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Hillslope asymmetry maps reveal widespread, multi-scale organization

Michael J. Poulos,[1] Jennifer L. Pierce,[1] Alejandro N. Flores,[1] and Shawn G. Benner[1]

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[1] Hillslope asymmetry is the condition in which oppositely-facing hillslopes within an area have differing average slope angles, and indicates aspect-related variability in hillslope evolution. As such, the presence, orientation and magnitude of asymmetry may be a useful diagnostic for understanding process dominance. We present a new method for quantifying and mapping the spatial distribution of hillslope asymmetry across large areas. Resulting maps for the American Cordillera of the Western Hemisphere and the western United States reveal that hillslope asymmetry is widespread, with distinct trends at continental to drainage scales. Spatial patterns of asymmetry correlate with latitude along the American Cordillera, mountain-range orientation for many ranges in the western United States, and elevation in the Idaho Batholith of the Northern Rocky Mountains. Spatial organization suggests that non-stochastic, process-driven controls cause these patterns. The hillslope asymmetry metric objectively captures previously-documented extents and frequencies of valley asymmetry for the Gabilan Mesa of the central California Coast Range. Broad-scale maps of hillslope asymmetry are of interest to a wide range of disciplines, as spatial patterns may reflect the influence of tectonics, atmospheric circulation, topoclimate, geomorphology, hydrology, soils and ecology on landscape evolution. These maps identify trends and regions of hillslope asymmetry, allow possible drivers to be spatially constrained, and facilitate the extrapolation of site-specific results to broader regions. **Citation:** Poulos, M. J., J. L. Pierce, A. N. Flores, and S. G. Benner (2012), Hillslope asymmetry maps reveal widespread, multi-scale organization, *Geophys. Res. Lett.*, *39*, L06406, doi:10.1029/2012GL051283.

1. Introduction

[2] Hillslope asymmetry (HA) is a landscape characteristic defined here as the local difference in median slope angles between hillslopes with opposite aspects (i.e., facing-directions) within a given area. Although hillslope asymmetry within asymmetric valleys has been observed and studied for over a century [e.g., *Powell*, 1874] in a wide range of landscapes, its prevalence and spatial distribution has not been systematically quantified. *Parsons* [1988] observed that most microclimate-induced asymmetry studies below ~45°N latitude reported that N-aspects were steeper, while above ~45°N latitude steeper N- and S-aspects were equally frequent. However, this broader-scale trend remains largely unverified. Previous methods for manually quantifying asymmetry from topographic data include comparing slope angles on either side of a drainage [*Emery*, 1947] and measuring axial stream displacement relative to divides [*Garrote et al*, 2006], but an automated and spatially continuous method for measuring and mapping asymmetry is needed to establish its distribution over broader areas.

[3] The hillslope asymmetry metric is differentiated from valley asymmetry in that hillslope asymmetry compares all hillslopes within a given area rather than being limited to paired hillslope profiles on either side of a valley. While systematic valley asymmetry within an area likely produces hillslope asymmetry, other influences may cause slopes facing one direction to be steeper on average within an area (e.g., prominent escarpment edges). This generalized metric facilitates the systematic measurement of specific orientations of asymmetry (e.g., N vs. S-facing slopes) over broad areas by eliminating the need to delineate drainages and valley side-slopes.

[4] We explore a geospatial method for measuring hillslope asymmetry (HA) from digital elevation models (DEMs) and mapping it continuously across large areas. In theory, the spatial distribution, orientation and magnitude of HA should reflect variation in the responsible processes; spatially delineating HA may elucidate geomorphic controls on hillslope evolution.

[5] HA maps comparing median slope angles between N- and S-facing slopes, and between E- and W-facing slopes were produced at 250 and 90 m resolution for the American Cordillera between 60°N and 60°S, and at 250, 90 and 30 m resolution for the mountainous W. USA. The method was validated by comparing HA maps to the extent, frequency and type (e.g., steeper N-aspects) of valley asymmetry measured by *Dohrenwend* [1978] for the Gabilan Mesa in the central California Coast Range, USA. The influence of source-DEM resolutions was assessed by comparing source data and HA maps produced using a range of resolutions for the W. USA, the state of Idaho, and smaller areas within the Idaho Batholith. Our results indicate that hillslope asymmetry is widespread, varies directionally (e.g., N-facing slopes are not always the steepest), and that specific patterns extend over large, often distinct, geographical regions.

2. What Does Hillslope Asymmetry Indicate?

[6] The presence of HA is indicative of processes that cause hillslopes facing one direction to evolve differently than those facing the opposite direction. Slope asymmetry has been found to be associated with bedrock structure, lithology and topoclimatically-driven ecohydrologic feedbacks [e.g., *Carson and Kirkby*, 1972; *Parsons*, 1988]. *Powell* [1874] proposed that dipping sedimentary stratigraphy causes streams to incise

[1] Department of Geosciences, Boise State University, Boise, Idaho, USA.

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down-dip along resistant beds, preferentially undercutting slopes on one side of a valley. Structural tilting directly steepens slopes facing the direction of rotation by shifting streams laterally within drainages [*Garrote et al.*, 2006]. Bedding, jointing, fracturing and compositional heterogeneities affect hillslope processes and the resistance of opposing hillsides to weathering and erosion [*Hack and Goodlett*, 1960; *Carson and Kirkby*, 1972]. Drainage network development promotes asymmetry where competition for catchment area differs among hillslopes on opposite sides of a stream [*Wende*, 1995], and where basal streams preferentially undercut one aspect [*Melton*, 1960]. In topoclimatically-controlled models of HA development, the varying orientations of hillslopes relative to solar radiation and local wind patterns can alter moisture and energy balances, driving feedbacks that alter hydrologic processes, ecology, weathering, soil development and erosion among aspects [*Hack and Goodlett*, 1960; *Churchill*, 1981; *Burnett et al.*, 2008; *Istanbulluoglu et al.*, 2008].

[7] While the varying dominance of different asymmetry drivers may cause spatial variation in asymmetry types (e.g., regions with steeper N or S-aspects), variability may also result from hillslopes responding differently to similar drivers. For example, in central New Mexico, USA, decreased insolation on N-aspects appears to drive ecohydrologic feedbacks that increase vegetation cover and infiltration, ultimately inhibiting erosion and stabilizing N-aspects at steeper angles [*Istanbulluoglu et al.*, 2008]. In northeastern Arizona, however, decreased insolation promotes gentler N-aspects by increasing moisture persistence, which enhances the weathering of clay-cemented bedrock [*Burnett et al.*, 2008]. In the unvegetated and poorly-consolidated Badlands of South Dakota, greater moisture retention on N-facing slopes promotes saturation-related fluvial erosion [*Churchill*, 1981]. *Churchill* [1981] attributed differing responses to aspect-related microclimate among different locations to broad regional controls. We hypothesize that regional-scale controls are reflected in the spatial distribution of asymmetry.

3. Methods

3.1. Mapping Hillslope Asymmetry

[8] Hillslope asymmetry is mapped continuously across large areas by analyzing gridded slope and aspect data derived from digital elevation models (DEMs) using the spatial analyst tools in ArcMAP 10 to compare the elevation of each pixel to that of its eight surrounding pixels. Hillslope asymmetry is measured by spatially comparing slope and aspect datasets in MATLAB. Maps are generated by measuring and mapping HA, and then smoothing the data.

[9] In the first step, a large square measurement window (e.g., 5×5 km²) is moved column by column and row by row across the slope and aspect grids. Within each window, slope and aspect data are compared on a pixel-by-pixel basis to bin the slope data into 90° wide aspect-bins centered on each cardinal direction. The binned data is then used to calculate north vs. south (N–S) and east vs. west (E–W) HA values. For N–S HA, an index value, I_{N-S}, is calculated as the logarithm of the ratio of the median slope angle (°) for N-aspects, θ_n, to that for S-aspects, θ_s (i.e., $I_{N-S} = \log_{10}[\theta_n/\theta_s]$). Where $\theta_n < \theta_s$, $I_{N-S} < 0$; Where $\theta_n > \theta_s$, $I_{N-S} > 0$; Where $\theta_n = \theta_s$, $I_{N-S} = 0$. The same approach is used to assess E–W HA using the appropriate slope-binned data. *Emery* [1947] used a similar ratio to quantify the asymmetry of individual valleys, but our addition of a log-transformation makes ratio-based magnitudes comparable for different HA orientations (e.g., $\log_{10}(1/3) = -\log_{10}(3/1)$). To spatially represent all resulting HA values in grid format, a new dataset is created with the same pixel size and orientation as the source-DEM, and each HA value is assigned to the center pixel of the window within which it was measured.

[10] In the second step, a new smoothed dataset is created by calculating the median value of all the HA values from the first step within each measurement window (e.g., 5×5 km²), and assigning each average HA value to the associated center pixel of the window. This is a largely cosmetic step that reduces variability at the scale of the averaging window (5 km) while emphasizing broad-scale trends.

3.2. Parameters and Resolutions

[11] Parameters for the HA mapping method include the measurement-window size, aspect bin width, minimum slope and minimum data requirement. Each parameter was independently tested to understand its effect on HA spatial patterns (see Text S1 in the auxiliary material).[1] Window size determines the scale over which HA is measured and smoothed. Smaller windows capture the asymmetry of individual ridgelines and valleys but obscure broader-scale trends. Importantly, broad-scale underlying patterns were similar for all larger window sizes tested (e.g., 1×1, 3×3, 5×5, 10×10 and 20×20 km²). For the maps presented, a 5×5 km² window size is used for measurement and smoothing, which typically captures sufficient slopes within each aspect-bin.

[12] Aspect bin sizes of 30°, 60°, 90°, 120° and 150° yield the same orientations (e.g., steeper N-aspects) and spatial patterns of HA. However, larger aspect bins mute HA magnitudes and aspect-related slope variability by including slopes only slightly oriented towards the directions being measured, and smaller aspect bins limit the amount of data within each window. For maps presented here, we use an aspect bin width of 90°, dividing hillslope aspects into four cardinal quadrants (N = 315–360 and 0–45°; E = 45–135°; S = 135–225°; W = 225–315°).

[13] A minimum slope parameter of 5° excludes most non-hillslope landforms (e.g., alluvial surfaces) from the analyses. The minimum data parameter requires that at least 1% of the pixels within a window fulfill the aforementioned parameter limits for either aspect bin. Pixels failing these requirements are not assigned an HA value and appear colorless in the maps. The selected minimum slope and data limits map HA values up to the edge of hilly terrain (i.e., valley margins), where slopes are gentler and data fulfilling these requirements becomes limited, while preventing calculations where hillslopes representing either aspect are absent. Parameter tests using slope limits of 1, 3, 5, 10 and 15°, and minimum data values of 1, 5 and 10%, showed the same spatial patterns, but higher parameter values reduced spatial extents.

[14] Unavoidably, mixed-pixels sometimes occur across topographic transitions (e.g., valley bottoms and ridgelines),

[1]Auxiliary materials are available in the HTML. doi:10.1029/2012GL051283.

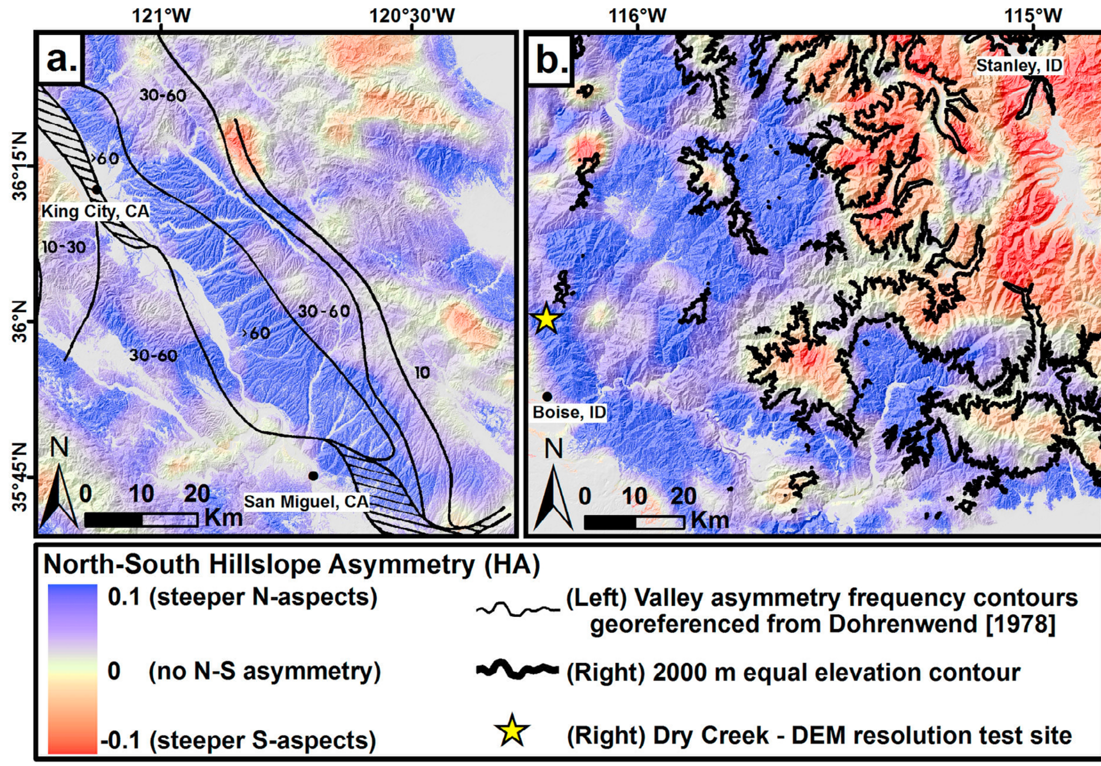

Figure 1. Maps of N–S Hillslope Asymmetry (HA) draped over hill-shaded imagery. Locations shown in Figure 3. HA of magnitude 0.1 is equivalent to a ~26% difference between oppositely oriented slopes (i.e., ~38° vs. 30°). Grey areas indicate HA was not calculated due to slopes gentler than 5° or insufficient data. (a) The Gabilan Mesa in the central California Coast Ranges, USA, exhibits pronounced HA, with steeper N-aspects, which matches valley asymmetry for the area reported by *Dohrenwend* [1978]. The extent of this regional HA is evident in Figure 2. (b) HA within the Idaho Batholith, USA, reverses in orientation along the 2000 m elevation contour.

subduing landform variability and reducing slope estimates. However, filtering out mixed-pixels with subdued slope angles by increasing the minimum slope does not affect spatial patterns of HA, perhaps because mixed-pixels are relatively infrequent.

[15] To demonstrate the mapping method, 90 m resolution v4.1 hole-filled Shuttle Radar Topography Mission (SRTM) DEMs (http://srtm.csi.cgiar.org/) were analyzed to produce HA maps for the American Cordillera between 60°N and 60°S by splitting the Cordillera into eight similar sized regions and re-projecting DEMs to UTM projections centered over each region. Inaccurately filled data holes, which most often occur on slopes facing away from the shuttle where incidence angle is large [*Jarvis et al.*, 2004], may bias results but affect a relatively small amount of the landscape; maps derived from DEMs with and without holes filled did not visibly differ. Data voids should be assessed before interpreting patterns for specific areas. For comparison, 30 m resolution United States Geological Survey (USGS) DEMs (http://seamless.usgs.gov/), which do not contain holes, were split into eight regions, re-projected to NAD83 projections, and analyzed to produce HA maps for the western United States.

[16] Coarser-resolution DEMs average-out topographic variations at scales less than their pixel size, effectively subduing slope estimates. We tested the influence of DEM resolution by assessing the features different resolutions captured, and comparing the patterns exhibited by the resulting HA maps (Text S2). Within an area with visibly steeper N-aspects and high-resolution data, we also compared aspect-bin average slope angles and HA values among 250 (SRTM), 90 (SRTM), 30 (USGS), 10 (USGS) and 1 m (LiDAR) DEMs.

4. Results: Hillslope Asymmetry Maps

[17] Assessment of hillslope asymmetry (HA) maps derived from 90 and 30 m DEMs verifies that the method captures previously observed trends in HA in the Gabilan Mesa of the central California Coast Range (Figure 1a) and determines the extent of HA in the Idaho Batholith (Figure 1b). In the Gabilan Mesa, *Dohrenwend* [1978] found that N-aspects were typically steeper and mapped the frequency of asymmetric valleys; steeper N-aspects were also measured by the 30 m resolution HA maps, and HA magnitude changes generally correspond with Dohrenwend's frequency maps (Figure 1a). In the Idaho Batholith a reversal in the sign of the N–S HA is apparent that roughly correlates with the 2000 m elevation interval (Figure 1b). Below 2000 m in elevation, landscapes exhibit steeper N-aspects on average, while above this elevation steeper S-aspects predominate. Within the Dry Creek Experimental Watershed (DCEW) of the southwestern Idaho Batholith (location Figure 1b) we compared slope angles and HA values derived from DEMs ranging in resolution from 250 to 1 m (Figure S1). All resolutions consistently captured the correct

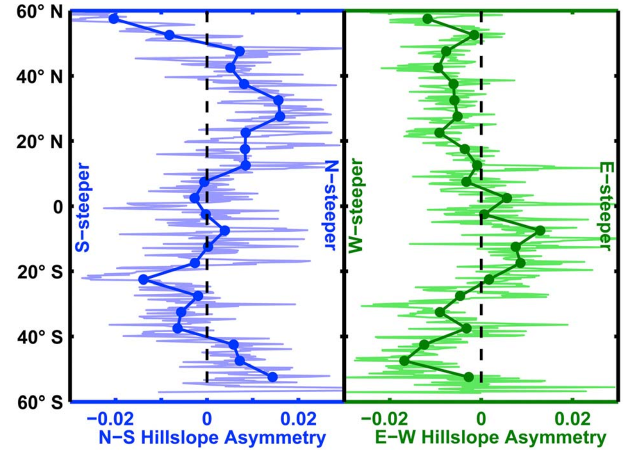

Figure 2. Average HA values within 5° (darker lines) and 0.25° (lighter lines) latitude-bins for the American Cordillera. Both N–S and E–W HA display gradual trends and reversals in sign with latitude, suggesting latitude-based influences.

sign (i.e., steeper N-aspects) of valley asymmetry observed in the field. Additionally, all resolutions yielded similar HA magnitudes, except the 250 m analysis, which underestimated HA values. Assessment of 250 m resolution slope data for the area revealed it failed to portray relatively low-gradient low-order drainages where the scale of measurement (i.e., ∼3 pixels) exceeded the maximum scale of valleys, but the minimum slope and data parameters prevented the calculation of HA values for these areas. Regardless, spatial patterns and magnitudes of HA derived from 250 m resolution data should be interpreted with caution. A caveat applies to all HA maps that the results are valid only for the landforms being compared, which should be assessed when investigating possible causes. Ideally, detailed site-specific comparisons of HA magnitudes should use finer resolutions which better capture the landforms of interest. Despite the shortcomings of 250 m data in low-gradient terrain, maps derived from 30, 90 and 250 m resolution DEMs yielded similar broad-scale spatial patterns within all areas tested. While the 250 m data appears useful for broad-scale assessment, all maps presented are derived from 90 or 30 m data.

[18] Analysis of the American Cordillera at 90 m resolution reveals distinct zones of HA at continental, mountain-range and smaller scales (Figure S2). We average the HA data within both 5° and 0.25° latitude bins (Figure 2) to capture latitudinal-trends and variability, respectively. T-tests of the 5° bins found mean HA values for all bins to be significantly different from zero (95% confidence; $p < 0.001$). Similarly, t-tests for the 0.25° binned data showed these trends to be significantly different from zero for 97% of the bins (95% confidence; $p < 0.001$). Latitude-based analysis reveals multiple continent-scale latitudinal trends in both N–S and E–W HA. In N. America, south-facing slopes are predominantly steeper throughout much of the Canadian Rockies, but below a transition at ∼49°N latitude N-facing slopes are steeper more often. This transition is evident in the 90 m N–S HA map for the American Cordillera (Figure S2). Along the Andes, the latitude-binned N–S HA sign reverses multiple times with latitude. For the E–W HA data, W-aspects are steeper on average at mid to high latitudes, while E-aspects are steeper near the equator (∼5°N to 20°S).

[19] The 30 m resolution HA maps for the western U.S. (N–S HA, Figure 3; E–W HA, Figure S3) show that both N–S and E–W HA are widespread, with pronounced patterns evident at mountain-range to watershed scales. Distinct patterns occur within major mountain and plateau provinces, such as the Rocky Mountains, the Colorado Plateau, the Columbia Plateau, the Sierra Nevada and the Cascade Mountains (Figure 3). Among all geophysical provinces, the most consistent broad-scale pattern is the reversal in the sign of HA on either side of prominent topographic features. For many mountain ranges with E–W components to the trends of their divides, N–S HA patterns are evident (Figures 3 and 1a). In contrast, for mountain ranges with N–S components to the trends of their divides, E–W HA patterns are often observed (Figure S3). In both cases, slopes facing the major crest line of the ranges are typically steeper. Notably the Big Horn, Wind River, Uinta, Book Cliffs, Uncompahgre, San Juan and Blue Mountain ranges, as well as many of the smaller ranges within the Basin and Range province, exhibit range-scale trends in N–S and/or E–W HA (Figures 3 and S3).

[20] While the large-scale orientation of mountain ranges and land surfaces may influence HA, there is not a regular pattern to this asymmetry. For example, while slopes facing the major divides are steeper in the northern Cascade Mountains, this pattern appears to reverse in the southern Cascades (Figure S3). The Sierra Nevada exhibits a similar but less pronounced reversal in hillslope asymmetry orientation relative to range-scale divides. Importantly, HA patterns for other ranges, such as the Pacific Coast Mountains, do not appear to relate to range-scale topography.

[21] Elevation-based trends are not evident in the HA maps at the scale of the western U.S., and statistical analysis did not reveal N- or S-aspects to be more frequently steeper above 2000 m elevation as observed in central Idaho.

5. Discussion

[22] Widespread HA in mountainous landscapes indicates that opposite-facing hillslopes often evolve differently. The existence of distinct regions of HA indicates process-based controls; zones of consistent HA may be useful for determining which influences (e.g., faulting, bedding orientation, topoclimate, drainage-development, etc.) control asymmetry development within a region. While such analysis is beyond the scope of this paper, we discuss here the information inherent to the scales and extents of HA patterns. While coarser resolution data inherently limits the minimum scale of landforms analyzed, the regularity of patterns among resolutions indicates consistent HA between smaller and larger-scale landforms.

[23] The American Cordillera exhibits multiple reversals in the sign of both N–S and E–W bin-averaged HA values with latitude (Figure 2). In N. America, the reversal in sign of N–S HA at roughly 49° latitude is generally consistent with the work of *Parsons* [1988], a meta-analysis of 28 site-specific studies on topoclimate-induced valley asymmetry that found a tendency of steeper N-aspects between 30–45°N latitude, and equal tendencies toward steeper N- or S-aspects above 45°N. *Parsons* [1988] suggested this

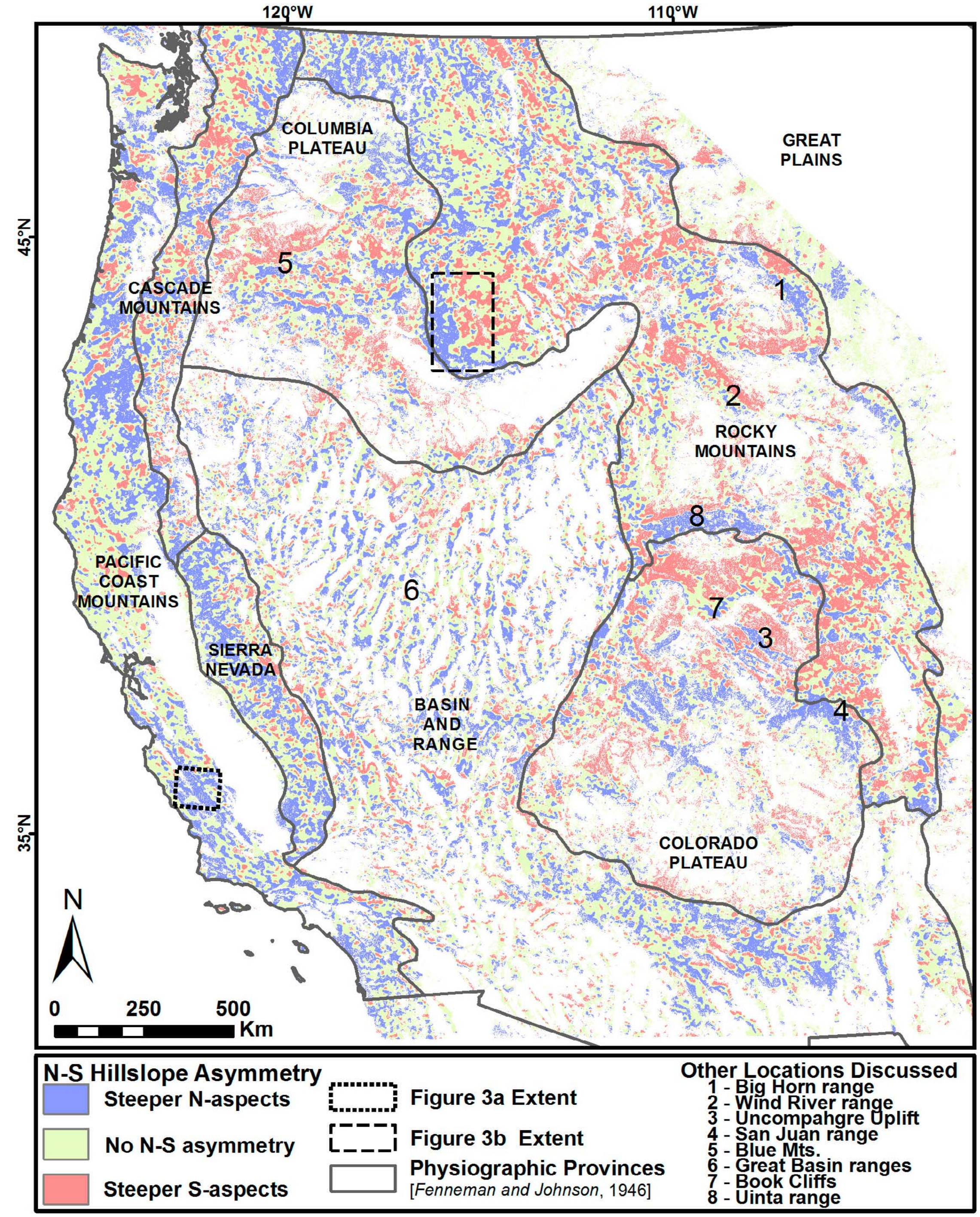

Figure 3. Map of the W. USA showing HA for N- and S-aspects. Colors denote HA of least 0.04 in magnitude, meaning slopes of one orientation were more than 10% steeper (°) than those oriented opposite (i.e., 33° vs. 30°). No values calculated for white areas because slopes were gentler than 5° or data was insufficient. Note the patterns associated with mountain ranges.

change in N–S valley asymmetry orientation is driven by insolation changes with latitude. Accordingly, an opposite trend should be evident in the southern hemisphere. Our data indicates an opposite reversal occurring at ∼38°S that is perhaps the S. Hemisphere equivalent of the transition in the N. Hemisphere. The E–W HA gradually reverses from steeper W-aspects, on average, for high and mid-latitudes to steeper E-aspects between 5°N and 20°S. The E-W HA trends in the N. Hemisphere largely mirror those in the S. Hemisphere (e.g., above and below ∼10°S). The simplest explanations for latitudinal trends in both N–S and E–W HA are influences that vary at latitude scales, such as insolation, atmospheric circulation (e.g., locations of Hadley cell circulation), or continental-scale tectonics (e.g., differential subduction and uplift rates, or mountain-range orientation and elevation). While latitudinal trends might be indicative of global processes driving HA, the range of variability captured by the 0.25° latitude-binned data and evident at smaller scales in the HA maps emphasizes that regional influences often overprint latitude-based influences.

[24] Range-scale HA patterns are visually evident in the W. USA. The variability in HA at the scale of mountain ranges suggests that prominent topographic features influence HA. Specifically, slopes facing central drainage divides of ranges tend to be steeper. It is unclear whether this is related to range-scale topoclimate (e.g., orographic precipitation and/or insolation variability) or other effects (e.g., mountain building and/or drainage evolution).

[25] The reversal of HA orientation with elevation in the Idaho Batholith suggests that elevation-dependent processes can also exert a dominant control on HA development. Factors possibly influencing HA that vary with elevation include precipitation, temperature, vegetation type and density, and changes from fluvial to periglacial and glacial process dominance, which differ in erosive efficiency [*Naylor and Gabet*, 2007]. Visual inspections of DEMs reveal that above the 2000 m elevation threshold, cirque-like features become evident exclusively on N-aspects. The extent of this higher elevation region is roughly consistent with regional glacial extents [*Amerson et al.*, 2008]. In the nearby Bitterroot Range of the Northern Rockies, *Naylor and Gabet* [2007] found that exclusive glaciation of N-aspects caused ridgelines to shift south, decreasing overall elevation gradients and reducing average slope angles for N-aspects. Glacial versus fluvial process dominance among aspects might explain the more frequent steeper S-aspects above the $\sim$49°N threshold evident with latitude (Figure 2), as the Canadian Rockies were extensively glaciated by the Cordilleran ice-sheet and mountain glaciers.

6. Conclusions

[26] We have developed a robust method for mapping hillslope asymmetry (e.g., valley asymmetry) at a variety of scales. Maps reveal asymmetry is widespread in a majority of the mountainous environments of the American Cordillera and exhibit spatial patterns correlating with latitude, elevation and mountain-range-scale topographic features. Spatial patterns evident in hillslope asymmetry maps likely reflect driving processes, and may help identify regions in mountainous landscapes where specific tectonic, climatic and hydrologic forcing mechanisms influence landforms.

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S. G. Benner, A. N. Flores, J. L. Pierce, and M. J. Poulos, Department of Geosciences, Boise State University, 1910 University Dr., Boise, ID 83725, USA. (sbenner@boisestate.edu; lejoflores@boisestate.edu; jenpierce@boisestate.edu; mikepoulos@boisestate.edu)