribution with elevation for glaciated terrains has already been observed in other places (e.g. van der Beek and Bourbon, 2008 Geomorphology). Please cite some references.

Thank you for pointing out this very relevant paper. We have now included this reference in several places of our revised manuscript.

Page 7, line 7: "other climatic controls such as precipitation rates". How variable are the mean precipitation rates between the different studied catchments? Please discuss this point.

We have added text to address this point at the bottom of this paragraph. We now state, "Furthermore, mean annual precipitation is likely a poor indicator of erosion in our unglaciated catchments since areas of the Mürz valley that display the highest non-glacial erosion rates tend to be drier than more slowly eroding portions of the Koralpe range (~BMLFUW, 2007)."

Page 7, line 11: "correlations between elevation and either rock uplift or erosion rates". Unclear, please clarify. I think this would rather be "correlations between elevation or rock uplift and erosion rates". Also, correlations from Vernon et al. 2009 are based on thermochronology and thus imply much longer timescales than Holocene, and they do not consider frost-cracking. Please correct.

We have changed this to read "correlations between elevation and erosion rates." The Vernon reference has been removed.

Page 7, line 13: “elevation poorly correlates with the abundance of steep (>35ÌŁ) slopes”. On Figure 3, there seem to be some non-linear correlation between elevation and fraction of the basin >35˚. Please rephrase or discuss further this point.

This section now reads, “elevation poorly correlates with the fraction of steep (>35˚) slopes, notably in the rapidly eroding, previously-glaciated basins where the abundance of steep topography varies widely despite similar mean basin elevations".

Page 7, line 16: “While frost-cracking may enhance erosion at alpine sites, it does not appear to explain the patterns and variability in erosion rates across our catchments”. Maybe frost-cracking is occurring (or had occurred in the Lateglacial period) for previously-glaciated catchments, but for non-glaciated catchments the mean elevations are too low to consider this effect. Would it be possible?

The reviewer notes an interesting potential correlation between the intensity of frost cracking and past glacial history, while we are not able to completely rule out this mechanism, we have expanded our discussion to provide multiple lines of evidence that it is not the primary control. The text now reads:

“It might be hypothesized that the intensity of frost-cracking processes are (or were) greatest in our previously glaciated catchments, thus potentially explaining the distribution of erosion rates. Across our study basins, catchment mean slope and elevation are correlated (Fig. 3), however, elevation poorly correlates with the fraction of steep (>35˚) slopes, notably in the rapidly eroding, previously-glaciated basins where the abundance of steep topography varies widely despite similar mean basin elevations. Therefore, the elevational proxy for frost cracking does not correspond to topographic indicators of rapid erosion in our study area. Furthermore, this mechanism is not supported if elevation is a proxy for the intensity of frost-cracking, as we find large differences in erosion rates at basins of the same elevation (Table 2). While frost-cracking may enhance erosion at alpine sites, it does not appear to explain the patterns and variability in erosion rates across our catchments."

Page 7, lines 24-25: “If catchment erosion were driven by increased river incision, then we should observe higher area-normalized stream gradients in rapidly eroding catchments”. What are “area-normalized stream gradients”? Also, did the authors study the river profiles to identify such perturbations. I would suggest the authors to show some river profiles and/or hypsometric curves for the studied catchments to illustrate the discussion about river incision (see also my general comment). Same question for the sentence on Page 8, line 7-8. This is difficult to see the fluvial domain on figure 6, so I would encourage the authors to show some figures focused on the fluvial part of catchments (river profiles, slope-area diagrams).

Here, we have clarified this text by rewording as:

“If catchment erosion were driven by increased river incision, then we would expect steeper stream gradients in rapidly eroding catchments. Legrain et al. (2015) observed correlations between higher normalized stream steepness indices and erosion rates within the Koralpe region of our study area, but only within small non-glaciated catchments.”

As noted earlier, we focus specifically on hillslope erosion in this manuscript. The manuscripts by

Legrain et al. (2015) and Robl et al. (2008) have previously presented and discussed detailed river profiles across our study region of the Austrian Alps.

Page 8, lines 3-6. How about lithological variations (and thus erosional resistance) as a potential control on the spatial variability in erosion rates?

Lithology may indeed influence erosion rates across the range, however not so much as to overprint glacial history. For example, the weakest lithology is found in the Styrian basin catchments, which are underlain by Miocene sediments. Erosion rates in this region are slightly higher than those in the adjacent Koralpe range, underlain primarily by much stronger bedrock. However, these erosion differences are much smaller than those found between previously glaciated and unglaciated basins.

Page 8, line 15: "processes solely within the hillslope domain". Did the authors also look at local relief as a potential topographic metrics for erosion rates?

We now provide measurements of local relief in table 2, which scale closely with slope measurements.

Page 8, line 22: "Compiling previously reported cosmogenic 10Be-derived rates across the Alps". Did the authors report here the original erosion rates or did they recalculate erosion rates with uniform/updated production rate? Please clarify and discuss potential implications for comparing erosion rates across the Alps.

All previously published rates compiled in Figure 7 and discussed here have been rescaled to a consistent high-latitude, sea-level production rate of 4.0 a/g/y. Please see our related response to general comment B.

Page 9, line 1: "we might expect Holocene erosion to reflect exhumation and uplift. . .". How can erosion reflect exhumation and uplift? This appears unclear, please rephrase.

This text has been changed to, "We might expect Holocene erosion to reflect uplift or rates of long term exhumation across the range."

Page 9, lines 4-7: "Long-term exhumation rates from thermochronometric ages are largely attributed to deep tectonic processes that increased during the Cenozoic". Please rephrase, long-term exhumation rates are also driven by Plio-Pleistocene changes in erosion following climatic forcing as well as drainage modifications, not only tectonics.

We have rephrased to state that these rates have been partially attributed to deep tectonic processes, thus not leaving out other interpretations.

Page 9, lines 12-13: "with highest modern and LGM precipitation occurring in the northern slopes of the Alps and decreasing to the south and east". Moisture patterns have changed between the LGM and modern (Florineth and Schluchter, 1998) so I am not sure that precipitation maxima have always been on the northern Alpine slopes. Please clarify.

The citation has been altered to (Florineth and Schlüchter, 2000). Though the strength of in the westerly and southerly airflows have altered precipitation patterns, these authors suggest that

generally both modern and LGM climates suggest decreasing precipitation to the east.

Page 10, line 3: Please correct “mm/ka” by “mm/ky” for consistency.

Changed.

Page 10, line 5: “49 mm/yr” would rather be “49 mm/ky”. Please correct.

Changed

Tables and Figures: - Figure 1: I would suggest to add main massifs, basins and maybe river names on Figure 1b to help the readers following section 2.1 and to link with subsequent figures.

Done

Figure 2: Please indicate replicates on Figure 2b with a star or different symbol. Also, I would suggest to also add the data from Legrain et al. (2015) on this figure, that may be helpful to compare them already at this stage, no (as they appear on figure 3)?

Figure 2 and 3 only show data generated using the 250-500 um size fraction (i.e., no replicates are shown). Table 2 provides data for other size fractions for comparison.

Figure 3: Maybe use different symbols (or open/filled) to differentiate between glaciated/non-glaciated basins?

We have distinguished previously glaciated and unglaciated basins in Figure 2. We believe adding new symbols to Figure 3 would make the figure too busy and decrease readability.

Figure 4: Why is the “basin erosion” legend reversed in panel a? Panels c and d are nice and informative, I am wondering if similar panels with elevations would be informative? On panel b, what are the criteria for “partially glaciated” and how does it relate to figure 2 with glaciated/non-glaciated? Please clarify.

The legend and color scale for basin erosion are consistent across all figures. We have added text to the results section and legend to figure 2 to clarify partially glaciated basins, in which only the uppermost elevations were glaciated.

Figure 5: Would it be possible to use different symbols for glaciated/non-glaciated catchments?

Please see our response to the comment on Figure 3.

Figure 6: This figure is difficult to read at present. I think that the slope distribution for the hillslope domain is already illustrated by panels c and d of figure 3, so I would recommend to show here only the fluvial domain (>103 m2) to better highlight any differences between the different rivers.

Figure 6 shows how slope distributions scale with accumulation area, and therefore highlight both the hillslope (far left) and fluvial (far right) domain.

Figure 7: I would be curious to see if there is any correlation between mean basin elevation and erosion rate across the Alps. Did the authors look at this or can add the corresponding figure if informative?

Though we do not provide this data in a figure, it is available in table 2. However, erosion rates are poorly correlated with elevation across unglaciated basins.

Table 1: I would suggest to also indicate the "integration time" for the reported denudation rates. In the footnote, please correct "negative and fast muons" by "slow and fast muons".

Table 2: In the footnote, please replace "Pleistocene" by "LGM". What is the maximum ice coverage during the Pleistocene (do we have evidence ofr more extended glaciations before the LGM in this part of the Alps)?

Changed

I hope these comments and suggestions may be useful for revising the manuscript, and I look forward to seeing it published.

Many thanks again to this reviewer for helpful comments that have improved our manuscript.

Peter van der Beek – Reviewer 2

Many thanks to Peter van der Beek his thoughtful and insightful review. Below we detail how we address the reviewer's comments.

Dixon et al. provide new detrital cosmogenic 10Be data to constrain erosion rates of nearly 30 catchments in the easternmost Alps (Austria and Slovenia). While earlier studies in this area have argued for a tectonic control on erosion rates, with catchments influenced by recent uplift recording higher rates than catchments to which this recent phase has not (yet) been communicated, the extended dataset presented here shows that the main controlling parameters on erosion rates are basin relief and mean slope, which the authors argue to be influenced by glacial preconditioning.

This study provides interesting new data that significantly tone down previous interpretations, and provides an integrated view of Holocene erosion rates in the Alps. It is therefore timely and definitely suitable for publication in Earth Surface Dynamics. While my overall evaluation of this manuscript is thus positive, I recommend it be returned to the authors for moderate revisions before final acceptance. These pertain to some apparent misconceptions or imprecisions in the writing, as well as the intriguing slope-area relationships that may merit some more discussion. As most of my comments are rather specific, I will list them tied to page and line numbers below:

Page 1, line 13: the Hergarten et al. model is based on a fundamental misconception: it mistakes a glacial imprint on topography for a transient tectonic signal. It would be preferable if this fundamentally flawed study were not perpetuated in the literature any more than it needs to; I would thus suggest the authors to refrain from citing it, particularly in the abstract.

We have removed citations from the abstract, but not from the remaining text. Regarding the Hergarten et al. paper, we recognize that it presents an alternative, and to some controversial, view to common Alps geomorphologic paradigms. In this manuscript, we cite the paper primarily for its role in the debate on tectonic vs glacial controls on topography and erosion – regardless of whether its view is widely accepted. As for the controversy about the causes for the lack of steep slopes at high elevations in the Alps we note that the jury is still out on this matter and a whole sale rebuttal of the Hergarten model is unjustified. In particular we note that (a) large parts of the eastern Alps is characterized by karstified plateaux bearing Oligocene fluvial gravels indicating that they cannot be caused by glacial processes (Frisch et al., 2000); (b) planation surfaces are also found on peaks above 2000 m surface elevation that are outside the glacial icecap (Legrain et al., 2014); and (c) Morphometric analysis of the Alps shows that glaciated and never glaciated parts of the Alps show similar slope-elevation distributions (Robl et al., 2015).

Page 1, line 23: Although Legrain et al. do invoke "deep lithospheric processes", it is not sure these are required for the easternmost Alps. In contrast to the west, convergence is still active in the East (e.g. Serpelloni et al., Geophys. J. Int., 2005) and the inversion of the Pannonian basin can be linked to a change in crustal stress fields from extension to compression (itself possibly linked to a deep lithospheric cause, however).

We have removed the citation from the abstract.

Page 2, line 7. The process of valley deepening and widening described above is not, in fact, the cause of the "glacial buzzsaw". The generation of widespread low-relief surfaces at elevations around the average Quaternary ELA (the topographic fingerprint of the "buzzsaw") is rather linked to efficient cirque retreat, possibly aided by periglacial (frost-cracking) processes. See Mitchell and Montgomery (Quat. Res., 2006) and Egholm et al. (ESurf., 2015) for discussions of these processes.

Thank you for clarifying the process behind the term. We edited this text to address the buzzsaw in general terms and not link to valley widening and deepening.

Page 2, line 9: Isostatic rebound will cause rock uplift but will not in itself increase relief. Relief increase is due to the fact that glacial erosion is strongly non-uniform or "selective", deepening valleys while having limited effects on higher parts of the landscape.

This section is reworded, "Glacial erosion may increase mountain relief and cause isostatic uplift of rocks."

Page 2, line 14: Norton et al. (Geology, 2010) would be a good complementary (or alternative) reference here.

We reference this work by Norton elsewhere in the manuscript, but do not find it more relevant than current citations at this text.

Page 2, lines 26-27: This presentation of the findings of Wittmann et al. (2007) is slightly misleading. In fact, their regression of denudation rates versus rock-uplift rates gave a slope of 1.0 ± 0.25, i.e. erosion rates could be either higher or lower than rock- uplift rates, and these authors include a lengthy discussion of the potential implications of this finding. Champagnac et al. (2009) did subsequently argue, based on a subset of this data, that rock-uplift rates were lower than denudation rates, but even their analysis is not equivocal on this point.

We have changed this text to state: "Wittmann et al. (2007) and Champagnac et al. (2009) noted that erosion rates scale with – and may exceed – uplift rates in the central Alps,

Page 3, line 1: again, why do you need to invoke deep lithospheric processes in a region where convergence is still ongoing?

We have removed this text as the underlying mechanism is unimportant in this section. The text now reads, "In the eastern portion of the range, accelerated rates of river incision and hillslope erosion since 5 Ma have been suggested to record late Tertiary uplift (Legrain et al., 2015; Wagner et al., 2010)."

Page 3, lines 12-14: there are several regional names here (Styrian (Alps?), Levanttal Alps, Gleinalpe, Koralpe, Schladmig Tauern, Seckauer Tauern, Pohorje) that are not know to a non-Austrian readership. They should be indicated on the map of Fig. 1.

We now cite figure 1 earlier, provide labels on figure 1, and reference figure 2 (which further highlights these regions).

Page 3, lines 16-18: a geological map might make this description of the regional geology easier to follow.

Though we recognize the use of an extra site figure, we have elected not to include a geological map as our study sites span two separate countries with lithologic boundaries not easily merged as mapped.

Page 3, lines 27-28: "but appears conspicuously unrelated" to what? This is unclear

This text is deleted.

Page 4, line 24: Norton et al. (2008) is not in the reference list.

Reference added.

Page 4, line 25: it is laudable that the authors try to take snow shielding into account in their calculation, but how reasonable is it to extrapolate a snow-depth – elevation relationship determined for central Switzerland to eastern Austria? The most comprehensive climatology database to date that I know of (Frei and Schaer, Int. J. Clim. 1998) shows that both mean-annual and winter precipitation is significantly lower in eastern Austria than in central Switzerland.

Please see our detailed response to Reviewer 1 regarding snow shielding.

Page 4, lines 25-27: Can you provide some information on the geology of the sampled catchments, at least reporting the aerial percentage of quartz-bearing lithologies in Table 2? Were topographic and relief measures only calculated on the quartz-bearing part of the catchments or the entire catchments?

Page 5, line 25: the Roering et al. (2001) model was actually designed to model shallow landsliding, not really hillslope creep.

This text has been changed to "or by non-linear diffusive transport"

Page 6, line 1: "higher erosion rates in general" is unclear: what erosion rates are you discussing here?

This sentence fragment has been removed.

Page 6, lines 5-9: it could be useful here to show a plot of the combined datasets (the current dataset and that of Legrain et al., 2015).

We have added Legrain data to expanded panels in Figure 2.

Page 6, line 25: "segmented" rather than "segmenting".

This sentence is reworded.

Page 7, line 1: A similar relief structure was described for glacially influenced catch- ments in the western Alps by van der Beek and Bourbon (Geomorphology, 2008).

Citation added.

Page 7, lines 11-12: The Vernon et al. (2009) reference is inappropriate here, as these authors did not discuss frost-cracking as a potential mechanism controlling spatial variations in erosion rates (moreover, these authors were looking at long-term exhumation rates from thermochronology data, on which the influence of frost cracking would be much harder to substantiate).

Thank you. The citation has been removed.

Page 7, lines 12-16: these arguments to rule out frost cracking as a mechanism controlling the variation of erosion rates are not completely convincing. First, it would be good to show the correlation between mean catchment elevation and erosion rate and to show that this correlation is weaker than that between mean catchment slope and erosion rate (this is what the authors appear to argue). Second, the fact that basins of the same average elevation show large differences in erosion rate does not necessarily rule out frost cracking, as this process depends on mean-annual temperature and its variation rather than elevation (which is just taken as a convenient proxy). The aspect of the basins (north- versus south-facing) as well as their geology may play a major role in modulating frost-cracking efficiency. Page 7, line 30: slab detachment has become the preferred "deus-ex-machina" mech- anism to "explain" uplift rates in the Alps. The data reported by Qorbani et al. (2015) provide only a very indirect indication for possible slab detachment. In the absence of more clearly resolved seismic tomography imagery for the European Alps, I feel we should be careful in invoking this mechanism . . .

We have reworded this sentence to more carefully cite this related study. We now state:

"seismic anisotropy suggests slab detachment could provide the tectonic mechanism for surface uplift in this Eastern region (Qorbani et al., 2015)."

Page 8, lines 8-15 (and Figure 6). There is something in this Figure I do not understand. Apparently (unless there is a problem with the x-axis) this slope-area plot is for extremely small catchment areas (<1 km2), i.e. for the most part within the hillslope domain (the hillslope – fluvial transition typically occurring at catchment areas of 10^5- 10^6 m^2. At these small catchment areas, the data should show either increasing slope with area (diffusional hillslopes) or no relationship between slope and catchment area (landslides, debris-flow domain). Yet the data show very good slope-area scaling, with larger concavities for glaciated than for non-glaciates catchments (as expected). So either the area axis is in km2 rather than m2 (which would make sense) or something very curious is going on.

Importantly, the reviewer's careful scrutiny of this figure led us to uncover a mistake in how the x-axis was derived and presented. In the original figure, the x-axis was a pixel-based accumulation metric mislabeled as an accumulation area (meaning a value of 100 reflected the upslope area of 100 pixels, not 100 m^2 as presented by the axis label). This calculation was performed on a 10 m DEM, and therefore our x-axis scaling was off by two orders of magnitude (such that 100 pixels reflects 10^4 m^2). We have fixed this axis scaling in the revised figure, though we note that this small change does not alter the interpretation nor specifically address the reviewer's confusion above. As the reviewer

points out, the data shown in this figure resides primarily in the hillslope domain. The expected scaling the reviewer mentions is one observed in log-log space. Our plot provides slope in degrees as a linear y-axis. These slope values are primarily between 5-35 degrees, and therefore far too steep to represent channels, which normally exhibit slopes <1 degree. We indeed observe a strong decrease in mean slope with log accumulation area in this plot, however in a traditional log slope – log area plot, the scaling of this hillslope domain would appear subdued and near horizontal, especially when compared to fluvial slope values that vary across several, very small orders of magnitude).

A more general comment on Section 3.4: possibly your best potential argument for a control by glacial preconditioning on erosion rates would come from your 5 catchments in the Seckauer Tauern. There are 3 unglaciated and 2 glaciated catchments, with for the rest fairly similar characteristics (at first glance at least). There are also 2 catchments that have significantly higher erosion rates than the other 3. Are these the two formerly glaciated catchments? If so, bingo!

Indeed the reviewer is correct that these morphometric differences are primarly delineated in the Seckauer Tauern between glaciated and only partially glaciated catchments. We have altered the manuscript to better point this out, and figure 2 now provides distinct symbols based on glacial history.

General comment on Section 3.5: the fact that erosion rates appear to systematically increase toward the west is, however, not easily explained by a mechanism of glacial preconditioning of topography. On page 9 (lines 11-28) the authors attempt to invoke paleo-climate variations and possibly thicker ice cover in the western Alps, but in the absence of any data this remains somewhat speculative. Several studies have reported average LGM ice thickness for the studied catchment areas; it may be interesting to have a closer look at this, compile this data where it is missing and see if there is a relationship with millennial erosion rates. However, a more simple relationship may exist between present-day rock uplift (as inferred from GPS studies) and erosion rate

We have enhanced this discussion by adding a figure showing compiled erosion rates versus longitude (Fig. 7c). Importantly, we find no systematic east to west variation in erosion rates across the range. Instead, average erosion rates are relatively uniform across the western and central alps despite significant local variability, while only rates in the far eastern study region appear significantly different from other regions of the Alps. This figure highlights that local variability exceeds variability at an orogeny scale.

– GPS-derived rock-uplift rate data have now been published for most of the Alps, including the western Alps (cf. Nocquet et al., Scientific Reports 2016). If a strong relationship with rock-uplift rates exists (and uplift rates are similar to or higher than erosion rates) then a tectonic or geodynamic control on these laterally varying rates should be invoked.

Unfortunately, similar reliable data is not easily found for the far eastern Alps.

Page 9, line 4: the arguments used by Persaud and Pfiffner (2004) to suggest active ongoing tectonics in the part of the central Alps they were studying were not particularly convincing. Not sure it is worth citing this here.

We have not removed the citation, as the debate in the literature is important, instead we have changed the language to "though some dispute this latter mechanism as a driver of modern rock uplift (e.g. Persaud and Pfiffner, 2004)."

Page 9, lines 23-25. This is a long and complex phrase. It is important for your arguments though; you may want to reformulate it.

We have reorganized this paragraph to better formulate our argument that multiple lines of evidence indicate paleoclimate has a lasting imprint on topography and post-glacial erosion rates across the range. The original three arguments in this long sentence are now spread through the paragraph with their relevant citations.

Comments on Figures

Overall, I'm not sure the organisation of the figures is the most logical and effective. Some could be merged; others appear to be missing. Figure 1: Needs to show the different regions sampled (Styrian Alps, Levanttal Alps, Gleinalpe, Koralpe, Schladmig Tauern, Seckauer Tauern, Pohorje). A simple way to do this would be to color-code the catchments and add a legend (in that case Fig. 2a would not be needed anymore). An additional panel with a simplified geological map could also be useful here. Figure 2: (a) can be combined with Figure 1. If you want to keep a map with the catchments here, it may be more useful to color-code them according to rate, so that the reader can see the spatial variation in erosion rates easily.

The suggestions above include minor reorganizations of figures already provided in the manuscript. Figure 1 provides larger context for the manuscript, and the color-coding of sample catchments by region is provided in figure 2 for ease of comparison with the associated plot of erosion rates. Figure 4 then provides the color-coding of catchments by erosion rates, for ease of comparison with the detailed slope distributions. This current order of figures follows the organization of manuscript text. We also believe the presentation and separation of results and discussion in the revised manuscript will help improve the logical flow of the manuscript.

An additional plot of erosion rate as a function of mean-catchment elevation would be useful (see specific comments above).

We include this data in table 2, though we have chosen not to include this specific figure.

Figure 6: Check the scale for this plot (see comment above)!

Please see our response to the reviewer's comment to page 8, line 8.

Figure 7. Not sure the erosion rate versus slope plot is the most effective here. An interesting plot could be simply erosion rates versus longitude (to show whether there is really an east-west increase or this is only apparent); otherwise suggested plots (see above) would be erosion rate versus average-LGM ice thickness and/or erosion rate versus present-day rock uplift rate (GPS data).

We agree with the reviewer that an added (or substituted) plot of erosion rates vs. LGM ice thickness or GPS-based uplift rates would be a useful addition. However, unfortunately these data are not

compileable across the entire range, primarily due to the lack of consistent quantitative data at our sites at the far eastern edge of the Alps. The current plot of erosion rates vs. slope, is one that allows us to place our data with other previously measured erosion rates, in the context of topographic variables that are measurable across the entire Alpine range. We have added a third panel that shows compiled erosion rates vs. longitude, which helps address patterns of erosion variability across the orogen.

Marco G. Jorge – Public Comment

I find the manuscript very interesting and look forward to its final version. Below, please find some comments and proposed edits that may help improving the manuscript.

Thank you to Marco Jorge for his detailed comments that help improve the clarity of our manuscript.

-- Introduction --

Page 2, Sentence L3-5. Suggest rephrasing. Second clause does not preclude first clause.

Reworded.

L7. Perhaps, the transition to glacial buzzsaw concept is not properly backgrounded by previous sentence.

We have reworded this text to clarify.

L13. Suggest rephrasing for flow with previous sentence. E.g., first say that glacial landscapes can be preserved . . ., influencing. . .

To transition to the next sentence, we have changed to "Glacial processes significantly alter landscapes, and therefore leave a lasting topographic legacy that …"

L15. Widely glaciated mountain belts?

We have changed to "in modern mid- and high-latitude mountain belts".

L16. References missing.

This sentence refers to the previous paragraph, which is well cited.

L18. Rephrase: not all glaciers are. . .

Changed

L25. Complete "Climate's influence on . . .

"Climate's influence on mountain belt erosion"

—- Section 2.3, Digital Terrain Analysis —-

Page 4, L31. Suggest mentioning that SRTM is 1 arc-second, instead of 80 m grid (dependence of cell size on latitude).

Thank you. We have clarified this point in the text.

Page 5, L4-5. This remark, specifically the last sentence, is too precise, or off what would be reasonable to discuss based solely on the differences in the topographic metrics. Basin slope gradient average is not indicative of local

scale morphometry independently of DEM cell size and an average gives no information about spatial variation. Either remove or rephrase and extend this discussion by adding more information (references?).

Grid-scale influence on mean slope values have been previously recognized and discussed by a number of authors. Here, we provide a reference to Zhang and Montgomery (1994).

(Table 2: refer that slope gradient values are averages)

Done

Which parameters were used for stream and catchment delineation? Was a flow accumulation threshold used? I presume from Fig 1 that delineation was based on the location of sampling sites (basin outlet). I believe it is important to justify location of sampling sites as well as its influence on basin delineation and morphometry.

We clarify that catchments were delineated upstream of sample points.

—- Section 3, results and discussion —-

The message would be clearer and the manuscript a better read if the discussion was separated from the results; there would be less back and forth. The discussion would benefit from the inclusion of further morphometrics (e.g., of elevation dispersion). In instances, the conclusions within the discussion overshoot what would be reasonable to conclude from the presented data (see below). I think that it is important to include an evaluation of lithology as a conditioning factor of the observed differences in erosion rates (even if it is null).

We have separated Results and Discussion sections, and agree that this change makes a significant improvement to the readability and clarity of the manuscript.

Page 5, L11. which lowland basin catchments? In the Styrian Basin?

Clarified.

L22. Rephrase. “these data” refers to both mean elevation and slope gradient but this sentence and following sentences address slope only.

We have specified that we are referring to the DEM scale.

L23. Whereby –> where

Changed to, ‘such that’

L23, 24. The described relationship between mean slope and erosion rates does not imply non-linear relationship. Perhaps reword results.

This text has significantly changed

Page 6, L11-13 (paragraph’s last sentence) Recommend rephrasing. Remove first clause and reword last clause.

Thank you. This sentence was unclear. We have reworded.

L16-21. This is too simplistic. For example, note that glaciated catchments generally are higher in elevation and non-glaciated catchments vary widely in mean elevation (Table 2) (differences in potential energy).

We have noted this wide variation in mean elevation.

L25. segmenting –> segmented

Changed.

L23-36. Too simplistic and somewhat confusing. Differences in average elevation between basins and elevation-slope relationships within basins are different things. Why should the relative location of the steepest slopes be positively related to basin average slope gradient? Justification for interpreting that to be signal of past glacial sculpting is insufficient.

The distinct patterns of local mean slopes with binned elevation persist regardless of whether you compare the same elevations between basins, or the distribution of slope within some nondimensional value of relief within the basin.

Page 7, L11. 'However' should be preceded by semi-colon.

Changed.

L14-16. Is the abundance of slopes >35◦ in gradient a good proxy for frost cracking? Address it directly.

We have reworded this section.

L24, 25 (Sentence). Explain; and what are area-normalized stream gradients? (area of what?)

We have significantly improved our description of these figures and metrics.

L26, 27 (Sentence). Add reference. Last paragraph. What is the authors' take on this discussion?

We cite Legrain in the previous sentence, and here indicate that their results are only applicable to non-glaciated portions of the Eastern Alps.

Page 8, L5-7. It was referred before that Legrain et al., 2015 looked at non-glaciated basins. Does "previously suggested" refer to Legrain et al., 2015?

Changed.

—- Conclusions —- Page 9, L1. "Repeated" meaning supporting previous studies? –> Add references

Here, we refer to multiple sets of data presented in this study, not to previous work.

Page 10, L2, 3. Not clear where these values are from; add references?

Data presented without references are from this study. We cite Legrain et al., 2015 for their background erosion rates.

Glaciation's topographic control on Holocene erosion at the eastern edge of the Alps

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Abstract.

What is the influence of glacial processes in driving erosion and uplift across the European Alps? It has largely been argued that repeated erosion ~~through~~ and glaciation sustain~~s~~ isostatic uplift and topography in a decaying orogen. But, some ~~insist~~ parts of~~that~~ the Alps ~~are an orogen~~ may still be actively uplifting via deep lithospheric processes ~~(e.g., Hergarten et al., 2010)~~. We add insight to this debate by isolating the role of post-glacial topographic forcing on erosion rates. To do this, we quantify the topographic signature of past glaciation on millennial scale erosion rates in previously glaciated and unglaciated catchments at the easternmost edge of the Austrian Alps. Newly measured catchment-wide erosion rates, determined from cosmogenic ^{10}Be in river-borne quartz, correlate with basin relief and mean slope. GIS-derived slope-elevation and slope-area distributions across catchments provide clear topographic indicators of the degree of glacial preconditioning, which further correlates with erosion rates. Erosion rates in the eastern-most, non-glaciated basins range from 40 to 150 mm/ky and likely reflect underlying tectonic forcings in this region, which have previously been attributed to recent (post 5 Ma) uplift ~~(Legrain et al., 2015)~~. By contrast, erosion rates in previously glaciated catchments range from 170 to 240 mm/ky and reflect the erosional response to local topographic preconditioning by repeated glaciations. Together, these data suggest that Holocene erosion across the Eastern Alps is strongly shaped by the local topography relict from previous glaciations. Broader, landscape-wide forcings, such as the widely debated deep mantle-driven or isostatically-driven uplift, result in lesser controls on both topography and erosion rates in this region. Comparing our data to previously published erosion rates across the Alps, we show that post-glacial erosion rates vary across more than two orders of magnitude ~~with poor topographic indicators of controls~~. This high variation in post-glacial erosion may reflect combined effects of direct tectonic and modern climatic forcings, but is strongly overprinted by past glacial climate and its topographic legacy.

1 Introduction

The climatic control on erosion in mountain belts remains a longstanding and active debate in geomorphology. Some of this debate has focused on whether spatial gradients in precipitation can be invoked to drive gradients in erosion or whether these rates are more strongly controlled by their tectonic setting (e.g., Burbank et al., 2003). While some studies have argued for modern precipitation controls on erosion (e.g. Bookhagen et al., 2005), climate's imprints via glacial processes are widely recognized to significantly alter a landscape. For example, abrasion and plucking of bedrock by overlying glacial ice widens and deepens valleys (Brocklehurst and Whipple, 2002). Glacial erosion may increase mountain relief and cause isostatic uplift of rocks (e.g., Champagnac et al., 2007; Molnar and England, 1990). ~~Via~~ Through ~~this~~ an erosional 'buzzsaw', glaciers have been suggested to set the limit on mountain range height and relief (e.g., Egholm et al., 2009, Mitchell and Humphries, 2015) and accelerate mountain erosion (e.g., Herman et al., 2013). ~~The isostatic rebound from glacial erosion and retreat causes uplift of rocks and increases mountain relief (e.g., Champagnac et al., 2007; Molnar and England, 1990).~~ Post-glacially, rivers export unconsolidated sediments stored in basins (Hinderer et al., 2001, Hoffmann et al., 2007, Wittmann et al., 2016), and steep glacial headwalls and valley sides undergo accelerated hillslope erosion. The resulting post-glacial sediments can become effective tools for rivers to rapidly incise their beds (Jansen et al., 2011). Glacial processes significantly alter landscapes, and therefore~~Glaciers also leave~~ leave a lasting topographic legacy that influences erosion, relief, and possibly uplift tens of thousands of years after glacial retreat (e.g., Salcher et al., 2014). Together, these processes and observations may suggest that glacial forcings are the dominant control on landscape evolution in modern mid- and high-latitude mountain belts.

Notwithstanding the clear topographic and erosional effects that glacial processes imprint in the landscape, there has been notable pushback on the idea that climate via glaciation is the dominant driver of erosion in diverse mountain belts. For example, not all glaciers are ~~not~~ efficient eroders, and glaciers frozen to their base may instead protect bedrock from erosion in high topography (Thomson et al., 2010). Even across glacial-interglacial time periods, fluvial incision may outpace glacial erosion in valley bottoms (Montgomery and Korup, 2011). Furthermore, global compilations of erosion rates across multiple temporal scales show similar erosion rates by glaciers and rivers, and these data suggest that tectonics likely controls erosion rates over millennial and longer timescales regardless of glacial history (Koppes and Montgomery, 2009).

This debate ~~on~~ regarding climate's influence on mountain belt evolution has been especially active for the European Alps, where both glacial and tectonic forces have been invoked as principle drivers of erosion and uplift (Cederbom et al., 2004; Fox et al., 2015; Mey et al., 2016). Wittmann et al. (2007) and Champagnac et al. (2009) noted that millennial-scale erosion rates ~~exceed scale~~vary with – and may exceed – modern uplift rates in the central Alps, and that correlations between topography, uplift, and erosion suggest glacial and post-glacial erosion alone may explain rates of uplift in the region via isostasy. Norton et al. (2010b) and (2011) further argued that glaciation drives uplift, based on the observation that ~~youthful~~

~~tectonic features such as~~ river knickpoints are highly correlated with previous glacial cover and glacial equilibrium line altitudes. However, it has also been suggested that ongoing collision and active convergence in the eastern Alps may either ~~alone~~ primarily drive uplift (Hergarten et al., 2010) or significantly contribute to changes in relief across the Cenozoic (Legrain et al., 2014). In the eastern portion of the range, accelerated rates of river incision and hillslope erosion since 5 Ma have been suggested to record late Tertiary uplift ~~resulting from deep lithospheric processes~~ (Legrain et al., 2015; Wagner et al., 2010). These relatively local observations have been coupled with landscape evolution models to suggest the Alps as a whole are not a decaying orogen as a glacial-driver of uplift and erosion may suggest, but instead a young mountain range still experiencing tectonic rejuvenation (Hergarten et al., 2010, Robl et al., 2015).

Here, we add insight into to the debate on the role of glaciers in driving Holocene Alpine erosion, by quantifying landscape morphology and ^{10}Be-derived denudation rates (hereafter called erosion rates) in both unglaciated and previously glaciated basins of the far Eastern Alps. We find that the past glacial history exerts a stronger control on erosion rates across the eastern Alps than previously invoked tectonic forcings.

2 Approach

2.1 Study Site

Our study region lies in the easternmost ~~section~~ region of the European Alps (Fig. 1), composing the Styrian as well as several intramontane basins and adjacent massifs that make up the Alpine uplands: The Lavanttal Alps (including Gleinalpe and Koralpe), the Schladming Tauern, the Sekauer Tauern, and Pohorje in Slovenia (Fig. ~~1~~2a). The Styrian Basin (part of the Pannonian Basin) was a shallow marine basin throughout much of the Miocene, becoming brackish and finally freshwater during basin inversion, which commenced around 10 Ma (Bada et al., 1999; Cloetingh et al., 2006). These kilometer thick Miocene sediments now underlie a gentle hilly terrain that has uplifted some 300 m above sea level in the last 7 Ma (e.g., Legrain et al., 2014). The upland regions of adjacent m~~M~~assifs are made up of high grade metamorphic rocks, with local limestone in the range north of the basin.

Our study region is unique as the only part of the Alps in which unglaciated and formerly glaciated mountainous catchments can be found in immediate proximity. During the glaciation periods of the past million years, only the western portion of the study region was pervasively glaciated (Figure 1). East of the contiguous Alpine ice cap, only isolated cirque glaciers occurred at elevations above 2000 m, for example in the summit region of the Koralpe range. In unglaciated portions of our study area, previous geomorphic work has recognized two distinct landscape morphologies: a low-gradient, low-relief upland region and a higher-gradient, higher-relief region downstream of river knickpoints (Legrain et al., 2014; Robl et al., 2008). Millennial erosion rates from small basins within these regions correlate with slope and the degree of incision (Legrain et al., 2015). These two morphologies are interpreted to represent the relict and incising portions of a landscape

responding to ~~a propagating wave of~~ incision initiated at ~4 Ma (Wagner et al., 2010). ~~This~~ The timing of incision coincides with inversion and uplift of the Styrian and northern Molasse Basins~~, but appears conspicuously unrelated~~. No work thus far has compared erosion rates in the previously glaciated and unglaciated portions of this landscape.

2.2 Deriving erosion rates from *in-situ* produced cosmogenic ^{10}Be

Use of the cosmogenic nuclide ^{10}Be in river sand is now standard for quantifying rates of erosion over millennial timescales in diverse landscapes (Granger and Schaller, 2014; Portenga and Bierman, 2011; von Blanckenburg, 2005). Cosmic ray bombardment of Earth's surface produces these nuclides in-situ, and their concentrations reflect the time that minerals spend within the upper few meters of Earth's surface. ^{10}Be concentrations in quartz collected from river sands reflect erosion rates spatially integrated across the basin. We sampled 26 rivers in the Eastern Alps of Austria and Slovenia for cosmogenic ^{10}Be analysis, targeting both previously glaciated and unglaciated catchments across the region (Table 1-2). Sand was collected from channel bottoms and active channel bars, integrating along ~20 m reaches at each river location. Samples were oven dried and sieved to extract the 250-500 µ~~u~~m size fraction. In addition to the 250-500 µm fraction, three samples were also sieved at 500-800 µm so that we– could check for grain size dependence of ^{10}Be concentrations. Heavy and magnetic minerals were removed using magnetic and density separation methods. Standard hydrochloric and hydrofluoric chemical leaches removed non-quartz minerals and etched weathering rinds from quartz to remove meteoric ^{10}Be. We digested 40 g of clean quartz in a 5:1 concentrated hydrofluoric acid: nitric acid mixture, along with 215 µg of an in-house developed ^{9}Be carrier derived from phenakite crystal. Beryllium was extracted from digested quartz and oxidized using methods outlined in von Blanckenburg et al. (1996). We measured ^{10}Be/^{9}Be ratios on BeO targets with accelerator mass spectrometry at ETH Zürich in Switzerland in June of 2010 and 2011. Initial AMS results are normalized to AMS standard S2007N, with an isotope ratio of 2.81 x 10^{-11}. All results are renormalized to the 07KNSTD standardization. Table 1 presents analytical results. ^{10}Be concentrations are blank corrected by subtraction (average ^{10}Be/^{9}Be ratio of five chemical processing blanks = 2.72 ± 2.21 x 10^{-15}).

^{10}Be concentrations were used to derive catchment-wide erosion rates, following scaling factors from Dunai (2000), absorption laws for nucleonic interactions from Schaller et al. (2002), and muonic absorption laws from Braucher et al. (2003). We determined basin-averaged production rates using an ArcGIS-based production model, 10 m gridded elevation data, a sea-level, high latitude total production rate of 4.0 atoms/g_{qtz}/year (Phillipps et al., 2016), and assuming slow and fast muons contribute ~1.2% and 0.65% of total production (Braucher et al., 2003)~~.~~. Corrections for skyline shielding were made following Norton and Vanacker (2009). We calculated snow-shielding following Norton et al. (2008) using elevation-snow depth relationships previously determined in the Swiss Alps by Auer (2003). Elevation-snow depth relationships likely vary spatially and temporally across the Alps;~~,~~ however, ~~and~~ these estimates provide ~~a~~ best-available constraints on snow shielding. Because our cosmogenic ^{10}Be concentrations only reflect erosion rates in the parts of the basin with quartz-bearing lithologies, ~~we set production rates equal to zero in~~ parts of drainage basins with carbonate terrains were excluded to

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calculate integrated basin ^{10}Be production rates (Table 1). ^{10}Be derived erosion rates are presented in Table 2. We compile other ^{10}Be derived erosion rates from across the Alps to gain a regional picture of Holocene erosion. These rates, published in 9 different prior studies (Delunel et al., 2010; Glotzbach et al., 2013; Legrain et al., 2015; Norton et al., 2008; Norton et al., 2010; Norton et al., 2011; Savi et al., 2014; Wittmann et al., 2007; Wittmann et al., 2016), were derived assuming different sea level, high latitude (SLHL) production rates. To aid comparison of rates across disparate studies, we recalculate all compiled rates using a consistent SLHL production rate of 4.0 atoms/g/yr, regardless of original scaling factors.

2.3 Digital Terrain Analysis

Catchment topography was analyzed using two digital elevation models: 10 m gridded data available from the Austrian Geological Survey (BEV) and ~~80 m~~three arc-second (~80 m in this region) gridded data from the Global Shuttle Radar Topography Mission (SRTM). Terrain attributes, stream networks and catchment extents were extracted in ArcGIS on both sets of gridded data. Catchments were delineated upstream of sample points (Table 2). Several catchments lay within Slovenia, and outside the extent of the Austrian 10 m data. Table 2 provides basin-wide terrain attributes, including comparison of variables extracted from 80 m and 10 m digital elevation models. Though the scale of these ~~data sets~~DEMs are very different, the resulting topographic metrics are quite similar, with only a slight lowering of average slopes in the coarser data. This similarity highlights the fact that local slopes are largely controlled by landscape-scale patterns. If local slopes were variable at a small spatial scale, then analysis of 10 m and 80 m gridded data would likely result in notable differences (e.g., Zhang and Montgomery, 1994).

3 Results ~~and Discussion~~

^{10}Be-derived erosion rates vary from 39 to 238 mm/ky across our study catchments of the Eastern Alps. ~~3.1 Geographic distribution of denudation rates~~

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Catchment wide erosion rates generally show distinct patterns based on their geographic setting ~~regions across the Eastern Alps~~ (Fig. 2a,b; Tables 1-2). Rates across Gleinalpe and Koralpe range from 39-~~104~~ 94 mm/ky. The erosion rates measured in catchments entirely within the Styrian Basin (101-114 mm/ky; Fig. 1) are notably higher than the rates within the adjacent Koralpe range. Streams in these lowland-basin catchments of the Styrian Basin drain largely unconsolidated sediments of Miocene age that form low-relief hillslopes. Tributaries of the Müürz river valley in the northeast exhibit a broad range in erosion, from 81-151 mm/ky. Catchment erosion rates in the Schladminer and Seckauer Tauern range from 71-238 mm/ky. The highest rates in this region (>170 mm/ky) correspond to basins that lie within the range of the last glacial maximum ice and reflect the region that was previously glaciated (see Fig. 1). Within the Seckauer Tauern, at the edge of LGM ice, several basins were only partially glaciated (Fig. 2), such that only small portions of the catchment (uppermost elevations) show evidence of glacial impact. Measured erosion rates in these catchments are similar to unglaciated rates in other portions of the study area.

~~3.2 Correlations between denudation and topographic metrics~~

The broad regional differences in basin erosion rates are complemented by relationships between these rates and topographic form of the basins (Fig. 2a,b). Mean basin slope generally increases ~~linearly~~ with mean elevation (Fig. 3a; r^2=0.64, p<0.001). This increase in slope is partially controlled by a marked increase in the proportion of slopes that are steeper than 35° at high elevations (Fig. 3a). Measured erosion rates also generally increase with increasing mean basin ~~elevation (r^2=0.34, p<0.001) and~~ slope (Fig. 2b; r^2=0.58, p<0.001). These correlations persist across catchments of disparate drainage areas (Fig. 3b).~~These data are consistent with trends previously observed across other mountain ranges (e.g., Cyr et al., 2010; Ouimet et al., 2009), whereby erosion rates increase non-linearly with mean catchment slope. This non-linear relationship may result either by the dominance of threshold-driven landsliding in controlling erosion across the range (e.g., Montgomery and Dietrich, 1994) or by non-linear dynamics in hillslope creep (Roering et al., 2001). Either of these erosional mechanisms may result in a similar form to the non-linear relationships between erosion rates and slope (e.g., DiBiase et al., 2010). We note that both erosion rates and catchment mean slope correlate with the proportion of the catchment that exceeds 35° (Fig. 2b), and that these steep slopes generally are void of soil cover.~~

~~Considering the overall trend of increasing erosion rates with basin slope and higher erosion rates in general, it is surprising that several basins at lowest elevations do not follow this trend (Fig. 2,4). Low elevation catchments in the Styrian basin to the south erode at faster rates than catchments in the middle uplands of the Koralpe range (Fig. 2). These high erosion rates at low elevation have previously been linked to tectonic transience in the Koralpe range, such that a wave of incision and erosion propagating upslope has accelerated erosion, but not yet reached upper relict landscapes. Legrain et al. (2015) mapped the transition between incising and upland relict hillslopes, and found that erosion rates in small basins (< 1 km²) across Koralpe correlate with the fraction of the catchment below transient propagating knickpoints. Catchment morphology and erosion rates within these small basins show greater variability at mid-to-low elevations than the larger basins studies here, and reflect the local topographic and erosional response of hillslopes to transient river incision (Legrain et al., 2014; Robl et al., 2008). Higher rates in the Styrian Basin compared to uplands of Koralpe, therefore likely reflect this erosional response to river incision and tectonic processes across the range. However, with the exception of these high rates in the Styrian Basin, this local-scale topographic variability and transience attributed to tectonics is not strongly reflected in the large basins studied in this paper, which integrate across this variability spatially.~~

Catchments in the Schladminger Tauern and northern parts of the Seckauer Tauern were glaciated in the Pleistocene (Fig. 2a). These catchments exhibit the most rapid erosion rates across the study area (Fig. 4a; 170-230 mm/ky), and have higher average slopes than non-glaciated and only partly-glaciated basins (Fig. 4b,c,d). Hillslope gradients of unglaciated and partially glaciated basins tend to be normally distributed about mean and modal slopes that range widely from ~5-25° (Fig.

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4c). In comparison, previously glaciated basins show higher mean and modal slopes >25° with a negative skew towards low values. Furthermore, we find that these two domains also show clear distributions of slope with elevation. ~~We~~By segmenting each catchment into distinct elevation bins between 50 m contours, ~~and~~we determined the relationship between mean slope angle and mean elevation within the bins (Fig. 5). Dissimilar patterns emerge in how slope varies with elevation within previously-glaciated and non-glaciated catchments. For example, high gradient hillslopes within the non-glaciated basins tend to occur at the upper portions of these basins, well above the mean elevation. However, the steepest hillslopes of glacially sculpted basins are found at elevations well below the mean (< 1,500 m elevation compared to average elevations of ~1,800 m).

4 Discussion

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4.1 Topographic controls on erosion rates

Correlations between ^{10}Be derived erosion rates and mean catchment slope (Fig. 2b) are~~These data are~~ consistent with trends previously observed across other diverse mountain ranges (e.g., Cyr et al., 2010; Ouimet et al., 2009). ~~whereby~~such that erosion rates increase non-linearly with mean catchment slope. This non-linear relationship may result either by the dominance of threshold driven landsliding in controlling erosion across the range (e.g., Montgomery and Dietrich, 1994) or by non-linear ~~dynamics in hillslope creep~~ diffusive transport (Roering et al., 2001). Either of these erosional mechanisms may result in a similar form to the non-linear relationships between erosion rates and slope (e.g., DiBiase et al., 2010). ~~We note~~Considering that both erosion rates and catchment mean slope correlate with the proportion of the catchment that exceeds 35° (Fig. 2b), and that these steep slopes generally are void of soil cover, it is likely that local slopes >35° within catchments undergoing erosion rates of ~200 mm/ky correspond to thresholds for soil cover in this landscape.

~~Considering~~Though we find a general~~ the overall~~ trend of increasing erosion rates with basin slope~~ and higher erosion rates in general,~~ this pattern is largely held by two unique clusters of data: unglaciated basins that exhibit low erosion rates and low to moderate slopes, and previously glaciated basins with high slopes and erosion rates. Within each of these domains, the erosion rate-slope relationships are less clear. Furthermore, it is surprising that several basins at the lowest elevations in the Styrian basin to the south erode at faster rates than catchments in the middle uplands of the Koralpe range ~~do not follow this trend~~ (Fig. 2,4). ~~Low elevation catchments in the Styrian basin to the south erode at faster rates than catchments in the middle uplands of the Koralpe range (Fig. 2). T~~These ~~high~~slightly higher erosion rates at low elevation have previously been linked to both weaker lithologies and tectonic transience in the Koralpe range, such that a wave of incision and erosion propagating upslope has accelerated erosion, but not yet reached upper relict landscapes. Legrain et al. (2015) mapped the transition between incising and upland relict hillslopes, and found that erosion rates in small basins (< 1 km^2) across Koralpe correlate with the fraction of the catchment below transient propagating knickpoints. Catchment morphology and erosion rates within these small basins show greater variability at mid-to-low elevations than the larger basins studies here, and

reflect the local topographic and erosional response of hillslopes to transient river incision (Legrain et al., 2014; Robl et al., 2008). Higher rates in the Styrian Basin compared to uplands of Koralpe, therefore likely reflect this erosional response to river incision and tectonic processes across the range, rather than lithologic differences. ~~However, with the exception of these high rates in the Styrian Basin, t~~This local-scale topographic variability and transience attributed to tectonics is likely only reflected in the high rates in the Styrian Basin, and not otherwise strongly reflected in the large basins studied in this paper, which we believe integrate spatially across this variability ~~spatially~~.

~~3.3~~4.2 ~~Topography and erosion rates in previously glaciated and non-glaciated catchments~~Glacial Legacies and their influence on Holocene Erosion in the Eastern Alps

~~Catchments in the Schladminger Tauern and northern parts of the Seckauer Tauern were glaciated in the Pleistocene (Fig. 2a). These catchments exhibit the most rapid erosion rates across the study area (Fig. 4a; 170–230 mm/ky), and have higher average slopes than non-glaciated and only partly-glaciated basins (Fig. 4b,c,d).~~ We hypothesize that topography – erosion relationships reflect the control of glacial legacies on mountain erosion in this Alpine system. Indeed, we find that the fastest eroding catchments were previously eroded in the Pleistocene and have higher higher averaged slopes than unglaciated ones (Fig. 2). ~~these higher slopes in glaciated catchments reflect glacial sculpting of topography.~~ However, basin average slope angles ~~(Fig. 2)~~ only provide limited proof of concept since we find a wide range of mean values across both unglaciated and glaciated basins. Distribution of slopes within each catchment provide an added ~~Therefore, to better distinguish a~~ topographic fingerprint of past glaciation (Fig. 3). Mean slopes tend to be greater at low elevations than high elevations in the faster eroding, glacially sculpted catchments. ~~we explore the distribution of slopes within each catchment.~~

~~Hillslope gradients of unglaciated basins tend to be normally distributed about mean and modal slopes that range from ~5-25° (Fig. 4c). In comparison, previously glaciated basins show higher mean and modal slopes >25° with a negative skew towards low values. Furthermore, we find that these two domains also show clear distributions of slope with elevation. We segmenting each catchment into distinct elevation bins between 50 m contours, and determined the relationship between mean slope angle and mean elevation within the bins (Fig. 5). Dissimilar patterns emerge in how slope varies with elevation within previously-glaciated and non-glaciated catchments. For example, high gradient hillslopes within the non-glaciated basins tend to occur at the upper portions of these basins, well above the mean elevation. However, the steepest hillslopes of glacially sculpted basins are found at elevations well below the mean (< 1,500 m elevation compared to average elevations of ~1,800 m).~~ This detailed distribution of slope and elevation within glaciated basins is not ~~consistent~~ distinct from ~~with~~ the general trend of increasing mean basin slope with mean basin elevation across the study area (Fig. 3a). The distribution of slope by elevation within basins (Fig. 5) therefore represents a local signal not reflective of the larger regional trend, and we consider it a fingerprint of past glacial sculpting, consistent with characteristic slope-elevation curves and relief in glacial and non-glacial catchments ~~slope-elevation curves (predicted by~~ Robl et al., ~~(~~2015; van der Beek and Bourbon, 2008).

Considering that these previously glaciated basins erode at rates roughly three times faster than average non-glaciated basins, this slope distribution similarly provides a predictive tool for erosion rates (Fig. 5).

Importantly, past-glaciation may have other impacts on measured erosion rates that must also be considered. ^{10}Be-derived rates presented in this study are calculated assuming erosion has been constant sufficient time for the landscape surface to attain steady-state ^{10}Be concentrations. This assumption may not be correct when erosion rates have been variable over the integration time of ^{10}Be accumulation, or if the surface has been zeroed by deep erosion, as is likely the case for previously glaciated areas. Furthermore, this assumption may result in non-trivial overestimation in calculated erosion rates, especially in slowly eroding terrain (Glotzbach et al., 2013; Norton et al., 2010; Wittmann et al., 2007). Using non-steady state calculations from Lal (1991) and assuming ^{10}Be concentrations at the surface began to accumulate only after deglaciation at 15 ka, would result in as much as a 9% difference in calculated erosion rates from steady-state rates presented in table 1 (based on steady state erosion rates for glaciated basins of 172-203 mm/ky). This steady-state assumption therefore results in a non-trivial, but still relatively small bias to calculated erosion rates, considering our glaciated basins erode roughly a factor of two times faster than non-glaciated basins, and up to a factor of five times faster than background erosion rates near 40 mm/ky.

Another complication of measuring ^{10}Be derived denudation rates in complex previously-glaciated terrain results from the potential that glacial erosion products, potentially remobilized from storage in moraines or flood plains, will have inherited ^{10}Be concentrations associated with preglacial times. This may occur if glaciers have incompletely zeroed surface concentrations via shallow erosion (Delunel et al., 2014) or if glacial advance overrode soils and later incorporated them into glacially eroded sediments (Wittmann et al., 2007). In this case, ^{10}Be concentrations may instead underestimate erosion rates, though this effect should be the largest in currently glaciated or recently glaciated catchments. A final complication may arise due to the fact that previously glaciated catchments may contain high altitude, low gradient areas such as cirque valleys. If these portions of the landscape did not deliver sediment, perhaps because trapped in cirque lakes, then they should be excluded from calculated production rates. Hence catchment-wide production rates would decrease, and so would denudation rates. This could result in erosion rates in glacially conditioned catchments to be lower than calculated.

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3.4 Competing controls on Holocene erosion rates

We find compelling evidence of topographic control on erosion; however, other competing hypotheses may explain some of the range of erosion rates found across the region. For example, other climatic controls such as precipitation rates have been invoked to explain fast erosion rates in high peaks of the Alps (Anders et al., 2010). In the Western and Italian Alps, several lines of evidence were used to suggest that post-glacial climates drive the bulk of exhumation and erosion in the region. Multiple studies have suggested that temperature-driven frost cracking processes likely control Holocene erosion rates, based

on correlations between elevation and ~~either rock uplift or~~ erosion rates (Delunel et al., 2010; Savi et al., 2015~~; Vernon et al. 2009~~). It might be hypothesized that the intensity of frost-cracking processes is (or was) greatest in our previously glaciated catchments, thus potentially explaining the distribution of erosion rates. Across our study basins, catchment mean slope and elevation are correlated (Fig. 3a)~~;~~; however, elevation poorly correlates with the ~~abundance~~ fraction of steep (>35°) slopes, notably in the rapidly eroding, previously-glaciated basins where the abundance of steep topography varies widely despite similar mean basin elevations. ~~Therefore~~Therefore, the elevational proxy for frost cracking does not correspond to topographic indicators of rapid erosion in our study area. Furthermore, ~~Furthermore,~~ we find large differences in erosion rates at basins of the same elevation (Table 2). While frost-cracking may enhance erosion at alpine sites, it does not appear to explain the patterns and variability in erosion rates across our catchments. Furthermore, mean annual precipitation is likely a poor indicator of erosion in our unglaciated catchments since areas of the Mürz valley that display the highest non-glacial erosion rates tend to be drier than more slowly eroding portions of the Koralpe range (~BMLFUW, 2007).

Our measured hillslope erosion rates in the Eastern Alps may also be driven by rock uplift and river incision across the region. Previous work has suggested that glaciation during the last glacial maximum (LGM) may drive a Holocene erosional response across the Alps and thereby enhance uplift (Wittmann et al., 2007). Providing a mechanism to engineer this link, Norton et al. (2010a) used observations of correlated river knickpoints and LGM equilibrium line altitudes (ELAs) to suggest that topographic imprint of glacial erosion leads to increased river incision post-glacially, which in turn strengthens the positive feedback between rock uplift and erosion. Could this same mechanism be invoked to explain high erosion rates in our previously glaciated catchments? If catchment erosion were driven by increased river incision, then we ~~should~~ would expect ~~observe~~ steeper stream ~~higher area-normalized stream~~ gradients in rapidly eroding catchments. Legrain et al. (2015) ~~observed~~ observed correlations between ~~this~~ higher normalized stream steepness indices and erosion rates~~correlation~~ within the Koralpe region of our study area, but only within small non-glaciated catchments. Therefore, evidence of incision-driven hillslope erosion was found only in the absence of glacial forcings. This finding led these authors to suggest that tectonic uplift in the Eastern Austrian Alps could reasonably explain both 500 m of relief change and a factor-of-three spatial variation in Holocene erosion rates. The scale of uplift (encompassing both the Pannonian basin and entire eastern end of the Alps) ~~suggests~~ may reflect deep-seated lithospheric processes (Legrain et al., 2015), and~~, and s~~ seismic anisotropy suggests slab ~~lab detachment (Qorbani et al., 2015) may~~ detachment could provide the tectonic mechanism for surface uplift in this Eastern region (Qorbani et al., 2015).

Erosional response to rock uplift may explain local erosional differences within non-glaciated catchments studied here. For example, following Legrain's model, low-elevation catchments in the Styrian basin lie within the incised region below river knickpoints, while higher-elevation catchments in Koralpe with lower erosion rates include significant portions of 'relict terrain'. Importantly, this surface uplift mechanism cannot similarly account for erosional differences between glaciated and non-glaciated basins. The glaciated basins studied here would fall within the 'relict landscape' region mapped by Legrain et

al. (2015) as above river knickpoints, and therefore our high erosion rates do not correlate with area below knickpoints~~ as previously suggested~~. Furthermore, if uplift drove erosion in these basins, then we would expect to see higher area-normalized stream gradients in more rapidly eroding catchments reflecting the enhanced river incisional response. Figure 6 shows local hillslope gradients within each catchment, binned by accumulation area, the upslope and upstream contributing area for all points within the basin. While mean basin slopes are generally higher in more rapidly eroding glaciated catchments, these higher gradients occur only at the uppermost portions of the catchments – at small upslope accumulation areas less than ~ 10^2 m^2 that are within the hillslope domain. By comparison, local stream gradients in glaciated and non-glaciated basins are similar at the larger contribution areas (approaching 10^5 m^2 area) that reflect the fluvial domain. The variability in within-basin slope seen only at low contributing areas indicates that the morphological differences within our large catchments studied here are driven by processes solely within the hillslope domain. The lack of evidence of incision-driven erosion further supports our conclusions that topographic forcings, and not rock uplift, are largely responsible for the patterns in erosion we observe here.

3.5 Erosion and Topography across the Alpine Range

While post-glacial topography largely explains the range of erosion rates found at the far end of the Eastern Alps, we note that these measured erosion rates are still significantly lower than measurements across other regions of the Alps (Fig. 7a). The highest rates measured in our study region are amongst the lowest measured across the Alpine range. Compiling previously reported cosmogenic ^{10}Be-derived rates across the Alps, we find mean basin slope and Holocene erosion rates are generally weakly correlated (linear regression, r^2=0.26, p<0.001), providing ~~little~~ limited predictive power for assessing erosion patterns (Fig. 7b) at an orogen scale. ~~This~~ A lack of correlation is not surprising at high mean slope angles and rapid erosion rates since erosional processes become non-linear approaching threshold slope angles (e.g., DiBiase et al., 2010). Poor correlations between most topographic metrics and Alpine erosion rates have been noted before (e.g., Norton et al., 2011; Salcher et al., 2014; Wittmann et al., 2007). Complexities in lithologic variation can partially explain the high scatter in erosion rates at steep gradients (e.g., Norton et al., 2011) since rock strength and fracturing may control slope thresholds. Weaker lithologies often correspond to low hillslope gradients (e.g., Norton et al., 2011) and normalized stream steepness indices (Sternai et al., 2012) in the absence of other controls. Despite some lithologic influence, orogen-scale controls on Holocene denudation rates have remained relatively elusive.

We might expect Holocene erosion to reflect ~~exhumation and~~ uplift or rates of long term exhumation across the range. In the central Alps, some of the observable modern rock uplift has been attributed to a combination of an isostatic response to Holocene erosion (Champagnac et al., 2007; Wittmann et al., 2007) and ice melting (Barletta et al., 2006). T~~; however~~hough~~, this~~ some dispute this latter mechanism ~~has been~~as a ~~disputed to~~ driver of modern rock uplift (e.g. Persaud and Pfiffner, 2004), r~~.~~ecent flexural models based on glacial ice thickness suggest that glacial isostatic adjustment primarily explains the

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magnitude and patterns of modern uplift (Mey et al., 2016). Long-term exhumation rates from thermochronometric ages ~~are largely~~have been partially attributed to deep tectonic processes that increased during the Cenozoic (Cederbom et al., 2011), possibly due to slab detachment focused primarily in the west (Baran et al., 2014; Fox et al., 2014; Fox et al., 2015~~; Fox et al., 2014~~), but also potentially observable in the Eastern Alps (Qorbani et al., 2015). Short-term rates of uplift and erosion and modern topographic metrics appear to poorly or only partially reflect this broad tectonic signal (Koons, 2009; Norton et al., 2011; Vernon et al., 2009), though along-orogen tectonic differences cannot be ruled out in contributing to the variation in erosion rates (Baran et al., 2014). However, at an orogen scale and with the exception of the far eastern Alps where erosion rates are low, average erosion rates vary little with longitude across the range despite high local variability (Fig. 7c).

Climate variability should also be considered in controlling erosion at an orogen scale. Precipitation patterns vary across the range, with highest ~~modern and~~ LGM precipitation occurring in the northern slopes of the Alps and decreasing to the south and east (Florineth and Schlüchter, ~~1998~~2000). Modern precipitation varies from ~400 to >3000 mm/yr across the orogen, also generally decreasing to the east, and small scale variations in topography have a pronounced effect on local patterns (Isotta et al., 2014). This means that precipitation varies at both large and small scales across the orogen. There is reason to believe that modern precipitation gradients should control Holocene erosion and sediment transport by influencing the discharge of sediment out of a basin, controlling landslide thresholds, and by influencing the magnitude of river incision. While similar relationships have been observed across other mountain ranges (e.g., Bookhagen et al., 2005), explicit links between modern precipitation and post-glacial hillslope erosion remain elusive in the Alps (Bennett et al., 2013; Schlunegger and Norton, 2013). However, multiple lines of evidence, including data presented here, suggest that paleoclimate may instead have a greater and ~~have a~~ lasting imprint on landscape topography and erosion. Anders et al. (2010) found precipitation is inversely correlated with the elevation of cirque floors in portions of the Swiss Alps, suggesting a climate-driven glacial buzzsaw across the region. Furthermore, glacial erosion during the Pleistocene resulted in notable increases in valley-scale topographic relief (Sternai et al., 2012; Valla et al., 2011). ~~Considering precipitation varies across both small and large scales across the range, this variation is reflected in ice volumes, and the~~Because these glacially driven topographic legacies persist to modern day, we propose that modern hillslope response to glacial history can partly explain ~~orogen~~local-scale variability in erosion rates. Though focused locally in the Eastern Alps, our new erosion rates and topographic analysis add weight to an increasingly compelling argument that local Holocene denudation rates across the Alps, which often poorly reflect other broader tectonic and climatic controls, are overprinted by the local topographic legacy of glacial sculpting. It is not yet clear whether the topographic legacy and its influence on Holocene erosion directly reflects the local magnitude of past glaciation (e.g., LGM ice thickness), or perhaps if erosional and morphometric variability in previously glaciated portions of the Western and Central Alps is especially variable since modern hillslope response to deglaciation may be considered transient.

4 Conclusions

Our study provides ~~repeated~~ multiple lines of evidence that Holocene erosion in the eastern Austrian Alps is driven by glacial legacies that set local topographic forcing and hillslope morphology. Previous work in the region quantified that deep seated tectonic processes could explain almost a factor-of-three variation in erosion rates in unglaciated terrain (49-137 mm/~~ka~~ky; Legrain et al., 2015). Post-glacial topographic forcings account for an additional doubling over invoked tectonic forcings (resulting in erosion rates averaging 200 ~~mm/ka~~mm/ky and up to ~240 ~~mm/ka~~mm/ky in previously glaciated basins). Considering that glaciers ~~occupy~~ occupied uplands which are not yet reached by river knickpoints, then this glacial forcing is far in excess of background erosion rates inferred to be pre-Miocene (49 mm/ky~~r~~; Legrain et al., 2015). Therefore, despite evidence for young uplift across the eastern extent of the range, glacial processes still dominate the erosion signal, with deeper tectonic forcings likely observable only in the absence of strong local topographic forcings. Our new data suggest post glacial topographic forcing can account for a 4-5x increase over background hillslope erosion rates in the absence of tectonic forcings. Comparison with erosion rates across the Alpine range show that these glacially-enhanced rates are still among the lowest measured across the Alpine orogen, and that combined complexities in tectonic forcings (e.g., Wagner et al., 2010), modern and past climatic forcings (e.g., Anders et al., 2010) and transient erosional response to inherited topographic legacies (this study) must all be considered to understand ~~orogen-scale~~ controls on Alpine Holocene erosion.

Acknowledgements

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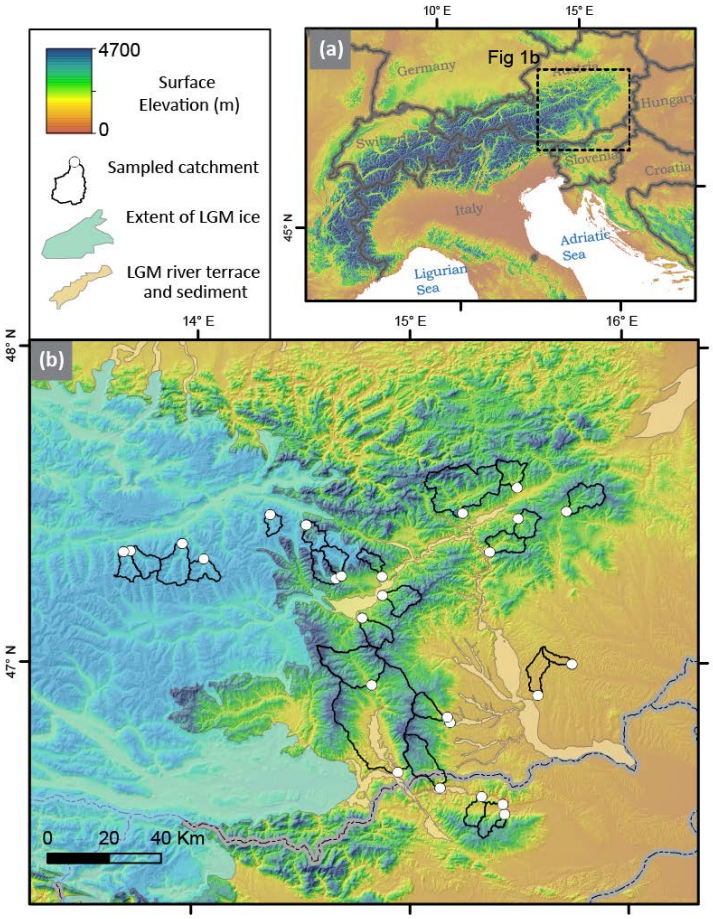
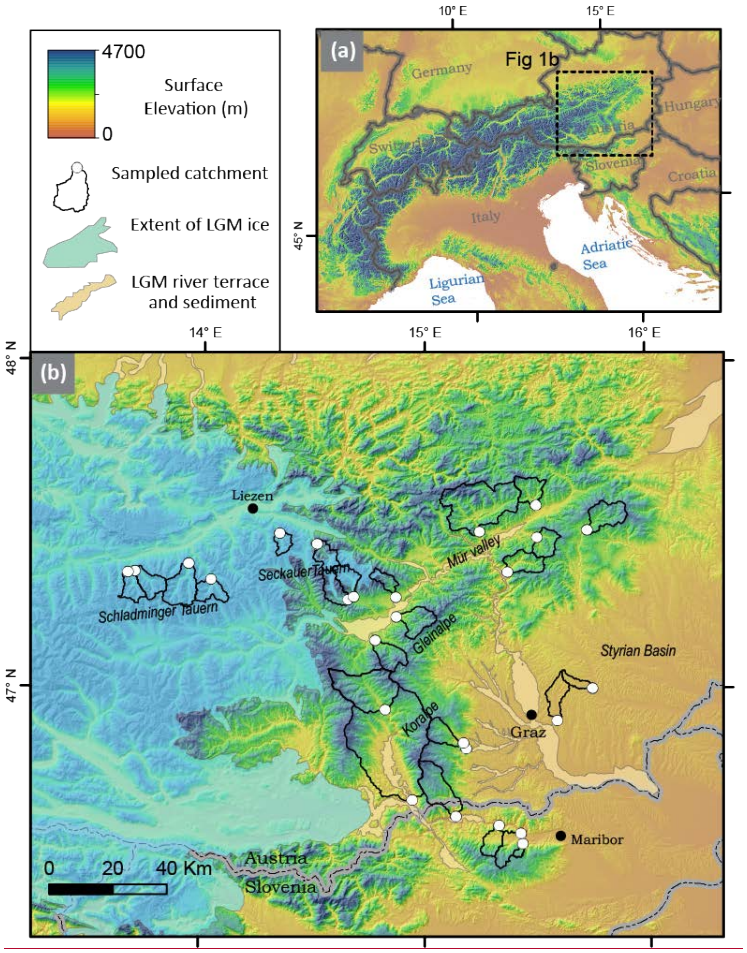
Figure 1. (A) The study area lies in the easternmost region of the European Alps, with sites located across both Austria and Northern Slovenia. (B) Catchment outlines and sampling points for our 26 river sand samples, used to measure millennial scale erosion rates across both previously glaciated and unglaciated catchments. Extent of Last Glacial Maximum (LGM) ice is shown by the blue shaded area. The boundary between the crystalline bedrock of the Alps and the Miocene sedimentary basin (Styrian Basin) follows roughly the 300 – 500 m elevation contour marked by the yellow color tones.


4700
Surface Elevation (m)
0
Sampled catchment
Extent of LGM ice
LGM river terrace and sediment
(a)
Fig 1b
Germany
Hungary
Slovenia
Croatia
Italy
Adriatic Sea
Ligurian Sea
10° E
15° E
45° N
(b)
14° E
15° E
16° E
48° N
47° N
0 20 40 Km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Surface Elevation (m)
0
Sampled catchment
Extent of LGM ice
LGM river terrace and sediment
(a)
Fig 1b
Germany
Hungary
Slovenia
Croatia
Italy
Adriatic Sea
Ligurian Sea
10° E
15° E
45° N
(b)
14° E
15° E
16° E
48° N
47° N
Liezen
Seckauer Tauern
Schladminger Tauern
Mur valley
Glemalpe
Styrian Basin
Koralpe
Graz
Maribor
0 20 40 Km
Austria
Slovenia

Figure 2. Geographic distribution of erosion rates. (A) Study catchments span several geologic regions marked by distinct massifs and basins. Catchment outlines and data points are color-coded by region. Dashed outlines represent basins that were previously glaciated during the LGM. Extent of LGM ice is shown by the thin grey line, and bolder grey lines mark national boundaries. (B) Erosion rates increase with mean basin slope and can generally be grouped by region (replicate samples shown).

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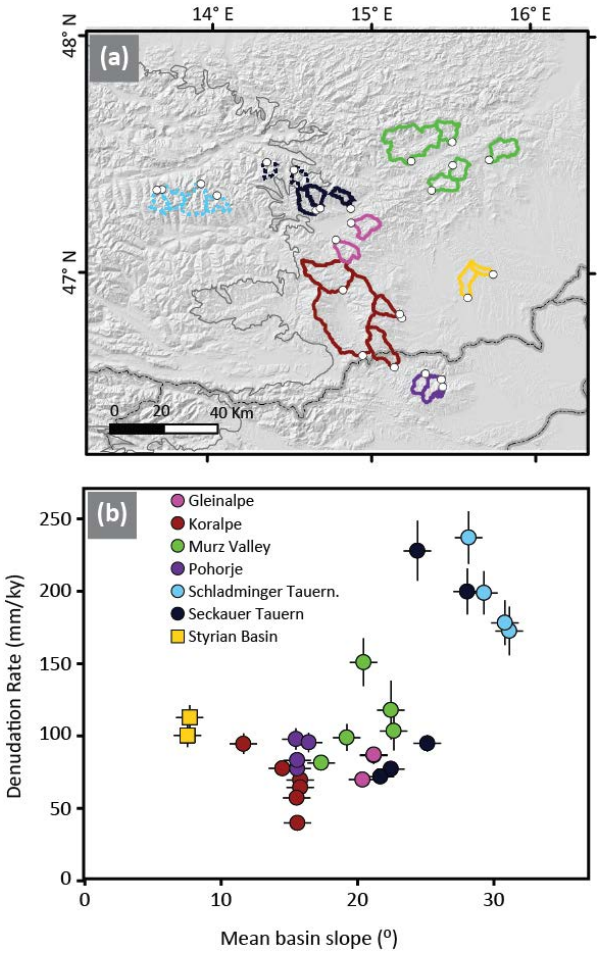
(a)
14° E
15° E
16° E
48° N
47° N
0 20 40 Km
(b)
Gleinalpe
Koralpe
Murz Valley
Pohorje
Schladminger Tauern.
Seckauer Tauern
Styrian Basin
Denudation Rate (mm/ky)
Mean basin slope (º)
0
50
100
150
200
250
0
10
20
30

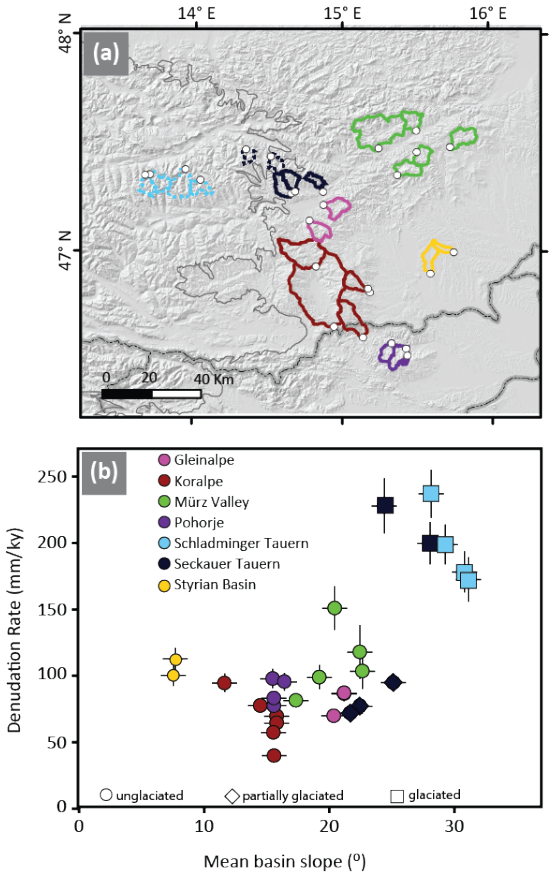
(a)
14° E
15° E
16° E
48° N
47° N
0 20 40 Km
(b)
Gleinalpe
Koralpe
Mürz Valley
Pohorje
Schladminger Tauern
Seckauer Tauern
Styrian Basin
Denudation Rate (mm/ky)
Mean basin slope (°)
unglaciated
partially glaciated
glaciated

Figure 3. (A) Study catchments show increasing mean slope with mean elevation (~~black~~ grey circles). The percent of slopes >35° within these basins increase non-linearly with elevation (blue squares), such that catchments at high elevations >1500 m show strong variation in the distribution of steep, threshold-style hillslopes. Small unglaciated basins studied by Legrain et al. (2015) in this same region show little systematic variation in slope with elevation (small open circles). Instead of reflecting the broader regional signal, mean slopes of these smaller basins are likely controlled by their position with respect to river knickpoints and proportion of the catchment that is actively incising. (B) Catchments sampled in this study range from ~3 to 950 km^2 (table 2). Catchment size appears to have limited systematic influence on mean basin slope and measured erosion rates, since basins of similar size show significant variation in both.

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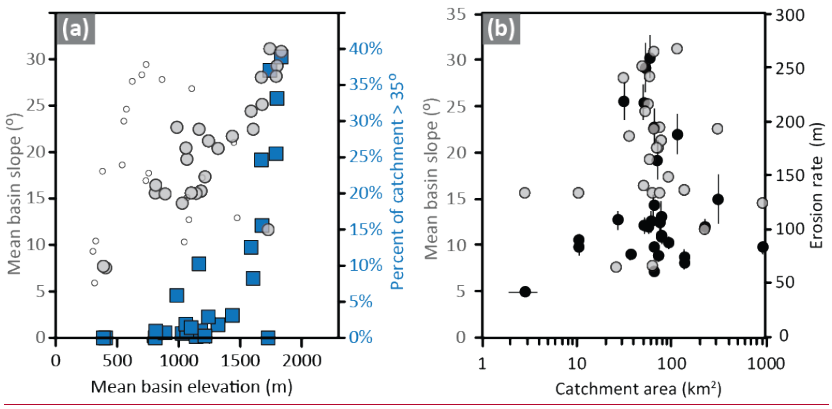
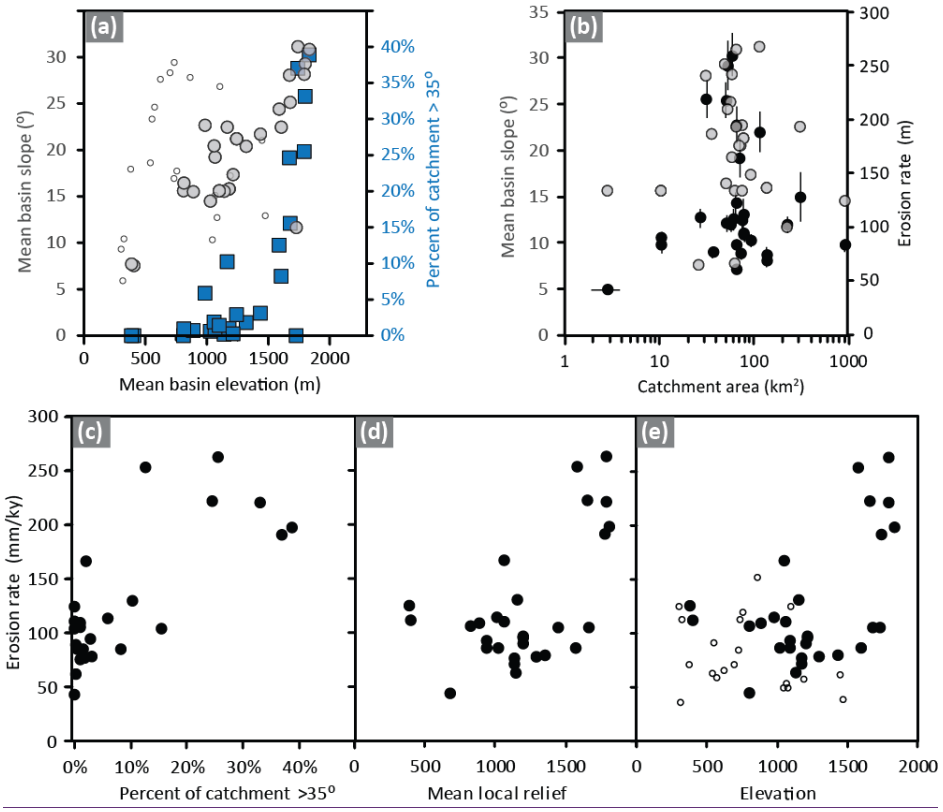

(a)
Mean basin slope (°)
Percent of catchment > 35°
Mean basin elevation (m)
(b)
Mean basin slope (°)
Erosion rate (m)
Catchment area (km²)


(a)
Mean basin slope (°)
Percent of catchment > 35°
Mean basin elevation (m)
(b)
Mean basin slope (°)
Erosion rate (m)
Catchment area (km²)
(c)
(d)
(e)
Erosion rate (mm/ky)
Percent of catchment >35°
Mean local relief
Elevation

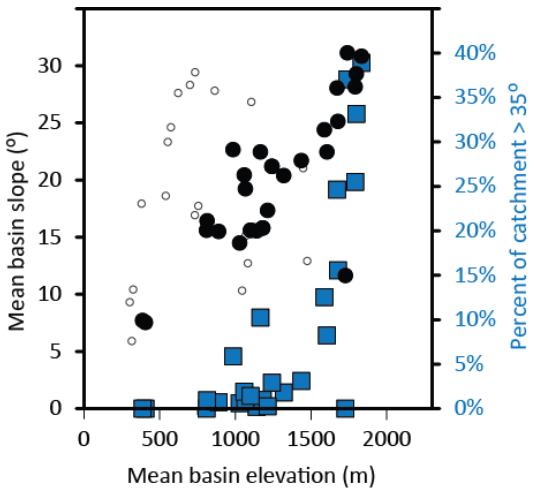

Mean basin slope (°)
30
25
20
15
10
5
0
0
500
1000
1500
2000
Mean basin elevation (m)
40%
35%
30%
25%
20%
15%
10%
5%
0%
Percent of catchment > 35°

Figure 4. (A) Map of sampled basins across the eastern Alps, color-coded for erosion rates. (B) Cumulative slope distributions color-coded by sample-region (same as Figure 2) show catchment morphology follows geographic groupings, with low-slope endmembers in the Styrian basin and high-slope endmembers represented by previously-glaciated basins of the Schladminger and Seckauer Tauern (dotted lines). Slope distributions across these basins also complement measured erosion rates. (C,D) Frequency and cumulative distributions of basin slope show that rapidly eroding, previously-glaciated basins tend to have higher mean and modal slopes than more slowly eroding basins. Colors in panels C and D correspond to the scale for basin erosion shown in panel A.

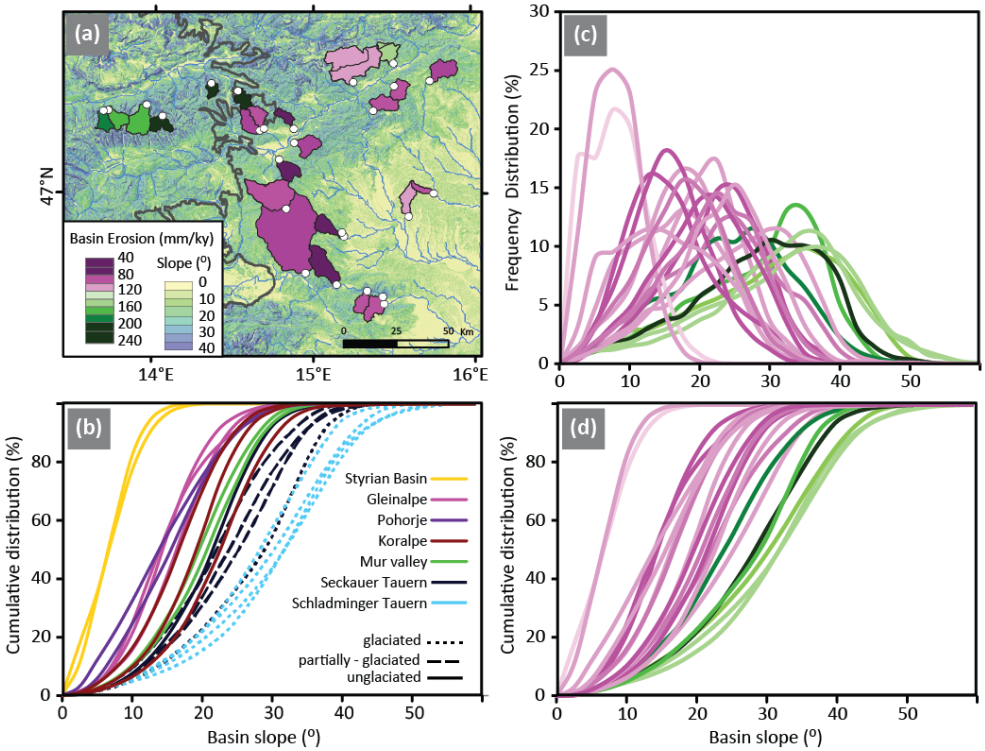


Figure 5. Variation of slope and elevation within sample catchments. Elevation is binned between 50 m contours, and catchment slopes are averaged within these bins. Hillslope angles are distinctly distributed with basin elevation between slow and rapidly eroding catchments; with highest slope angles found at middle elevations of previously glaciated basins and highest elevations of non-glaciated basins. Symbol colors correspond to the scale for basin erosion shown in Fig. 4a.

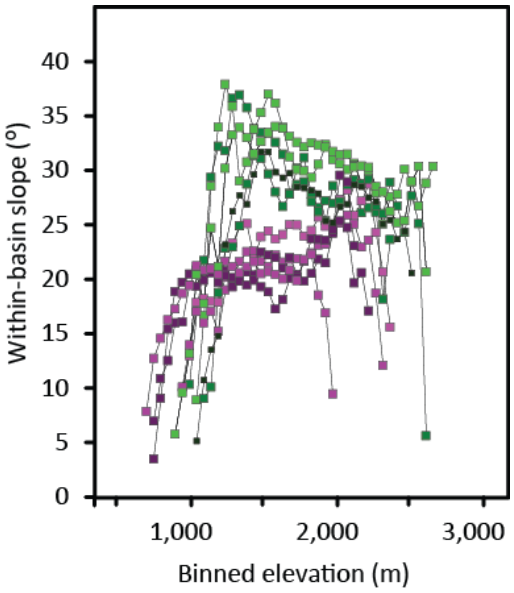
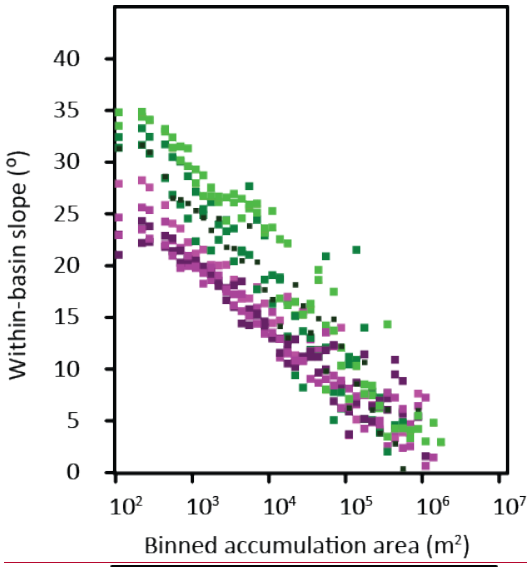


Figure 6. Slope-area plots for catchments across the study area. Accumulation area is calculated on a per pixel basis from the 10 m digital elevation model, and represents the upslope contributing area (drainage area). Slopes within each catchment are binned by increments of 0.2 $\log_{10}$ accumulation areas to show downslope and downstream changes in mean basin gradient. Binned values are color coded by erosion rate, and correspond to the basin erosion scale provided in Fig. 4a. Data points at large accumulation areas (>10^3-10^5 m^2) reflect local stream steepness, and plot within a similar range of values despite disparate erosion rates. However, data points at small accumulation areas (<10^2-10^4 m^2) represent upslope hillslope gradients and have distinct steepnesses based on the erosion rates of the basin and the glacial history. These data largely reflect disparate hillslope steepnesses between glaciated (rapidly eroding; green) and unglaciated (more slowly eroding; pink) catchments.


Within-basin slope (°)
40
35
30
25
20
15
10
5
0
10^2
10^3
10^4
10^5
10^6
10^7
Binned accumulation area (m²)

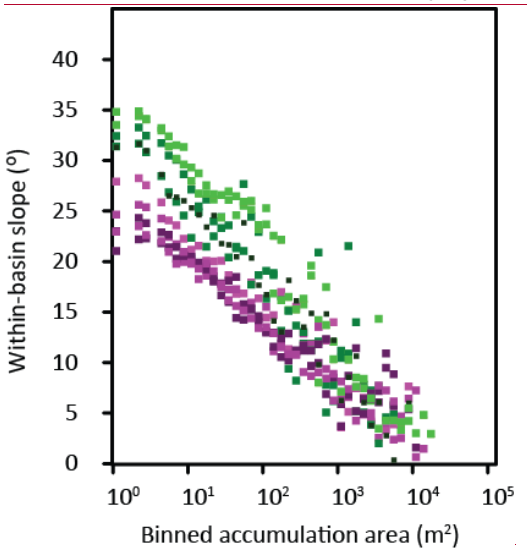
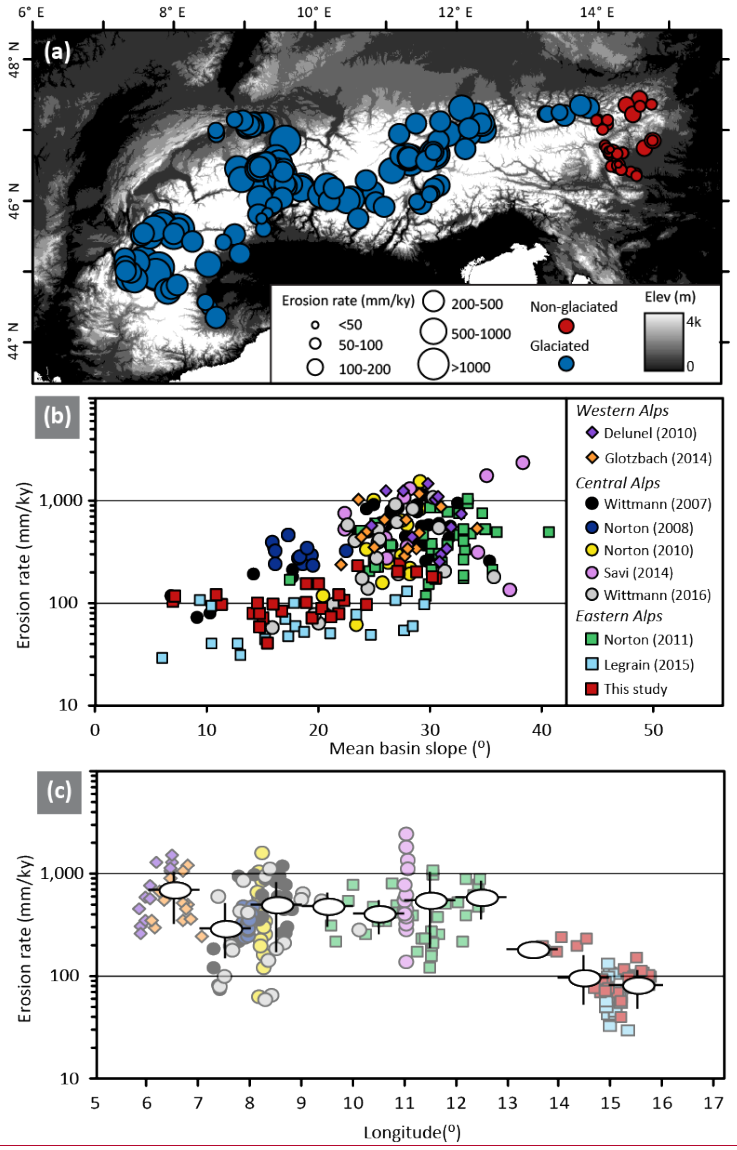
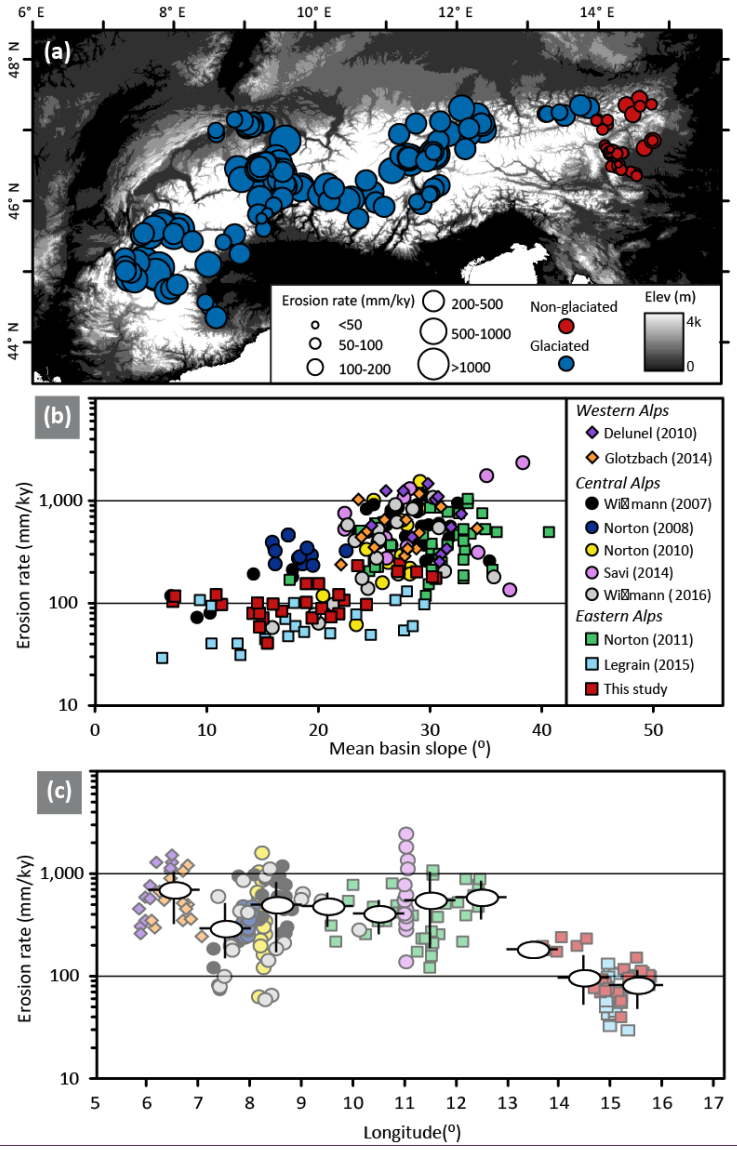

Within-basin slope (°)
40
35
30
25
20
15
10
5
0
10^0
10^1
10^2
10^3
10^4
10^5
Binned accumulation area (m²)

Figure 7. (A) Published erosion rates across the European Alps range from ~40 - 2,100 ~~mm/ka~~mm/ky, recorded by over 100 cosmogenic samples from ~~7~~ 9 studies that report both mean catchment slope and erosion rates. Published erosion rates were rescaled to a consistent sea level, high latitude production rate of 4.0 a/g/y. Symbol size reflects ~~the published~~ erosion rate, and symbol color reflects past glacial history (red = previously unglaciated; blue = previously glaciated). (B) Across the range, these rates vary only weakly, but significantly ~~-~~with mean basin slope (linear fit r^2=0.23; exponential fit r^2=0.34). ~~Rates from Legrain et al., 2015 were measured in small basins with areas <1 km^2, and are only shown in panel B~~ (C) Compiled erosion rates plotted against sample longitude. Symbols for individual samples are color–coded as in panel B, but with slight transparency so as to increase visibility of average erosion rates binned by 1 degree latitude (Grey ovals). Y-error bars reflect standard deviation (standard error is smaller than symbols). Despite variations in surface uplift, precipitation, and other potential controlling variables, we find little systematic east-to-west variation in average Holocene erosion rates across the range. Only rates in our far eastern study region appear to vary significantly from other portions of the Alpine range. ~~Panel A includes data from Savi et al. (2014); not included in Panel B due to lack of slope data.~~


(a)
6° E
8° E
10° E
12° E
14° E
48° N
46° N
44° N
Erosion rate (mm/ky)
<50
50-100
100-200
200-500
500-1000
>1000
Non-glaciated
Glaciated
Elev (m)
4k
0
(b)
Erosion rate (mm/ky)
1,000
100
10
0
10
20
30
40
50
Mean basin slope (°)
Western Alps
Delunel (2010)
Glotzbach (2014)
Central Alps
Wittmann (2007)
Norton (2008)
Norton (2010)
Savi (2014)
Wittmann (2016)
Eastern Alps
Norton (2011)
Legrain (2015)
This study
(c)
Erosion rate (mm/ky)
1,000
100
10
5
6
7
8
9
10
11
12
13
14
15
16
17
Longitude(°)


(a)
6° E
8° E
10° E
12° E
14° E
48° N
46° N
44° N
Erosion rate (mm/ky)
<50
50-100
100-200
200-500
500-1000
>1000
Non-glaciated
Glaciated
Elev (m)
4k
0
(b)
Erosion rate (mm/ky)
1,000
100
10
0
10
20
30
40
50
Mean basin slope (°)
Western Alps
Delunel (2010)
Glotzbach (2014)
Central Alps
Wi⊠mann (2007)
Norton (2008)
Norton (2010)
Savi (2014)
Wi⊠mann (2016)
Eastern Alps
Norton (2011)
Legrain (2015)
This study
(c)
Erosion rate (mm/ky)
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100
10
5
6
7
8
9
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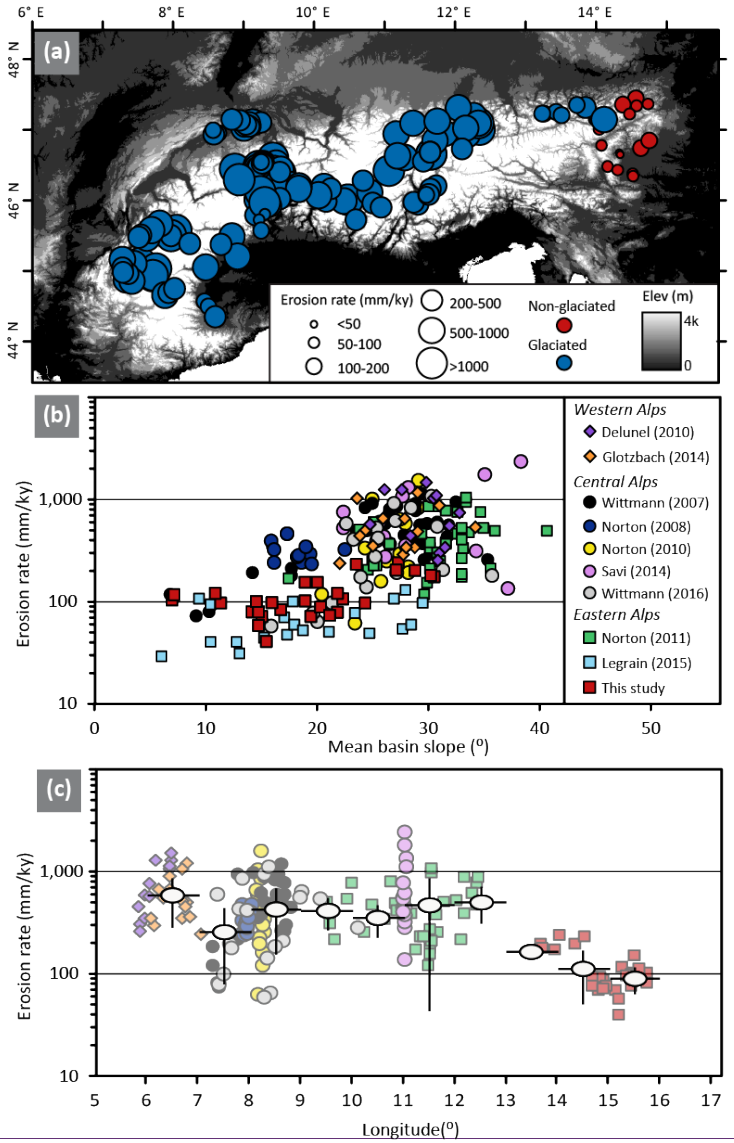
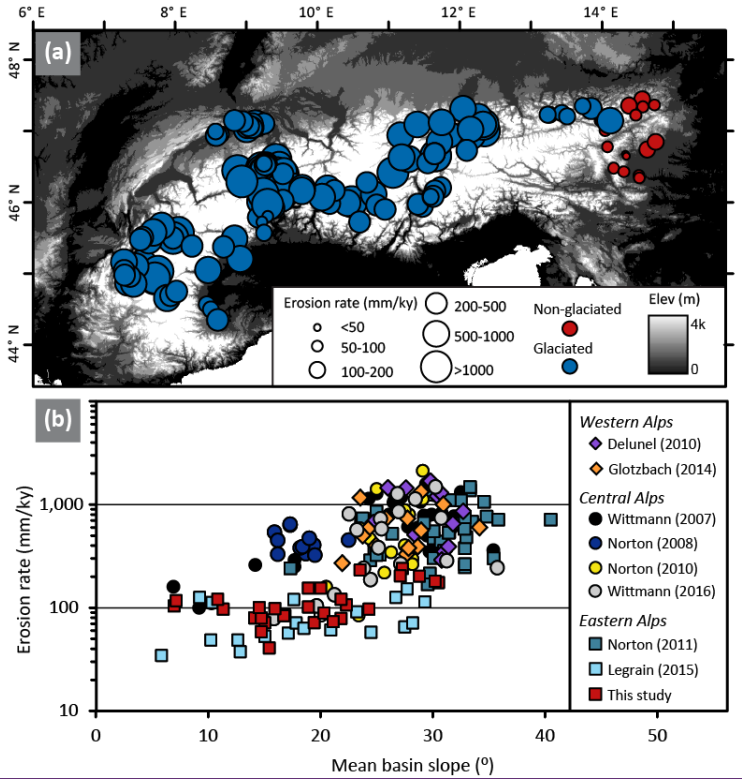
11
12
13
14
15
16
17
Longitude(°)


(a)
6° E
8° E
10° E
12° E
14° E
48° N
46° N
44° N
Erosion rate (mm/ky)
<50
50-100
100-200
200-500
500-1000
>1000
Non-glaciated
Glaciated
Elev (m)
4k
0
(b)
Erosion rate (mm/ky)
1,000
100
10
0
10
20
30
40
50
Mean basin slope (°)
Western Alps
Delunel (2010)
Glotzbach (2014)
Central Alps
Wittmann (2007)
Norton (2008)
Norton (2010)
Savi (2014)
Wittmann (2016)
Eastern Alps
Norton (2011)
Legrain (2015)
This study
(c)
Erosion rate (mm/ky)
1,000
100
10
5
6
7
8
9
10
11
12
13
14
15
16
17
Longitude(°)


(a)
6° E
8° E
10° E
12° E
14° E
48° N
46° N
44° N
Erosion rate (mm/ky)
<50
50-100
100-200
200-500
500-1000
>1000
Non-glaciated
Glaciated
Elev (m)
4k
0
(b)
Erosion rate (mm/ky)
1,000
100
10
0
10
20
30
40
50
Mean basin slope (°)
Western Alps
Delunel (2010)
Glotzbach (2014)
Central Alps
Wittmann (2007)
Norton (2008)
Norton (2010)
Wittmann (2016)
Eastern Alps
Norton (2011)
Legrain (2015)
This study

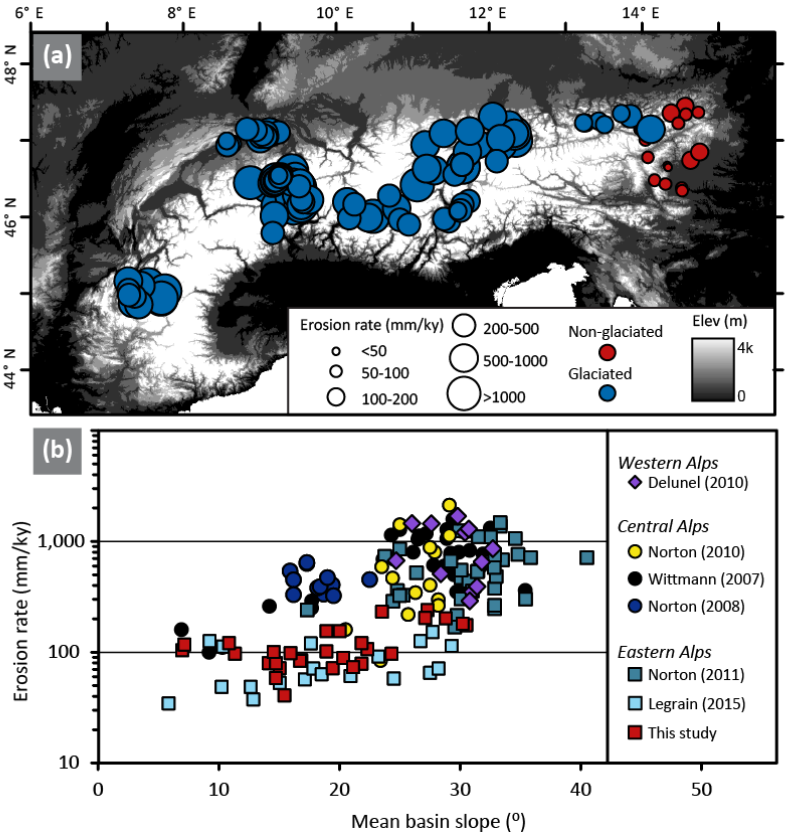


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Table 1. Data from cosmogenic nuclide analyses

Sample	Size Fraction (µm)	Long. (°E)	Lat. (°N)	Sample elev. (m)	Qtz. weight (g)	^{10}Be conc.* (x10^4 at/g $_{qtz}$)	Snow shielding factor #	Topographic shielding factor #	Production rate † (at / g $_{qtz}$/y)	Denudation rate (mm/ky)
Bistrica	250-500	15.139	46.613	382	30.2	10.87 ± 0.89	0.93	0.99	9.58	69.2 ± 6.4
Bistrica	500-800	15.139	46.613	382	30.2	11.74 ± 0.87	0.93	0.99	9.58	64.0 ± 5.6
Feistrichbach	250-500	14.778	47.151	717	31.2	12.79 ± 0.60	0.92	0.98	11.63	69.3 ± 4.2
Gleinbach	250-800	14.872	47.222	656	33.2	9.41 ± 0.56	0.92	0.98	10.46	86.3 ± 6.1
Gleinbach	500-800	14.872	47.222	656	35.1	9.35 ± 0.45	0.92	0.98	10.46	86.8 ± 5.0
Ingering	250-500	14.680	47.285	967	40.3	11.39 ± 0.56	0.89	0.96	14.50	94.3 ± 5.8
Kleinsolk	250-500	13.938	47.382	893	39.9	6.58 ± 0.57	0.88	0.93	15.53	172.5 ± 16.2
Krug	250-500	14.657	47.275	938	40.2	13.81 ± 0.78	0.90	0.97	14.24	76.5 ± 5.4
Lassnitz1	250-500	15.184	46.820	520	34.6	15.49 ± 0.62	0.96	0.99	7.48	39.2 ± 2.1
Lassnitz3	250-500	15.173	46.838	543	31.7	13.70 ± 0.60	0.93	0.99	9.95	56.7 ± 3.4
Lavant1	250-500	14.824	46.939	658	31.7	8.95 ± 0.58	0.89	0.99	11.02	94.3 ± 7.0
Lavant2	250-500	14.945	46.663	370	31.5	9.95 ± 0.58	0.94	0.99	9.81	77.4 ± 5.3
Mooskogel	250-500	15.372	47.359	490	39.0	7.04 ± 0.83	0.95	0.97	9.19	103.7 ± 13.4
Obertal	250-500	13.665	47.354	967	40.1	5.69 ± 0.38	0.88	0.94	15.52	199.0 ± 15.0
Pickelbach	250-500	15.750	47.003	326	30.7	4.91 ± 0.38	0.99	1.00	5.65	101.6 ± 8.3
Pohorju1	250-500	15.434	46.529	543	32.7	9.53 ± 0.78	0.94	0.99	9.29	77.2 ± 7.1
Pohorju1	500-800	15.434	46.529	543	31.5	8.86 ± 0.47	0.94	0.99	9.29	83.1 ± 5.1
Pohorju2	250-500	15.425	46.560	313	30.6	7.22 ± 0.50	0.95	0.99	8.85	98.1 ± 7.7
Ratten	250-500	15.732	47.487	752	30.3	10.10 ± 0.48	0.93	0.99	10.58	81.1 ± 4.8
Rottenmann	250-500	14.347	47.477	1077	35.5	5.51 ± 0.39	0.89	0.95	15.04	200.1 ± 15.9
SaintNico	250-500	14.038	47.335	1053	40.0	4.88 ± 0.33	0.88	0.95	15.93	237.5 ± 17.8
Seckaur	250-500	14.871	47.283	724	32.4	12.53 ± 0.70	0.91	0.98	11.77	71.3 ± 4.8
Stanz	250-500	15.506	47.465	650	29.5	7.71 ± 0.65	0.94	0.98	9.71	99.0 ± 9.3
Stiefing	250-500	15.592	46.905	304	31.2	4.35 ± 0.31	0.99	1.00	5.62	114.3 ± 8.5
Thorl	250-500	15.245	47.482	583	40.3	6.49 ± 0.97	0.91	0.97	9.81	118.2 ± 19.6
Triebental	250-500	14.516	47.444	1063	32.2	4.50 ± 0.38	0.90	0.96	13.95	228.7 ± 21.8
Untertal	250-500	13.698	47.357	999	40.5	6.53 ± 0.50	0.88	0.93	16.00	178.1 ± 15.4
Veitsch	250-500	15.502	47.564	672	34.2	4.96 ± 0.51	0.94	0.98	9.55	151.8 ± 16.5
Velka	250-500	15.328	46.585	372	34.3	6.91 ± 0.45	0.96	0.99	8.13	95.8 ± 6.8

* ^{10}Be concentrations measured at ETH-Zürich in June 2010 and 2011. Results normalized to Nishiizumi et al. (2007) 2007KNSTD standard, corrected for average of six chemical processing blanks (^{10}Be/^{9}Be = 2.72 ± 2.21 × 10^{-15}; µ ± s.d.).

\# Snow shielding calculated from annual Swiss snow data (Auer, 2003). Topographic shielding calculated from 10 m DEMs.

† Per-pixel production rates calculated for quartz-bearing lithologies following scaling laws of Dunai (2000) , Schaller et al. (2002), and Braucher et al. (2003) for nucleonic and muonic interactions. Based on compilation of sea level, high-latitude~~, sea-level~~ production rates of 4.0 atoms/g$_{quartz}$/yr for high-energy neutrons (Phillips et al., 2016), and assuming negative and fast muons compose 1.2% and 0.65% of total production rates respectively (Braucher et al., 2003). Mean catchment production rates include both topographic and snow-shielding correction factors.

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Table 2. Catchment denudation rates and morphometrics

Sample	Glacial History *	Catchment Area (km^2)	Avg. slope$^{1\#}$ (°)	Avg. slope$^{2\#}$ (°)	Mean Elevation (m)	Basin area >35° (%)	Mean Local Relief † (m)	Denudation Rate (mm/ky)
Gleinalpe								
Feistrichbach	U	74.8	20.4	19.5	1322	2%	1301	69.3 ± 4.2
Gleinbach	U	80.9	21.2	20.4	1243	3%	1201	86.3 ± 6.1
Koralpe								
Bistrica	U	141.2	15.8	15.1	1181	1%	1136	69.2 ± 6.4
Lassnitz1	U	2.9	15.6	15.5	810	0%	681	39.2 ± 2.1
Lassnitz3	U	66.3	15.5	14.8	1141	0%	1155	56.7 ± 3.4
Lavant1	U	234.5	11.6	11.4	1728	0%	1450	94.3 ± 7
Lavant2	U	952.3	14.5	14.2	1029	1%	1029	77.4 ± 5.3
Murz Valley								
Mooskogel	U	79.2	22.7	22.4	985	6%	1017	103.7 ± 13.4
Ratten	U	96.5	17.3	16.8	1213	0%	1198	81.1 ± 4.8
Stanz	U	62.3	19.2	19.0	1068	1%	1068	99 ± 9.3
Thorl	U	321.1	22.5	21.9	1166	10%	1157	118.2 ± 19.6
** Thorl-qtz	U	(163.7)*	-	-	-	-	-	118.2 ± 19.6
Veitsch	U	73.0	20.4	20.1	1060	2%	1071	151.8 ± 16.5
** Veitsch-qtz	U	(63.3)*	-	-	-	-	-	151.8 ± 16.5
Pohorje								
Pohorju1	U	10.9	15.6	14.8	1102	1%	948	77.2 ± 7.1
Pohorju2	U	78.3	15.5	14.6	890	1%	897	98.1 ± 7.7
Velka	U	52.5	16.4	16.0	814	1%	828	95.8 ± 6.8
Schladminger Tauern								
Kleinsolk	G	117.8	31.1	30.6	1742	37%	1779	172.5 ± 16.2
Obertal	G	51.8	29.3	28.9	1800	33%	1793	199 ± 15
SaintNico	G	60.3	28.1	27.4	1792	25%	1789	237.5 ± 17.8
Untertal	G	67.8	30.8	30.3	1834	39%	1808	178.1 ± 15.4
Seckauer Tauern								
Ingering	P	58.6	25.1	24.4	1679	16%	1670	94.3 ± 5.8
Krug	P	67.0	22.4	21.9	1606	8%	1574	76.5 ± 5.4
Rottenmann	G	32.2	28.0	27.2	1672	25%	1654	200.1 ± 15.9
Seckaur	P	37.7	21.7	21.2	1437	3%	1362	71.3 ± 4.8
Triebental	G	54.8	24.4	23.6	1590	13%	1587	228.7 ± 21.8
Styrian Basin								
Pickel	U	27.7	7.5	7.0	406	0%	408	101.6 ± 8.3
Stiefing	U	66.6	7.7	7.2	388	0%	394	114.3 ± 8.5

* Catchments defined as previously glaciated (G), partially glaciated (P) or unglaciated (U) in the LGM. Partially glaciated catchments were ice covered only in uppermost regions of the catchment.

$^{\#}$ Mean catchment slopes are calculated from both 10m DEMs (^{1}) and 80m 1-arc second DEMS (^{2}).

† Mean local relief calculated using a 5 km moving window.

**Thorl and Veitsch catchments contained significant non-quartz bearing lithologies.

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~~Region and Sample~~		~~Glacial History *~~	~~Catchment Area (km2)~~	~~10m slope (°)~~	~~80m slope (°)~~		~~Mean Elevation (m)~~		~~Denudation Rate (mm/ky)~~	
~~Gleinalpe~~										
	~~Feistrichbach~~	~~U~~	~~74.8~~	~~20.4~~	~~19.5~~		~~1322~~		~~69.3~~	~~± 4.2~~
	~~Gleinbach~~	~~U~~	~~80.9~~	~~21.2~~	~~20.4~~	~~1243~~	~~86.3~~	~~±~~	~~6.1~~	
~~Koralpe~~										
	~~Bistrica~~	~~U~~	~~141.2~~	~~15.8~~	~~15.1~~	~~1181~~	~~69.2~~	~~±~~	~~6.4~~	
	~~Lassnitz1~~	~~U~~	~~2.9~~	~~15.6~~	~~15.5~~	~~810~~	~~39.2~~	~~±~~	~~2.1~~	
	~~Lassnitz3~~	~~U~~	~~66.3~~	~~15.5~~	~~14.8~~	~~1141~~	~~56.7~~	~~±~~	~~3.4~~	
	~~Lavant1~~	~~U~~	~~234.5~~	~~11.6~~	~~11.4~~	~~1728~~	~~94.3~~	~~±~~	~~7.0~~	
	~~Lavant2~~	~~U~~	~~952.3~~	~~14.5~~	~~14.2~~	~~1029~~	~~77.4~~	~~±~~	~~5.3~~	
	~~Mooskogel~~	~~U~~	~~79.2~~	~~22.7~~	~~22.4~~	~~985~~	~~103.7~~	~~±~~	~~13.4~~	
~~Murz Valley~~										
	~~Mooskogel~~	~~U~~	~~79.2~~	~~22.7~~	~~22.4~~	~~985~~	~~103.7~~	~~±~~	~~13.4~~	
	~~Ratten~~	~~U~~	~~96.5~~	~~17.3~~	~~16.8~~	~~1213~~	~~81.1~~	~~±~~	~~4.8~~	
	~~Stanz~~	~~U~~	~~62.3~~	~~19.2~~	~~19.0~~	~~1068~~	~~99.0~~	~~±~~	~~9.3~~	
	~~Thorl~~	~~U~~	~~321.1~~	~~22.5~~	~~21.9~~	~~1166~~	~~118.2~~	~~±~~	~~19.6~~	
	~~$^{\#}$ Thorl-qtz~~	~~U~~	~~(163.7)*~~	~~-~~	~~10.9~~	~~1141~~	~~118.2~~	~~±~~	~~19.6~~	
	~~Veitsch~~	~~U~~	~~73.0~~	~~20.4~~	~~20.1~~	~~1060~~	~~151.8~~	~~±~~	~~16.5~~	
	~~$^{\#}$ Veitsch-qtz~~	~~U~~	~~(63.3)*~~	~~-~~	~~19.0~~	~~814~~	~~151.8~~	~~±~~	~~16.5~~	
~~Pohorje~~										
	~~Pohorju1~~	~~U~~	~~10.9~~	~~-~~	~~14.8~~	~~1102~~	~~77.2~~	~~±~~	~~7.1~~	
	~~Pohorju2~~	~~U~~	~~78.3~~	~~-~~	~~14.6~~	~~890~~	~~98.1~~	~~±~~	~~7.7~~	
	~~Velka~~	~~U~~	~~52.5~~	~~-~~	~~16.0~~	~~814~~	~~95.8~~	~~±~~	~~6.8~~	
~~Schladminger Tauern~~										
	~~Kleinsolk~~	~~G~~	~~117.8~~	~~31.1~~	~~30.6~~	~~1742~~	~~172.5~~	~~±~~	~~16.2~~	
	~~Obertal~~	~~G~~	~~51.8~~	~~29.3~~	~~28.9~~	~~1800~~	~~199.0~~	~~±~~	~~15.0~~	
	~~SaintNico~~	~~G~~	~~60.3~~	~~28.1~~	~~27.4~~	~~1792~~	~~237.5~~	~~±~~	~~17.8~~	
	~~Untertal~~	~~G~~	~~67.8~~	~~30.8~~	~~30.3~~	~~1834~~	~~178.1~~	~~±~~	~~15.4~~	
~~Seckauer Tauern~~										
	~~Ingering~~	~~UP~~	~~58.6~~	~~25.1~~	~~24.4~~	~~1679~~	~~94.3~~	~~±~~	~~5.8~~	
	~~Krug~~	~~UP~~	~~67.0~~	~~22.4~~	~~21.9~~	~~1606~~	~~76.5~~	~~±~~	~~5.4~~	

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	~~Rottenmann~~	~~G~~	~~32.2~~	~~28.0~~	~~27.2~~	~~1672~~	~~200.1~~ ± ~~15.9~~
	~~Seckaur~~	~~UP~~	~~37.7~~	~~21.7~~	~~21.2~~	~~1437~~	~~71.3~~ ± ~~4.8~~
	~~Triebental~~	~~G~~	~~54.8~~	~~24.4~~	~~23.6~~	~~1590~~	~~228.7~~ ± ~~21.8~~
~~Styrian Basin~~							
	~~Pickel~~	~~U~~	~~27.7~~	~~7.5~~	~~7.0~~	~~406~~	~~101.6~~ ± ~~8.3~~
	~~Stiefing~~	~~U~~	~~66.6~~	~~7.7~~	~~7.2~~	~~388~~	~~114.3~~ ± ~~8.5~~

~~* Catchments defined as previously glaciated across the entire catchment (G), partially glaciated (P) or unglaciated (U) in the PleistoceneLGM.~~

~~# Thorl and Veitsch catchments contained significant non-quartz bearing lithologies. Topographic metrics for quartz bearing regions alone provided separately.~~

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