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Interactive comment on "Millennial-scale denudation rates in the Himalaya of Far Western Nepal" *by* Lujendra Ojha et al.

Lujendra Ojha et al.

luju@jhu.edu

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REFEREE: The paper by Lujendra Ojha, Ken L. Ferrier and Tank Ojha presents seven 10Be-derived estimates of catchment-scale denudation rates in Western Nepal. These denudation rates fall within the range of values published elsewhere in Himalaya. The paper is clear, well written and illustrated.

It seems that the main interest of this contribution is to provide new denudation data in a region where they were lacking. The authors do not claim to revolution the debate between the climatic and tectonic control of denudation with their data, which is fair, but the scientific justification of the study is a bit short. Why was it "important" to fill this gap of data? Is it a key place? Was the sampling initially designed for some particular

question? The last sentence of the conclusion says that this study "illustrates the need for future denudation rate measurements in the region to test hypotheses". As it, I am not sure that this is the case. I agree that new data are always useful and that is why I think that this paper should be published. Nevertheless, this study shows that these new denudation data are not able to discuss the relative contribution between climate and tectonics. Thus where do we need to gather future samples to answer this question and why?

RESPONSE: We appreciate the reviewer's suggestions on how to strengthen the motivation for this study, particularly in describing why the study area is of interest and where future sampling should be focused. To address this, we added two paragraphs to the text, one at the end of the Introduction, which describes why this study area is of interest, and one at the end of Section 7, which describes where future sampling efforts may be most fruitfully directed. We also added a new figure (now Figure 2), as suggested by another reviewer, that shows where our samples are located within profiles of topography and stream power across this section of the Himalaya. The new text at the end of the Introduction is as follows.

"Previous studies suggest that the relative strengths of the controls on denudation rate in Far Western Nepal may differ from those in central Nepal. In central Nepal, the presence of a single, major mid-crustal ramp in the Main Himalayan Thrust (MHT) (e.g., Schulte-Pelkum et al., 2005; Bollinger et al., 2006; Nábělek et al., 2009; Elliott et al., 2016) has given rise to a steep topographic gradient with spatially focused exhumation and orographic precipitation (van der Beek et al., 2016). In Far Western Nepal, by contrast, the topography rises more gradually and induces a less intense focusing of orographic precipitation, and has been hypothesized to be a reflection of two distinct mid-crustal ramps, each smaller than the one in central Nepal (Harvey et al., 2015; van der Beek et al., 2016). This is consistent with apatite fission-track thermochronometric measurements that show that Myr-scale exhumation rates and specific stream power are significantly higher and more spatially focused in central Nepal than in Far

Western Nepal (van der Beek et al., 2016). To the extent that along-strike variations in uplift and orographic precipitation influence the spatial patterns and magnitudes of denudation rates, they may also induce along-strike variations in the feedbacks between climate, tectonics, and topography. In this study, we report new basin-averaged denudation rate measurements inferred from cosmogenic 10Be in stream sediment in Far Western Nepal to better understand denudation rate patterns in this segment of the Himalaya. Our measurements show that denudation rates in these basins are consistent with those both east and west of Far Western Nepal, suggesting similar controls on denudation across this portion of the Himalayan arc over millennial timescales, and they highlight the regions that may be most useful to target for future denudation rate measurements."

The following is the new text that has been added to the end of Section 7, which describes where it would be most useful to collect future samples.

"While our measurements are unable to isolate the controls on denudation rates on their own, they are nonetheless able to highlight regions in Far Western Nepal that may be useful targets for future denudation rate measurements. For example, the regions northeast of 100 km and southwest of 180 km in the swath in Figure 2 have few denudation rate measurements, and targeting small basins within these regions may be particularly instructive. For example, to isolate the sensitivity of denudation rates to rock uplift rate, it may be useful to target basins like Raduwa in the Subhimalaya and the southwestern portion of the Lesser Himalaya (Figure 3A), where topographic relief and rock uplift rates are hypothesized to be low, to determine whether the low denudation rate in Raduwa is typical of other basins undergoing similar tectonic forcing. Similarly, it may be helpful to target small catchments that lie over the hypothesized mid-crustal ramps (Harvey et al., 2015), where rock uplift rates may be higher, including small basins at relatively high elevation in the Greater Himalaya within the Karnali, Bheri, and Seti River basins (Figure 3B). Likewise, to assess the sensitivity of denudation rates to stream power, it may be useful to target small basins that isolate regions of high

SSP, like those at mid-elevations in the Bheri catchment and high elevations in the Seti catchment, as well as basins that isolate regions of low SSP, like those at low elevation in the southwestern portions of the Bheri, Karnali, and Seti basins (Figure 4C). While some of these sites are relatively remote and were beyond our ability to access them during this study, future field campaigns that are able to collect samples from these sites may be able to put stricter constraints on the couplings between denudation rate, rock uplift, and climate in Far Western Nepal."

REFEREE: The calculation of the denudation rates is correct and includes a good discussion of uncertainties. Yet, some aspects of these uncertainties could be improved: Dibiase (Earth Surf. Dynam., 6, 923-931, 2018) recently showed that the topographic shielding correction is usually unappropriated. As denudation values with and without topographic shielding are already given, the authors could only recall the Dibiase's paper.

RESPONSE: We agree that an accurate assessment of topographic shielding can be significant, especially in exceptionally steep topography, as DiBiase (2018) showed. To the extent that the model geometry adopted by DiBiase (2018) applies to our study basins, where our estimates of topographic shielding are relatively small (ranging from 0.6% to 2.5% among basins), this would increase our estimates of denudation rate by < 2.5%. To address this, we added the following text at Line 50 of Section 3.2.2.

"Recently, DiBiase (2018) showed that this approach can overestimate the extent of topographic shielding, particularly in steeply dipping catchments, and argued that topographic shielding factors should be 1 in basins with horizontal surrounding ridges. If this horizontal ridge geometry is applicable to our study basins, where our estimates of topographic shielding range from 0.9759 to 0.9939 (Table 2), then the denudation rates in Table 2 would be underestimated by 0.6% to 2.5%."

REFEREE: The uncertainty on production rate is not indicated. It can easily reach more than 10% and depends on the production rate model (which one was used in the

CRONUS calculator?) and thus should be propagated to the denudation rate uncertainty.

RESPONSE: Uncertainties in the production rate are incorporated directly into the denudation rate estimates computed by the CRONUS calculator, which it reports as the "external" uncertainty, and which does not report the production rate uncertainty separately. To address this, we added the following text at Line 40 in Section 3.2.3.

"The denudation rate uncertainties in Table 2 are the "external" uncertainties reported by the CRONUS calculator for the Lal/Stone production rate scaling scheme, and include propagated uncertainties on the 10Be production rate."

REFEREE: What is exactly the maximum grain size of quartz that was dissolved? Table S1 gives the distribution of grain sizes for each sample. I understand that all these grain sizes were dissolved together. Why doing this, while many studies have shown that the 10Be concentration is grain size dependent? The grain size distribution differs a lot between catchments. Does denudation rate correlate with the mean (or other metrics) grain size in this dataset, as observed in many other cases?

RESPONSE: As noted in Table S2, most of the samples were dominated by sand-sized sediment. We did not measure the size of the largest grains, but we estimate that the largest grains at Raduwa (which has the largest median grain size among our samples) were no larger than 40-50 mm in diameter. We analyzed all grain sizes in the proportion they were present in our samples for precisely the reason the reviewer notes, i.e., that 10Be concentrations are often inversely related to grain size (e.g., Brown et al., 1995, EPSL, p. 193-202). Analyzing only a single grain size would yield a biased estimate of the basin-averaged 10Be concentration and hence a biased estimate of denudation rate (e.g., Riebe et al., 2015, PNAS, p. 15,574-15,579). To avoid introducing this bias, we analyzed all grain sizes in our samples to obtain a representative estimate of the mean 10Be concentration. To clarify this, we added the following text at Line 44 in Section 3.1.

"We analyzed quartz in all sediment grain sizes to avoid introducing biases that would be associated with analyzing only a single grain size (e.g., Brown et al., 1995; Riebe et al., 2015)."

REFEREE: The lithological effect is nicely discussed by exploring two end-members scenarios where only the catchment head or the catchment foot provides quartz. However, how do the relationships between denudation and slope, steepness and stream power change when restricted to the upper or lower catchment parts? For example, by restricting the calculation of ks and mean stream power to the upper Budhiganga catchment, its "anomalous" high denudation may be shifted to the right on diagrams of Figure 4, in a more "classical" configuration. In the studied catchments there is a correlation between lithology (possibly quartz content) and elevation (10Be production rate), as elsewhere along the range. Could it be possible that the lithological effect explains the large dispersion observed between denudation and steepness (see for example Carretier et al., Earth Surface Processes and Landform, 2015)?

RESPONSE: We agree that lithology varies within each catchment, but we do not have sufficient information on quartz content in each lithologic unit to assess how much this might affect the denudation rate estimates, so we refrain from speculating on that issue here. As the manuscript notes at Line 30 in Section 5.4, "We are unaware of published quartz abundances in the underlying lithologies, so we do not recalculate denudation rate estimates for our study basins here." To illustrate how this might affect the estimates of basin-averaged ksn and specific stream power and hence the patterns in Figure 4, we expand on the hypothetical scenario for the Kalanga basin by adding the following text at Line 48 in Section 5.4.

"In this scenario, the inferred ksn and specific stream power estimates would be 46% and 44% higher in the high-elevation portion of the Kalanga basin, respectively, and 33% and 39% lower in the low-elevation portion of the Kalanga basin, respectively. Like the differences in the inferred denudation rates, these differences are relatively small compared to the scatter in the trends in Figure 5, suggesting that these effects are unlikely to be a major source of scatter in Figure 5."

REFEREE: The discussion on the erodibility of different rocks in the Budhiganga and Kalanga catchments, ruling out lithology as possible control of their different denudations, is maybe a bit short (paragraph 20). Are the crystalline rocks of the Budhiganga catchment weathered or fractured? Are the carbonates of the Kalanga layered and possibly more easy to erode? What do other studies in the region or close say about the lithological control of denudation (e.g. Lave and Avouac, JGR, 2001)? Furthermore, this discussion may change by restricting the calculation of ks and stream power to the quartz-rich lithology (previous comment).

RESPONSE: We agree that more detailed characterization of the erodibility of the local rock units would be useful for assessing lithologic effects on denudation rate in the study region, but we are unaware of measurements of the erodibility of these units that would be necessary to assess this. To address this, we expanded this section so that it now reads as follows at Line 18 in Section 7.

"We are unaware of measurements of the erodibility of each lithology in these basins, but current geologic maps suggest the difference between the inferred Budhiganga and Kalanga denudation rates is unlikely to reflect a lithologic control. The Budhiganga basin is dominated by crystalline rocks (migmatitic and calc-silicate gneiss, metavolcanics, orthogneiss, schist, and granite; Figure S1; Gansser, 1964; Arita et al., 1984; Upreti and Le Fort, 1999; DeCelles et al., 2001; Robinson et al., 2006), which tend to be relatively strong and inhibit rapid erosion, while the Kalanga basin is dominated by carbonates, which tend to be less resistant to erosion (Sklar and Dietrich, 2001). Thus, if denudation rates were dominantly controlled by lithology, then to the extent that the mapped lithologic units have erodibilities similar to those of analogous rocks in laboratory tests (e.g., Sklar and Dietrich, 2001), denudation in the Kalanga basin should be faster than that in the Budhiganga, not slower. Evaluating lithologic effects on denudation rate in the study area more rigorously will require new detailed geologic mapping and new measurements of lithologic characteristics (e.g., tensile strength,

fracture spacing, bedding thickness) in these units."

REFEREE: I feel that the answers to these comments are quite straightforward. I encourage the authors to add the suggested analysis.

Please also note the supplement to this comment:
https://www.earth-surf-dynam-discuss.net/esurf-2019-7/esurf-2019-7-AC4-supplement.zip

Interactive comment on Earth Surf. Dynam. Discuss., https://doi.org/10.5194/esurf-2019-7, 2019.