Response to Anonymous Referee #1

"In this contribution, Gelwick et al., presents an analysis of topography mostly associated with drainage divides in the Hengduan Mountains, with an additional focus on comparing the implications and predictions of a variety of divide stability / mobility metrics. Overall, the paper is well organized and clearly written. Drainage divide stability remains a topic of general interest within the geomorphology community, especially so in this particular region of the world, so the paper seems appropriate for ESurf in terms of audience. The majority of my comments on the paper are minor, which I can classify into three broad themes that I summarize below and then flesh out in line-by-line comments.

There are a variety of places where it seems like it would be good to cite additional papers and/or acknowledge prior work more clearly.

In part related to the first point, in a few places in the manuscript the authors seem to imply that the comparison between divide metrics is novel and/or that the general conclusions of comparing different divide metrics, either in the abstract or in specific landscapes is new, when in fact there are a variety of efforts in the prior literature, some that they cite and others that they don't (e.g., Forte & Whipple, 2018; Sassolas-Serrayet et al., 2019; Ye et al., 2022; Zhou et al., 2022). There is still definitely value in the detailed comparisons presented here, but at the same time, it would be good to acknowledge that many of these same points have been demonstrated by others before."

We agree with the reviewer that additional references are justified and have modified several sentences to include all of the suggested references and a few others from the literature. In addition to those added in response to other comments and described later, we modified the following passages (blue text is new):

L56-58: "Common metrics include mean hillslope gradient, mean local relief, stream channel steepness, channel head elevation, and hillslope curvature measured near the divide (Hurst et al., 2013; Whipple et al., 2017c; Forte and Whipple, 2018; Scherler and Schwanghart, 2020; Zhou et al., 2022)."

L59-62: "In addition to these local-scale metrics, χ, a transformed variable of the along-stream distance (Perron and Royden, 2013), has been widely applied to assess the general geometric stability of the drainage network pattern with the assumption that planform patterns in χ should be reflected in the distribution of divide elevation and symmetry (Willett et al., 2014; Beeson et al., 2017; Sassolas-Serrayet et al., 2019; Ye et al., 2022; Zhou et al., 2022)."

L69-70: "Metrics which reflect local erosion and uplift dynamics are thus more reliable predictors of instantaneous motion of specific drainage divides at a specific time (Whipple et al., 2017c; Sassolas-Serrayet et al., 2019; Dal Pai et al., 2023)."

L74-77: "Local-scale metrics are also subject to variations in local physical properties and transients and regularly exhibit large variability along drainage divides, as well as internal contradictions between metrics (Sassolas-Serrayet et al., 2019; Dal Pai et al., 2023). To mitigate this, studies often combine multiple metrics and/or take the mean value of all catchments along each side of a main drainage divide (Forte and Whipple, 2018; Sassolas-Serrayet et al., 2019; Zhou et al., 2022; Dal Pai et al., 2023)."

L315-318: "Metrics are computed on different spatial and, consequently, temporal scales; for example, χ_P is integrated across entire catchments and represents long-term trends in landscape evolution (Beeson et al., 2017; Whipple et al., 2017c; Forte and Whipple, 2018; Scheingross et al., 2020), while HSG is averaged across individual divide segments and adjusts to local, short-term changes to catchment structure."

L331-333: "This suggests that, despite several areas of localized uplift and heterogeneous lithology across the HDM (Fox et al., 2020), changes in uplift and erodibility are small enough, or slow enough, that χ_P values at the divides remain dominated by the length of the rivers and their area distributions in most places."

L338-342: "Additional reported drivers of cross-divide erosional differences include river capture (Willett et al., 2014; Beeson et al., 2017; Scheingross et al., 2020), non-uniform bedrock erodibility (Gallen, 2018; Wang et al., 2023; Mitchell and Forte, 2023), tectonic advection (Chen et al., 2021; He et al., 2021; Mitchell and Forte, 2023), landsliding (Dahlquist et al., 2018), endorheic lake expansion (Liu et al., 2021a), changes in precipitation patterns (Bian et al., 2024), and autogenic fluvial processes (Scheingross et al., 2020)."

L360-361: "Catchments surrounded by highly asymmetric divides migrating inward are particularly suggestive of active drainage reorganization, with the bounded catchments losing drainage area to their neighbors (Whipple et al., 2017a, b; Willett, 2017; Fox et al., 2020)."

"Finally, there could be some additional discussion of the methods in terms of how the values of the metrics are considered with respect to each other. At present, the methods rely heavily on readers knowing the specific operation of the referenced TopoToolbox functions to sort of follow what is being done, in even in the event that you do, it remains unclear exactly how they're treating some of the values. I highlight a specific example in the line-by-line comments."

We agree with the reviewer and, as discussed in a later response, have revised the final manuscript to include more detailed methods.

"Line-by-line comments:

L44-51: In this section, it seems worthwhile to highlight that the interpretation of this landscape in the context of surface uplift from drainage capture is not without controversy (Whipple, DiBiase, et al., 2017a, 2017b; Willett, 2017)."

Line 47 of the original submission was meant to indicate that the drainage-area exchange hypothesis is not without controversy: "Alternative explanations for these low-relief features include a delayed incisional response in small tributaries to propagating tectonic uplift from the ongoing India-Eurasia collision (Clark et al., 2006) and/or glacial planation (Zhang et al., 2016)."

To further balance the presentation of previous interpretations we add additional references (including those suggested by the reviewer) and expand the original paragraph discussing low-relief features in the HDM as follows, where new text is blue:

"A prime example of this connection between geometric network change and topography is observed in the high-elevation, low-relief areas scattered throughout the Hengduan Mountains (HDM), Southeast Tibet. Many of these low-relief features have been interpreted to result from river capture, where drainage area loss inhibits the ability of catchment erosion to keep pace with background (Yang et al., 2015; Willett, 2017; Fox et al., 2020; Yuan et al., 2021). This hypothesis is supported by several major river captures in the HDM which indicate significant, ongoing drainage reorganization in the region (Clark et al., 2004; Zheng et al., 2021). While few of these captures have been decisively dated, several have been confirmed or estimated to have occurred in the last 2-4 Ma (Kong et al., 2012; Liu et al., 2020; Sun et al., 2020; Yang et al., 2020). Another explanation for these low-relief features is a delayed incisional response in small tributaries to propagating tectonic uplift from the ongoing India-Eurasia collision (Clark et al., 2006; Whipple et al., 2017a, b). Glacial planation may have also played a role in their formation in previously glaciated areas (Zhang et al., 2016). Identifying transients in the river network can help to diagnose the origins of low-relief features in the HDM and distinguish between these hypotheses (Whipple et al., 2017a, b; Willett, 2017; Fox et al., 2020). Despite its critical role in shaping the landscape, the prevalence, intensity, and spatial distribution of geometric transience has not been systematically measured across the HDM on a large scale.

"L58: It might be prudent to add Forte & Whipple, (2018) to this list as the use of some of the metrics you list were more formally defined there as opposed to the cited Whipple et al., (2017)."

We agree with the reviewer and have added Forte & Whipple (2018) to the cited references.

"L180-182: A minor quibble, but while it's clear that you're calculating the same thing as Adams et al., (2020), is there a demonstrable reason why you're not using the same name as in Adams or other subsequent papers (e.g., Leonard et al., 2023; Leonard & Whipple, 2021)? While I would tend to agree that ksnP might be a more apt name since it incorporates a routed version of mean annual precipitation and thus is not truly discharge (as is effectively implied by calling it ksnQ as in Adams, etc.), I also would argue that it's generally a bad practice to knowingly introduce ambiguity into the literature by arbitrarily renaming a quantity that has been given a particular name in multiple publications."

We understand the reviewer's concern and gave thought to the terminology. However, we decided to follow the recently published paper by Ott et al. (2023) and use the term k_{snP}. As mentioned by the reviewer, the reason is that it is a more direct representation of the data going into the calculation. We think that the term k_{snQ} should be reserved for instances where actual discharge estimates (e.g., stream gage records, satellite-derived P – evapotranspiration data) are being used. While we might be furthering the ambiguity introduced by Ott et al. (2023), we believe that in the long-term it is better to advertise the use of the more accurate term in the geomorphic community. We have added a reference to Ott et al. (2023) when k_{snP} is introduced in the Methods section to reduce confusion.

"L201-205: This could be explained a little better. If I follow what you're doing, you calculate the mean upstream value of a given metric for the entire drainage network and then map values from the streams onto divides, which effectively "follows" the FLOWobj up the stream to divide segments? If that is correct, it seems like there should be a little more discussion of the implications of some of these. For example, in a case where a divide is basically between interfluves, would the upstream mean of the main channels (that are nominally orthogonal to this portion of the divide) be mapped with values from these main channels? If that's the case, is the across divide contrast relevant? It's easier to think about a scenario where a divide is between two channel heads with accumulating area above them, but in this case, it's not necessarily clear whether this method is appropriate for all metrics. Specifically, if you're treating ksn / ksnP in this way, that seems problematic as the upslope mean of ksn above a channel head would be basically the colluvial portion of the profile (where ksn is probably not really a valid metric to calculate). Clarification on these points would help readers understand both what you're doing, but also how to interpret your results."

We thank the reviewer for this comment and agree that the explanation in the original manuscript was vague. For improved clarity, we have expanded the paragraph spanning lines 199-214 in the Methods section as follows (blue text is new):

"Drainage divides for the HDM were determined using the *DIVIDEobj* function in Topotoolbox

(Scherler and Schwanghart, 2020). This generates a divide network, similar to a stream network, where divides can be ordered. Divide segments are separated from each other by drainage junctions so that each channel head has a corresponding and unique divide segment. For each divide segment, all pixels draining from the divide to adjacent streams on either side of the divide were used in the calculation for each geomorphic metric (*upslopestats* function). For CRR and HSG, stream pixels were removed, so that only hillslope pixels draining locally into the stream are included. In this way, we ensure that values for divide segments located between interfluves reflect local conditions and not the upstream average of the main channel. The mean metric values for every stream pixel were then projected to the drainage divides (*mapfromnal* function). For k_{sn} and χ, values from the stream were directly projected onto the hillslopes, without averaging, but with prior smoothing of k_{sn} values (*smooth* function).

Divide asymmetry was calculated for each geomorphic metric using a modified version of the *asymmetry* function in Topotoolbox (Scherler and Schwanghart, 2020), where the median of all pixels along the divide was calculated on either side of each divide segment before determining the asymmetry of the segment. This buffers outliers and double-counting of pixels in paired pixel comparisons of the original function. The *asymmetry* function was further modified to ensure that the direction of asymmetry is always perpendicular to the average orientation of the divide segment, which is important for comparison between geomorphic metrics. The magnitude of divide asymmetry was quantified using a modified version of the divide asymmetry index (DAI) proposed by Scherler and Schwanghart (2020):

$$DAI = \left|\frac{\Delta\mu}{\sum\mu}\right| , \quad (7)$$

where μ is the mean value of a given geomorphic metric on either side of a divide segment. By normalizing the across-divide differences by their sum, DAI allows for a simple comparison of asymmetry magnitudes within and across geomorphic metrics. DAI ranges between 0 and 1, for completely symmetric and maximally asymmetric divides, respectively. The MATLAB script we used to calculate DAI for all of the metrics is publicly available on Zenodo: https://doi.org/10.5281/zenodo.8416264."

For easy reference, we have also added direct links to the relevant code in the Methods section.

"L243-255: Throughout this section, you refer to supplemental figures S2 and S3 a lot, making it pretty hard to follow this section without referring to the supplement many times. I wonder if it might be better to move these two figures to the main text since you rely on them heavily."

This is a valid point. In the revised manuscript, we move Fig. S3 to the main text (now Fig. 4). We chose to leave Fig. S2 in the supplement, but have added a simpler version to the main text that includes the "main" metrics (CRR, HSG, k_{snP}, and χ_P). This new figure is shown below:

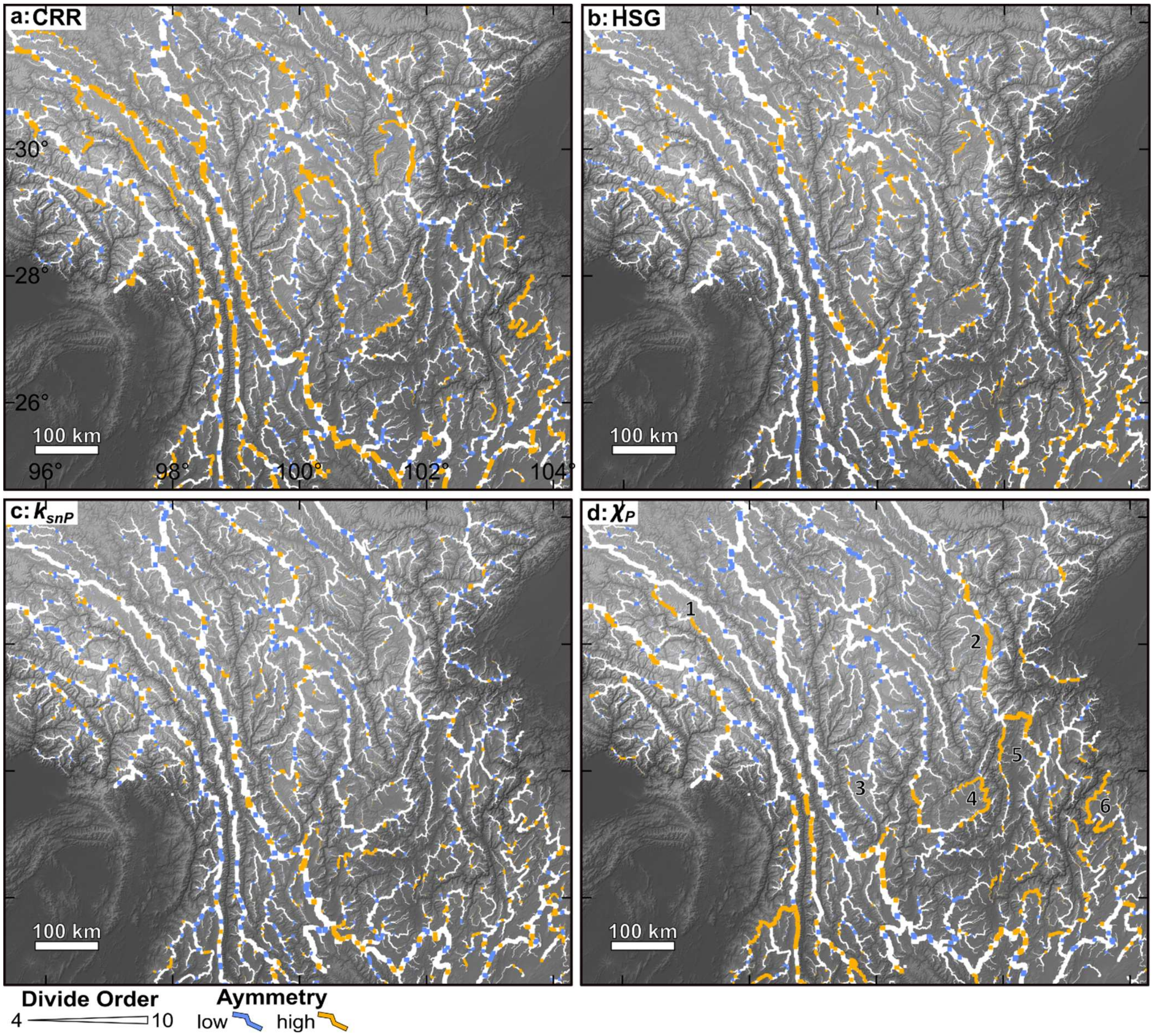

Figure 4: Locations of drainage divides with high (orange) and low (blue) asymmetry by geomorphic metric, where divide line thickness increases with divide Strahler order (4-10). White divides are not classified as having either high or low asymmetry. Panels include CRR (a), HSG (b), k_{snP} (c) and χ_P (d). Metric-specific thresholds for high and low DAI can be found in Table S1. Numbers in (d) correspond to low-relief landscape features labelled in Fig. 2d. See Fig. S3 for increased visibility of high and low asymmetry in low order divides.

"L289-294: As this is not a new insight in general terms (e.g., it's a central point of Forte & Whipple, 2018, among other papers), it would be good to add citations to indicate as such."

We agree and added the following references to following this statement (lines 293-294): "The integral metrics can thus reflect transient processes in distal parts of the catchment, rather than processes local to a divide (Whipple et al., 2017; Forte and Whipple, 2018)."

"L296-297: Did you mean to cite Adams here? It's not clear how that paper is relevant to the point you're making?"

Yes, we thank the reviewer for catching this mistake and have removed the reference in the revised manuscript.

"L319-324: This all makes sense, but the extent to which this is or is not a problem within your datasets are hard to assess. I.e., while it's certainly true that a particular metric on one (or both) side(s) of the divide effectively reaching its threshold would lead to underestimates of what the "true" DAI should be, this is only relevant if the metrics are in the right range, no? While this is a bit challenging to know a priori since there are not single global values of what appropriate thresholds for each metric are and it's not unreasonable to assume that some (or maybe even many) metrics may be near or at threshold given the tectonic activity of the region, it would be good to have some assessment of whether many (or any) of the raw values of the chosen metric display a threshold like behavior. I.e., if you just plotted all hillslope gradients on a histogram, do you see a distribution that's reflective of many values being at/near a suite of thresholds?"

The reviewer's suggestion of a histogram of hillslope values to confirm the existence of threshold behavior in this metric is an excellent one. Below we show a new supplemental figure we have added which shows a steep decline in the number of divides with hillslope gradients (HSG) above 30°, consistent with threshold behavior. Note that the y-axis is in log-scale. This figure has been added to the Supplement (Fig. S5).

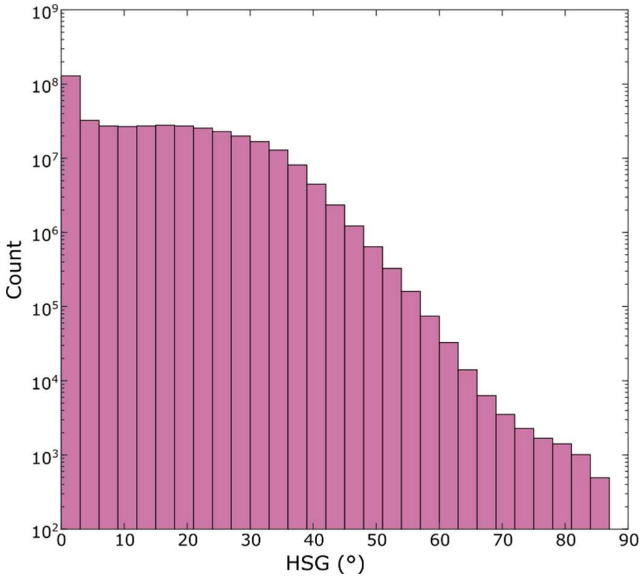

Figure S5. Histogram showing the distribution of hillslope gradient (HSG) values in the HDM. The data indicate an abrupt decline in the frequency of HSG values above ~30°, suggesting that hillslopes in the study region may reach a threshold steepness around this point.

We also added a reference to Liu et al. (2021b) who determined the threshold hillslope value for each catchment in the HDM (Salween, Mekong, Yangtze, Yalong, Dadu, and Min rivers) from their mode hillslope values. They measured mode values ranging from 26° (Mekong River) to 33° (Dadu River) and subsequently propose a threshold HSG value of 30 ± 5° for the HDM. We have added the following sentences to the manuscript in the paragraph spanning lines 319-324: "The histogram of HSG values in the HDM (Fig. S5) shows a marked decline in frequency above a slope of 30° in the HDM, indicating that hillslopes are reaching a threshold. This supports the 30 ± 5° HSG threshold determined by Liu et al. (2021) based on the mode slope values of major catchments in the HDM."

“L324-325: Even without the context of thresholds, this seems prudent as it’s not clear from first principles that a particular DAI based on different metrics would be expected to lead to the same rate of divide migration.”

Yes, exactly. We agree with this comment and, as it was not explicitly stated in the original manuscript, have modified the text from “Due to this potential for threshold behavior, we use metric-specific thresholds to distinguish drainage divides with high and low asymmetry” to “Due to this potential for threshold behavior and the expectation that a given DAI value corresponds to a different erosion rate in each metric, we use metric-specific thresholds to distinguish drainage divides with high and low asymmetry.”

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