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Criteria and tools for determining drainage divide stability

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ABSTRACT

Watersheds are the fundamental organizing units in landscapes and thus the controls on drainage divide location and mobility are an essential facet of landscape evolution. Additionally, many common topographic analyses fundamentally assume that river network topology and divide locations are largely static, allowing channel profile form to be interpreted in terms of spatio-temporal patterns of rock uplift rate relative to base level, climate, or rock properties. Recently however, it has been suggested that drainage divides are more mobile than previously thought and that divide mobility, and resulting changes in drainage area, could potentially confound interpretations of river profiles. Ultimately, reliable metrics are needed to diagnose the mobility of divides as part of routine landscape analyses. One such recently proposed metric is cross-divide contrasts in χ, a proxy for steady-state channel elevation, but cross-divide contrasts in a number of topographic metrics show promise. Here we use a series of landscape evolution simulations in which we induce divide mobility under different conditions to test the utility of a suite of topographic metrics of divide mobility and for comparison with natural examples in the eastern Greater Caucasus Mountains, the Kars Volcanic Plateau, and the western San Bernadino Mountains. Specifically, we test cross-divide contrasts in mean gradient, mean local relief, channel bed elevation, and χ all measured at, or averaged upstream of, a reference drainage area. Our results highlight that cross-divide contrasts in χ only faithfully reflect current divide mobility when uplift, rock erodibility, climate, and catchment outlet elevation are uniform across both river networks on either side of the divide, otherwise a χ-anomaly only indicates a possible future divide instability. The other metrics appear to be more reliable representations of current divide motion, but in natural landscapes, only cross-divide contrasts in mean gradient and local relief appear to consistently provide useful information. Multiple divide metrics should be considered simultaneously and across-divide values of all metrics examined quantitatively as visual assessment is not sufficiently reliable in many cases. We provide a series of Matlab tools built using TopoToolbox to facilitate routine analysis.

1. Introduction

Drainage divides are fundamental organizing boundaries within landscapes. The extent to which the topologic form of divides, and thus river networks as a whole, are largely static (e.g., Bishop, 1995; Oberlander, 1985) or are dynamic features, changing rapidly through progressive divide migration and/or discrete capture events has recently become a topic of considerable interest and some debate (e.g. Whipple et al., 2017c; Willett et al., 2014). Assessing whether a drainage divide is potentially mobile is important, not only for quantifying how landscape evolution is affected by the resulting changes in drainage area, but also because many of the topographic metrics we use to interpret climatic or tectonic change (e.g., Wobus et al., 2006) assume that drainage area has not changed significantly over the response timescale of a catchment (e.g., Howard, 1988; Kooi and Beaumont, 1996; Whipple, 2001). Violation of this static drainage area assumption at best complicates the interpretation of topographic metrics and at worst invalidates the inferences drawn from them (e.g. Whipple et al., 2017a, 2017b; Willett, 2017; Yang et al., 2015). While recent work suggests that under normal circumstances the rate of divide motion is slow compared to the rate of channel adjustment to drainage area change (Whipple et al., 2017c), the potential importance of drainage divide mobility suggests that assessments of divide stability should be a routine part of topographic analyses.

Metrics of the relative stability of drainage divides are not new, indeed Gilbert (1877) first proposed a means of assessing divide stability with his 'law of unequal declivities', positing that if a divide was asymmetrical, this would imply different erosion rates

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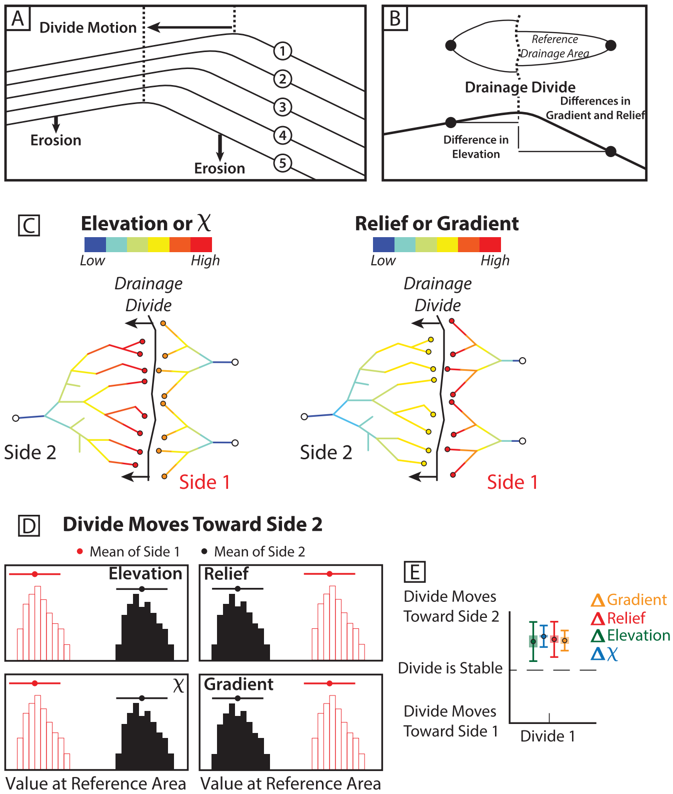

Fig. 1. A) Schematic of Gilbert's (1877) 'Law of Unequal Declivities', predicated on the idea that divides will move when erosion rates are not equal on either side of the divide and that this difference in erosion rate will likely be driven by differences in topographic gradient on either side of the divide. B) Reference drainage area used in all metrics for calculating across divide differences. C) Idealized form of maps of the four different divide metrics discussed in the main text in the case that they are all consistent and all indicative of divide motion to the left (Side 2). D) Corresponding plots of the distributions of values at minimum reference drainage areas. All metrics are predicated on the idea that the stable condition is nearly equal quantities on either side of the divide, however the prediction of motion direction based on across divide differences is different for the different metrics. For χ and elevation metrics, the divide should move towards the side with higher values, whereas for relief and gradient, the divide should move towards the side with lower values. E) Comparison of delta values for all four metrics with propagated uncertainties normalized such that positive and negative delta values indicate the same direction of divide motion across all metrics. If any portion of the mean or its uncertainty overlaps with the stable divide line, then we assume the divide is stable. Bars are considering standard deviation as the uncertainty, shaded boxes the standard error. Though not shown, bootstrap confidence intervals would be intermediate between these. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

on either side of the divide. The resulting across-divide erosion rate contrast would force the divide to move toward the side with lower slopes and erosion rates (Fig. 1A). The basic principles laid out by Gilbert (1877) have been used to develop more formal predictions of divide mobility, e.g. the 'probability of capture' parameter of Howard (1971). Recently, Willett et al. (2014) proposed a new method of assessing divide stability through the use of χ-maps. χ, discussed in more detail in the following section, can be used as a proxy for steady-state channel elevation and thus this quantity should be nearly equal on either side of a stable divide. Maps of drainage networks colored by χ can reveal χ-anomalies across divides, where the χ value at channel heads are higher on one side of a divide, suggesting that this divide is unstable and should move from lower to higher χ. Barring complicating factors, divide migration would continue until the topology of the drainage network and drainage area distribution has changed such that the χ-anomaly is removed. In a limited number of locations where such investigations have been undertaken, χ-anomalies appear coincident with an across-divide difference in average erosion rate, the underlying driver of divide motion (e.g., Beeson et al., 2017; Willett et al., 2014).

χ-maps are appealing as they are 1) relatively easy to calculate and 2) allow for a quick visual assessment of the stability of divides across a large area. There are, however, some challenges with their use and interpretation. Most significantly, the interpretation of χ-anomalies typically assumes uniform uplift, rock erodibility, and climate (Willett et al., 2014) and thus in situations where any of those parameters vary, as is often the case in natural systems, χ-anomalies can occur even when divides are stable (e.g. Whipple et al., 2017c). This led Whipple et al. (2017c) to propose a suite of alternative metrics of divide stability, largely an expansion of the ideas originally put forward by Gilbert (1877), including cross divide differences in channel elevation at a reference drainage area, mean headwater hillslope gradient, and mean headwater local relief. Whipple et al. (2017c) showed that for a simple synthetic landscape experiencing a non-uniform uplift rate, these alternative metrics were more consistent indicators of the current rate and direction of divide motion than across-divide differences in χ. Here we expand upon that work by 1) developing a set of user friendly Matlab based tools to produce maps of these alternative metrics along with χ-maps and to perform detailed analysis of multiple divide stability criteria, 2) applying these tools to two synthetic landscapes with non-uniform uplift and non-uniform lithology, 3) applying these metrics to three natural examples, and 4) comparing and contrasting the relative utility of these four different divide stability metrics.

2. Metrics of divide stability

2.1. Theory and limitations of metrics

Active motion of a drainage divide implies across-divide differences in erosion rates, thus many potential metrics of divide stability will essentially be topographic proxies for erosion rate. This was the basis for Gilbert's (1877) law of unequal declivities, which assumed that divides bounded by distinctly different gradients were unstable, with faster erosion on the steeper side progressively moving the divide towards the side with a gentler slope (Fig. 1A). In recent decades, empirical measures of erosion rate and comparison to various topographic metrics have suggested monotonic relationships at the catchment scale between erosion rates and normalized channel steepness (river slope normalized for drainage area) or local topographic relief (e.g., Harel et al., 2016; Kirby and Whipple, 2012; Lague, 2014) and at the hillslope scale between erosion rates and mean hillslope gradient, hillslope relief, and hilltop curvature (e.g., Hurst et al., 2013; Roering et al., 2007, 1999). Ultimately, divide motion is driven by differences in erosion rate at or in close proximity to the divide itself, so a metric like normalized channel steepness, which is only measurable away from the divide, may not be a viable proxy. Therefore, we choose to focus on gradient and relief. We do not consider hillslope curvature in our analysis, because accurate measurement of this quantity requires high resolution topographic data (e.g., Roering et al., 1999) and thus is not widely applicable to areas for which such data does not exist. Because mean gradients reach threshold values in steep landscapes and become insensitive to increases in erosion rate (e.g., Burbank et al., 1996; Montgomery and Brandon, 2002), if gradients on both sides of a divide are above ~0.7, then it is expected that the slope metric will no longer be sensitive to divide mobility. We also consider a third proxy, across-divide differences in channel elevation at a reference drainage area. Together we refer to these three metrics (mean upstream relief, mean upstream gradient, and elevation) as