HILLSLOPE ASYMMETRY MAPS
REVEAL WIDESPREAD, MULTI-SCALE ORGANIZATION

by

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The following individuals read and discussed the thesis submitted by student Michael John Poulos, and they evaluated his presentation and response to questions during the final oral examination. They found that the student passed the final oral examination.

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DEDICATION

This work is dedicated to my mother for encouraging me to pursue higher education.

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I am grateful for the opportunity to study such a multidisciplinary subject as valley asymmetry. This work would not have been possible without the previous research on the topic spanning well over a century. I have attempted to offer a new perspective on the phenomena of valley asymmetry, and I can only hope that my own work will be as inspiring as the previous research on the topic is to me.

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ABSTRACT

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.

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1. INTRODUCTION

Hillslope asymmetry 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° north latitude reported that northern-aspects were steeper, while above ~45° north latitude steeper northern- and southern-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.

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., north- vs. south-facing slopes) over broad areas by eliminating the need to delineate drainages and valley side-slopes.

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

Hillslope asymmetry maps comparing median slope angles between north- and south-facing slopes, as well as between east- and west-facing slopes, were produced at 250 and 90 m resolution for the American Cordillera between 60° north latitude and 60° south latitude, and at 250, 90, and 30 m resolution for the mountainous Western USA. The method was validated by comparing hillslope asymmetry maps to the extent, frequency, and type (e.g., steeper northern-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 hillslope asymmetry maps produced using a range of resolutions for the Western USA, the state of Idaho, and smaller areas within the Idaho Batholith. Our results indicate that hillslope asymmetry is widespread, varies directionally (e.g., north-facing slopes are not always the steepest), and that specific patterns extend over large, often distinct, geographical regions.

2. WHAT DOES HILLSLOPE ASYMMETRY INDICATE?

The presence of hillslope asymmetry 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 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 hillslope asymmetry 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).

While the varying dominance of different asymmetry drivers may cause spatial variation in asymmetry types (e.g., regions with steeper northern- or southern-aspects), variability may also result from hillslopes responding differently to similar drivers. For example, in central New Mexico, USA, decreased insolation on northern-aspects appears to drive ecohydrologic feedbacks that increase vegetation cover and infiltration, ultimately inhibiting erosion and stabilizing northern-aspects at steeper angles (*Istanbulluoglu et al.*, 2008). In northeastern Arizona, however, decreased insolation promotes gentler northern-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 north-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

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 hillslope asymmetry, and then smoothing the data.

In the first step, a large square measurement window (e.g., 5 x 5 km^2) 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) hillslope asymmetry values. For north-south hillslope asymmetry, an index value, $I_{N\text{-}S}$, is calculated as the logarithm of the ratio of the median slope angle (°) for northern-aspects, θ_n, to that for southern-aspects, θ_s (i.e., $I_{N\text{-}S} = \log_{10}[\theta_n/\theta_s]$). Where $\theta_n < \theta_s$, $I_{N\text{-}S} < 0$; Where $\theta_n > \theta_s$, $I_{N\text{-}S} > 0$; Where $\theta_n = \theta_s$, $I_{N\text{-}S} = 0$. The same approach is used to assess east-west hillslope asymmetry 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 hillslope asymmetry orientations (e.g., $\log_{10}(1/3) = -\log_{10}(3/1)$). To spatially represent all resulting hillslope asymmetry values in grid format, a new dataset is created with the same pixel size and orientation as the source-DEM, and each hillslope asymmetry value is assigned to the center pixel of the window within which it was measured.

In the second step, a new smoothed dataset is created by calculating the median value of all the hillslope asymmetry values from the first step within each measurement window (e.g., 5 x 5 km^2), and assigning each average hillslope asymmetry 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

Parameters for the hillslope asymmetry 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 hillslope asymmetry spatial patterns (Appendix A). Window size determines the scale over which hillslope asymmetry 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., 1x1, 3x3, 5x5, 10x10 and 20x20 km^2). For the maps presented, a 5x5 km^2 window size is used for measurement and smoothing, which typically captures sufficient slopes within each aspect-bin.

Aspect bin sizes of 30°, 60°, 90°, 120°, and 150° yield the same orientations (e.g., steeper northern-aspects) and spatial patterns of hillslope asymmetry. However, larger aspect-bins mute hillslope asymmetry 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 (northern aspects = 315-360 and 0-45°; eastern aspects = 45-135°; southern aspects = 135-225°; western aspects = 225-315°).

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 a hillslope asymmetry value and appear colorless in the maps. The selected minimum slope and data limits map hillslope asymmetry 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.

Unavoidably, mixed-pixels sometimes occur across topographic transitions (e.g., valley bottoms and ridgelines), 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 hillslope asymmetry, perhaps because mixed-pixels are relatively infrequent.

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 hillslope asymmetry maps for the American Cordillera between 60° north latitude and 60° south latitude 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 hillslope asymmetry maps for the western United States.

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 captured by different resolutions, and comparing the patterns exhibited by hillslope asymmetry maps derived from different resolutions (Appendix B). Within an area with visibly steeper northern-aspects and high-resolution data, we also compared aspect-bin average slope angles and hillslope asymmetry values among 250 (SRTM), 90 (SRTM), 30 (USGS), 10 (USGS), and 1 m (Light Detection And Ranging [LiDAR] derived) DEMs.

4. RESULTS: HILLSLOPE ASYMMETRY MAPS

Assessment of hillslope asymmetry maps derived from 90 and 30 m DEMs verifies that the method captures previously observed trends in hillslope asymmetry in the Gabilan Mesa of the central California Coast Range (Figure 1a) and determines the extent of hillslope asymmetry in the Idaho Batholith (Figure 1b). In the Gabilan Mesa, *Dohrenwend* (1978) found that northern-aspects were typically steeper and mapped the frequency of asymmetric valleys; steeper northern-aspects were also measured by the 30 m resolution hillslope asymmetry maps, and hillslope asymmetry magnitude changes generally correspond with Dohrenwend's frequency maps (Figure 1a). In the Idaho Batholith, a reversal in the sign of the north-south hillslope asymmetry is apparent that roughly correlates with the 2000 m elevation interval (Figure 1b). Below 2000 m in elevation, landscapes exhibit steeper northern-aspects on average, while above this elevation steeper southern-aspects predominate.

Within the Dry Creek Experimental Watershed (DCEW) of the southwestern Idaho Batholith (location Figure 1b), we compared slope angles and hillslope asymmetry values derived from DEMs ranging in resolution from 250 to 1 m (Figure 2). All resolutions consistently captured the correct sign (i.e., steeper northern-aspects) of valley asymmetry observed in the field. Additionally, all resolutions yielded similar hillslope asymmetry magnitudes, except the 250 m analysis, which underestimated hillslope asymmetry values. Assessment of 250 m resolution slope data for the area revealed it

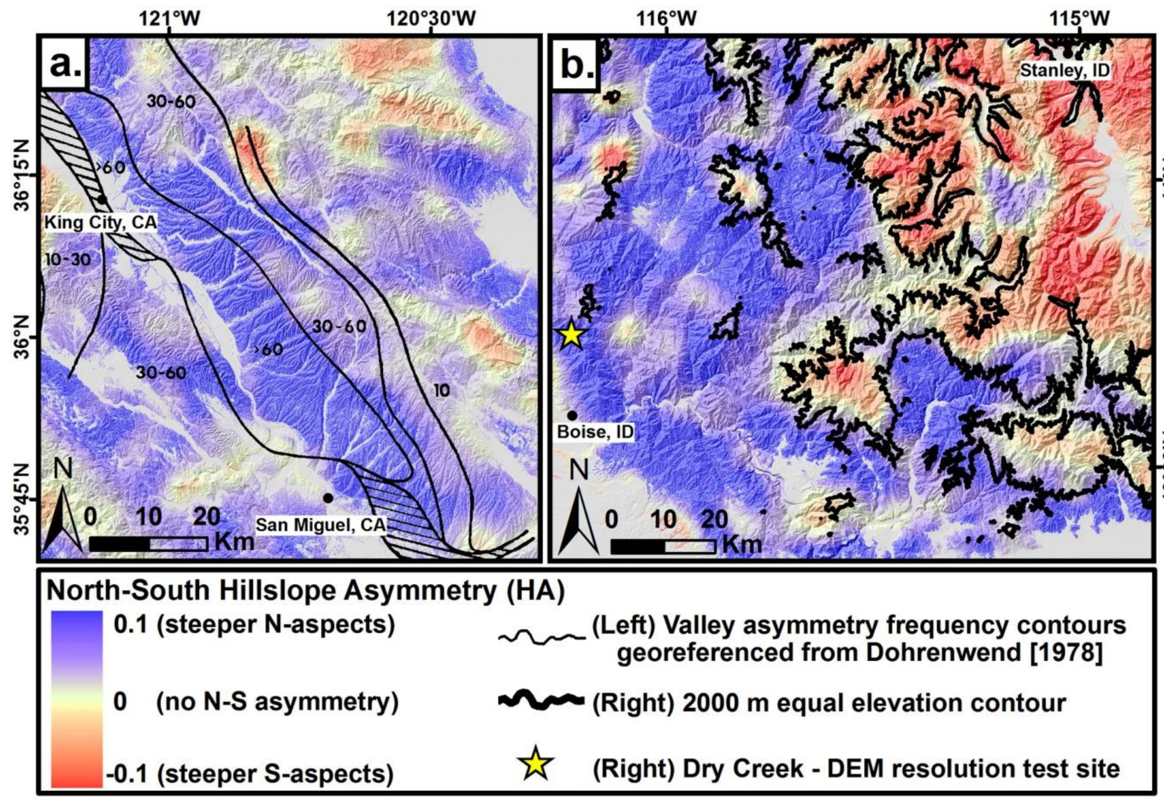

Figure 1. Maps of north-south hillslope asymmetry draped over hill-shaded imagery. Locations are shown in Figure 3. Hillslope asymmetry of magnitude 0.1 is equivalent to a ~26% difference between oppositely oriented slopes (i.e., ~38° vs. 30°). Grey areas indicate hillslope asymmetry was not calculated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

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 hillslope asymmetry values for these areas. Regardless, spatial patterns and magnitudes of hillslope asymmetry derived from 250 m resolution data should be interpreted with caution. A caveat applies to all hillslope asymmetry maps that the results are valid only for the landforms being

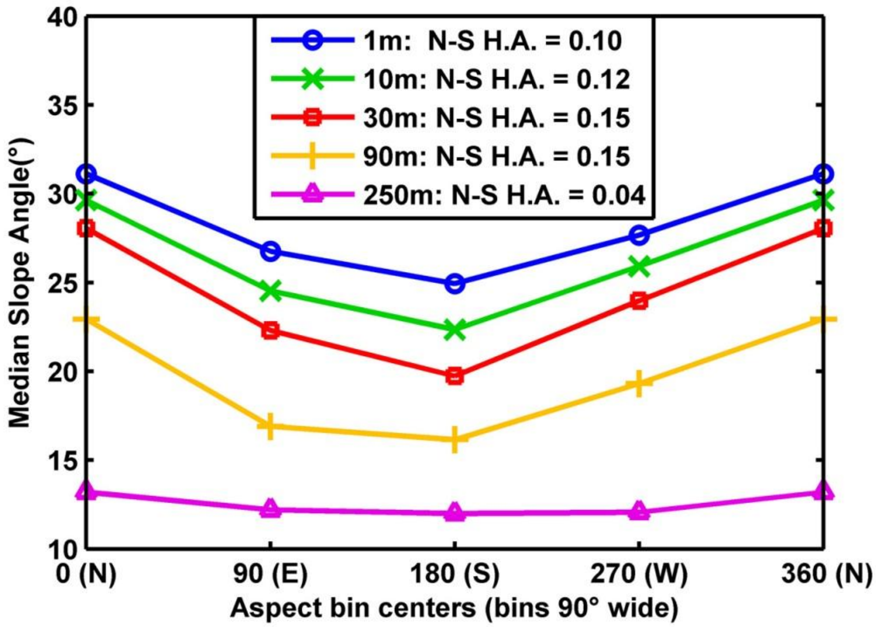

Figure 2. Resolution comparison of average slope angles within each aspect-bin (90° wide) for the Dry Creek watershed. The location of the watershed is shown in Figure 1. Analysis using all resolutions successfully captured the sign (i.e., orientation) of hillslope asymmetry (H.A. in legend) for the area, which exhibits visibly steeper northern-aspects when viewed in cross-section. Asymmetry magnitudes were similar for the 1, 10, 30, and 90 m results, but the 250 m data dramatically underestimates asymmetry in this location because valleys are not captured by the source data.

compared, which should be assessed when investigating possible causes. Ideally, detailed site-specific comparisons of hillslope asymmetry magnitudes should use finer resolutions that 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.

Analysis of the American Cordillera at 90 m resolution reveals distinct zones of hillslope asymmetry at continental, mountain-range, and smaller scales (Figure 3). We average the hillslope asymmetry data within both 5° and 0.25° latitude bins (Figure 4) to capture latitudinal-trends and variability, respectively. T-tests of the 5° bins found mean

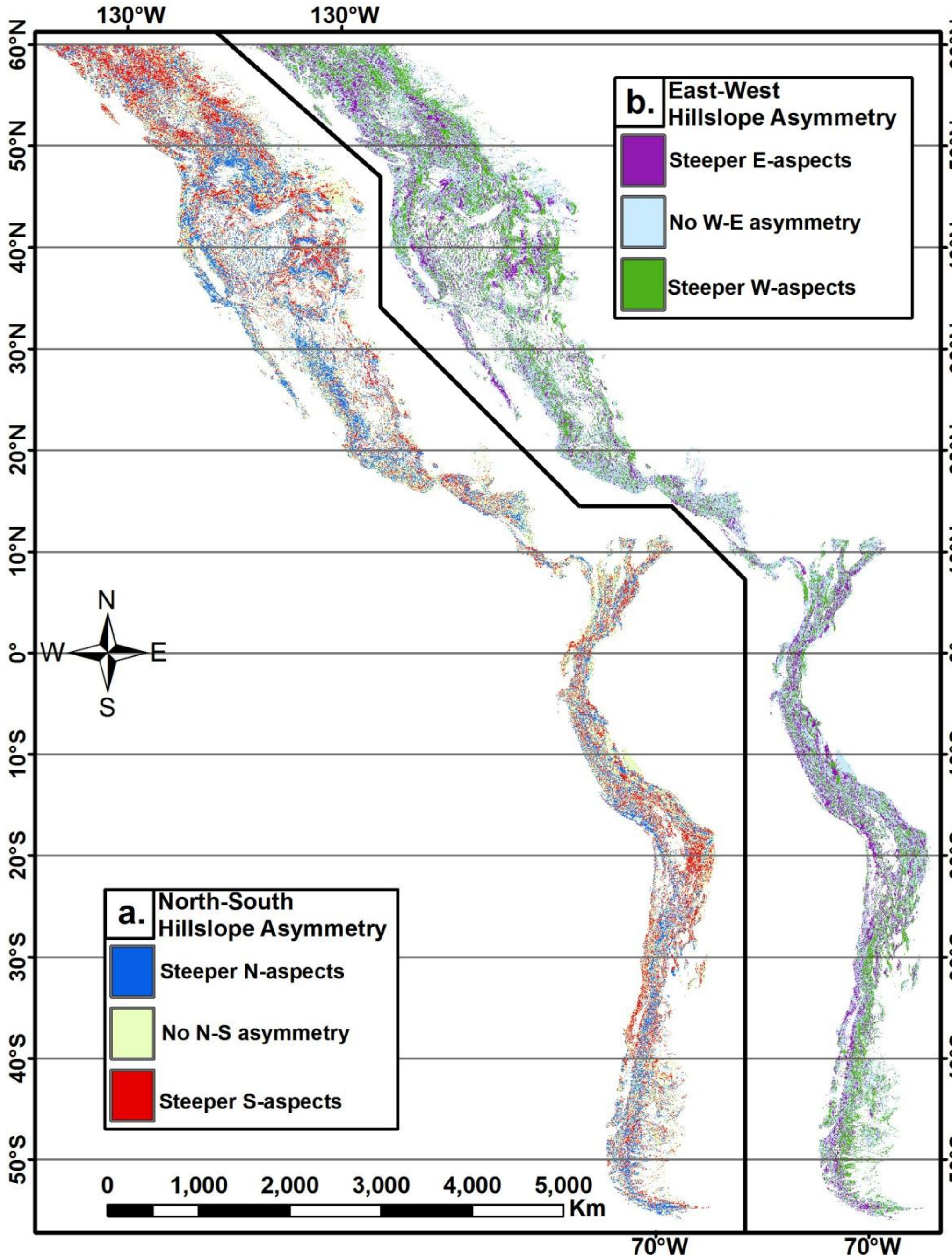

Figure 3. **Map of the American Cordillera in the Western Hemisphere showing hillslope asymmetry among a) northern- and southern-aspects, and b) eastern- and western-aspects. Red and blue areas represent hillslope asymmetry of least 0.04 in magnitude, meaning slopes of one orientation were at least 10% steeper, in degrees, than those oriented opposite (i.e., 33° vs. 30°). No values were calculated in white areas because they sloped less than 5°, which filters out non-hillslope environments, or contained insufficient data. Note the visible change in frequency of areas with steeper southern-aspects (i.e., redness), on average, above 49° N, in the Canadian Rockies, and below this, in the Western USA. These trends are summarized using latitude-binned data in Figure 4 and discussed in the manuscript.**

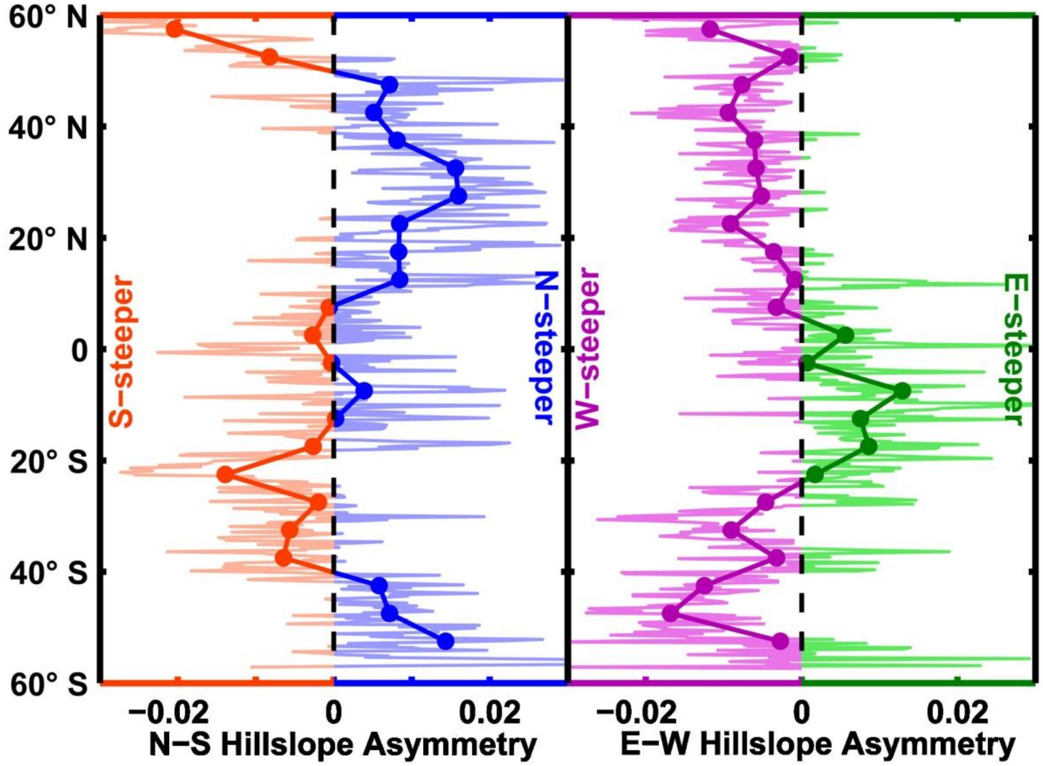

Figure 4. Average hillslope asymmetry values within 5° wide latitude-bins (darker lines), to show generalized latitude trends, and 0.25° (lighter lines) wide latitude-bins, to capture the variability within the larger bins, for the American Cordillera. Both north-south and east-west hillslope asymmetry graphs display gradual trends and reversals in sign with latitude, suggesting latitude-based influences.

hillslope asymmetry 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 north-south and east-west hillslope asymmetry. In North America, south-facing slopes are predominantly steeper throughout much of the Canadian Rockies, but below a transition at ~49° north latitude, north-facing slopes are steeper more often. This transition is evident in the 90 m north-south hillslope asymmetry map for the American Cordillera (Figure 3). Along the Andes, the latitude-binned north-south hillslope asymmetry sign reverses multiple times with latitude. For the east-west hillslope asymmetry data, western-aspects are steeper on average at mid-to-high latitudes, while eastern-aspects are steeper near the equator (~ 5° north latitude to 20° south latitude).

The 30 m resolution hillslope asymmetry maps for the western USA (north-south hillslope asymmetry, Figure 5; east-west hillslope asymmetry, Figure 6) show that both north-south and east-west hillslope asymmetry 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 5). Among all geophysical provinces, the most consistent broad-scale pattern is the reversal in the sign of hillslope asymmetry on either side of prominent topographic features. For many mountain ranges with east-west components to the trends of their divides, north-south hillslope asymmetry patterns are evident (Figures 5 and 1a). In contrast, for mountain ranges with north-south components to the trends of their divides, east-west hillslope asymmetry patterns are often observed (Figure 6). 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 north-south and/or east-west hillslope asymmetry (Figures 5 and 6).

While the large-scale orientation of mountain ranges and land surfaces may influence hillslope asymmetry, 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 6). The

Sierra Nevada exhibits a similar but less pronounced reversal in hillslope asymmetry orientation relative to range-scale divides. Importantly, hillslope asymmetry patterns for other ranges, such as the Pacific Coast Mountains, do not appear to relate to range-scale topography.

Elevation-based trends are not evident in the hillslope asymmetry maps at the scale of the Western USA, and statistical analysis did not reveal northern- or southern-aspects to be more frequently steeper above 2000 m elevation as observed in central Idaho.

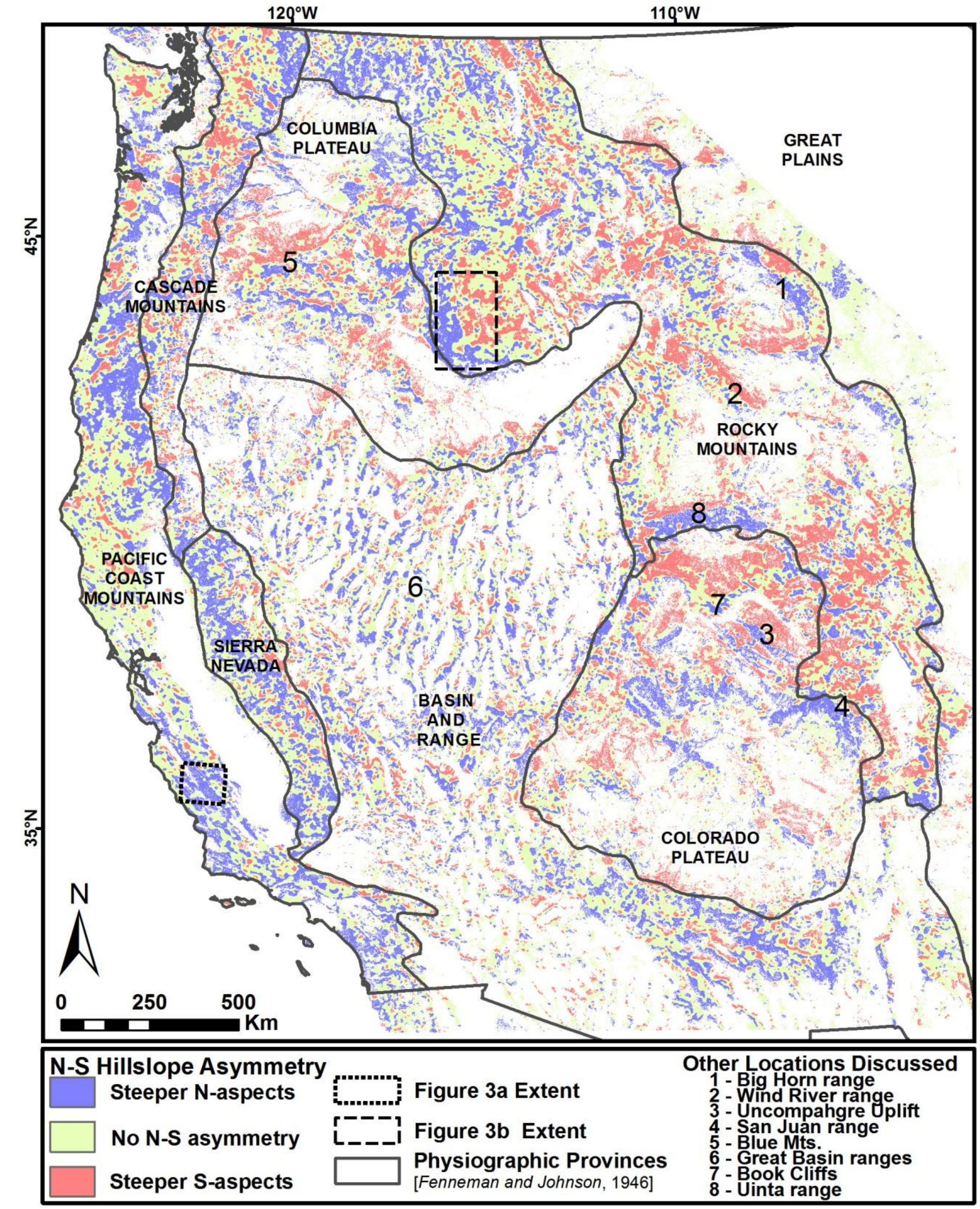

Figure 5. **Map of the Western USA showing hillslope asymmetry for north- and south-aspects. Colors denote hillslope asymmetry of least 0.04 in magnitude, meaning slopes of one orientation were more than 10% steeper (°) than those oriented opposite (i.e., 33° vs. 30°). No values calculated for white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

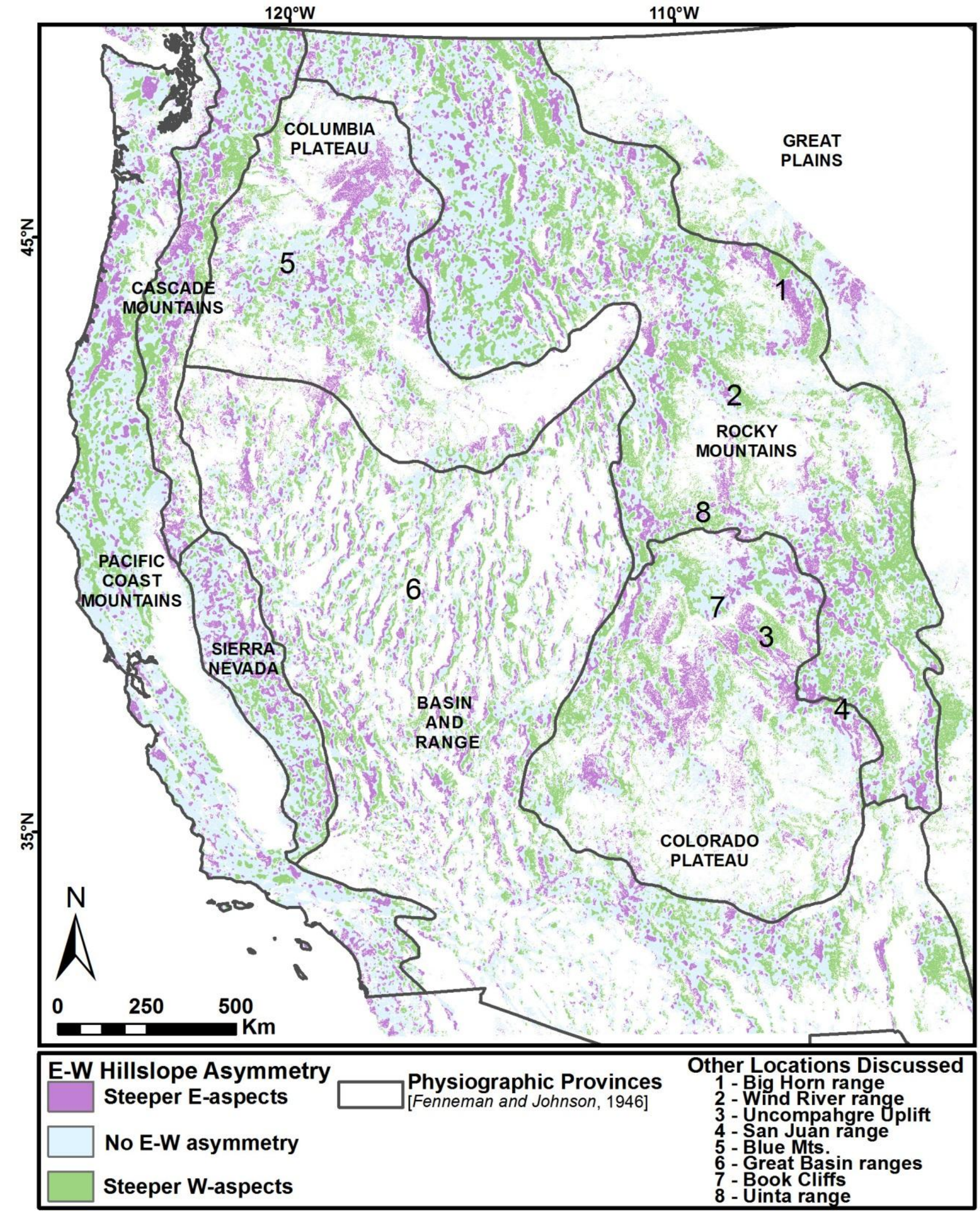

Figure 6. **Map of the Western USA showing hillslope asymmetry for eastern- and western-aspects. Colors denote hillslope asymmetry of least 0.04 in magnitude, meaning slopes of one orientation were more than 10% steeper (°) than those oriented opposite (i.e., 33° vs. 30°). No values calculated for white areas because slopes were gentler than 5° or data was insufficient. Note the patterns associated with major mountain ranges (numbered locations).**

5. DISCUSSION

Widespread hillslope asymmetry in mountainous landscapes indicates that opposite-facing hillslopes often evolve differently. The existence of distinct regions of hillslope asymmetry indicates process-based controls; zones of consistent hillslope asymmetry 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 thesis, we discuss here the information inherent to the scales and extents of hillslope asymmetry patterns. While coarser resolution data inherently limits the minimum scale of landforms analyzed, the regularity of patterns among resolutions indicates consistent hillslope asymmetry between smaller and larger-scale landforms.

The American Cordillera exhibits multiple reversals in the sign of both north-south and east-west bin-averaged hillslope asymmetry values with latitude (Figure 4). In North America, the reversal in sign of north-south hillslope asymmetry 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 northern-aspects between 30-45° north latitude, and equal tendencies toward steeper northern- or southern-aspects above 45° north latitude. *Parsons* (1988) suggested this change in north-south 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° south latitude that is perhaps the Southern Hemisphere equivalent of the transition in the Northern Hemisphere. The east-west hillslope asymmetry gradually reverses from steeper western-aspects, on average, for high and mid-latitudes to steeper eastern-aspects between 5° north latitude and 20° south latitude. The east-west hillslope asymmetry trends in the Northern Hemisphere largely mirror those in the Southern Hemisphere (e.g., above and below ~10° south latitude). The simplest explanations for latitudinal trends in both north-south and east-west hillslope asymmetry 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 hillslope asymmetry, the range of variability captured by the 0.25° latitude-binned data and evident at smaller scales in the hillslope asymmetry maps emphasizes that regional influences often overprint latitude-based influences.

Range-scale hillslope asymmetry patterns are visually evident in the Western USA. The variability in hillslope asymmetry at the scale of mountain ranges suggests that prominent topographic features influence hillslope asymmetry. 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).

The reversal of hillslope asymmetry orientation with elevation in the Idaho Batholith suggests that elevation-dependent processes can also exert a dominant control on hillslope asymmetry development. Factors possibly influencing hillslope asymmetry 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 northern-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 northern-aspects caused ridgelines to shift south, decreasing overall elevation gradients and reducing average slope angles for northern-aspects. Glacial versus fluvial process dominance among aspects might explain the more frequent steeper Southern-aspects above the ~49° north latitude threshold evident with latitude (Figures 3 and 4), as the Canadian Rockies were extensively glaciated by the Cordilleran ice-sheet and mountain glaciers.

6. CONCLUSIONS

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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APPENDIX A

Parameter Tests

Parameter tests investigate how changing a single parameter while holding the other parameters constant affects the resulting hillslope asymmetry maps. Within a region spanning Eastern Utah and Western Colorado, window size, minimum data, minimum slope, and aspect-bin width parameters are tested area by comparing hillslope asymmetry maps derived with each parameter setting. Additional parameter tests (not presented here) using higher resolution data (30 m and 10 m) for smaller areas showed similar results.

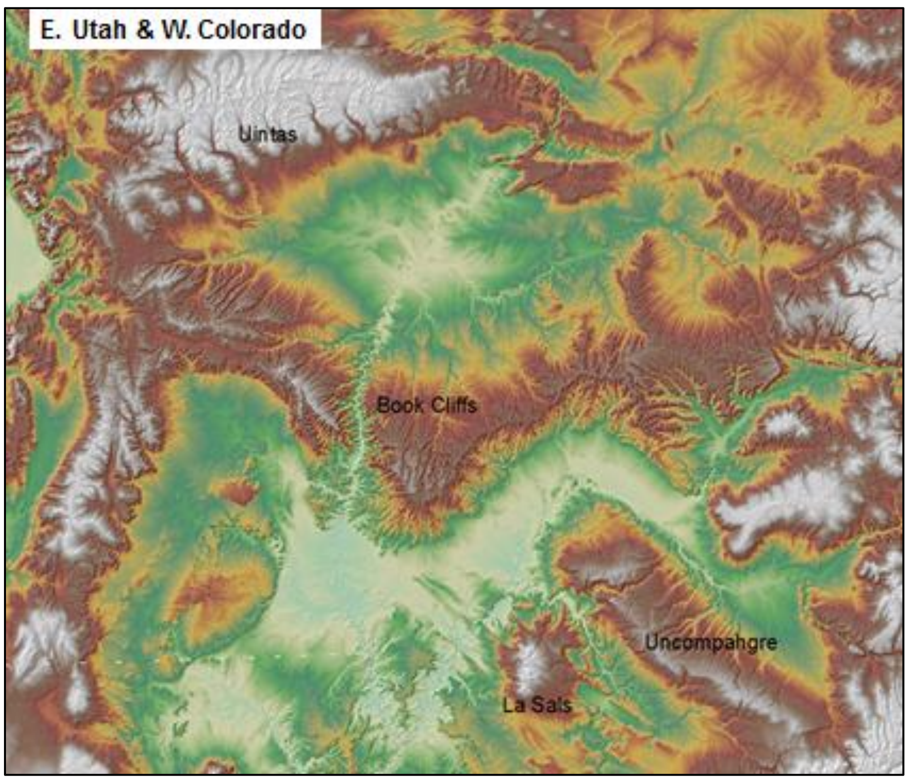

Figure A.1. Extent of parameter test region in Eastern Utah and Western Colorado.

<u>Window Size Parameter Test</u>

This parameter test involved changing the window size parameter to 1x1, 3x3, 5x5, 10x10, and 20x20 km². The resulting maps are shown in the next five figures. The other parameters were held constant at:

- Minimum slope = 5°
- Aspect window width = 90°
- Minimum data = 1%
- Dem Resolution = 90 m.

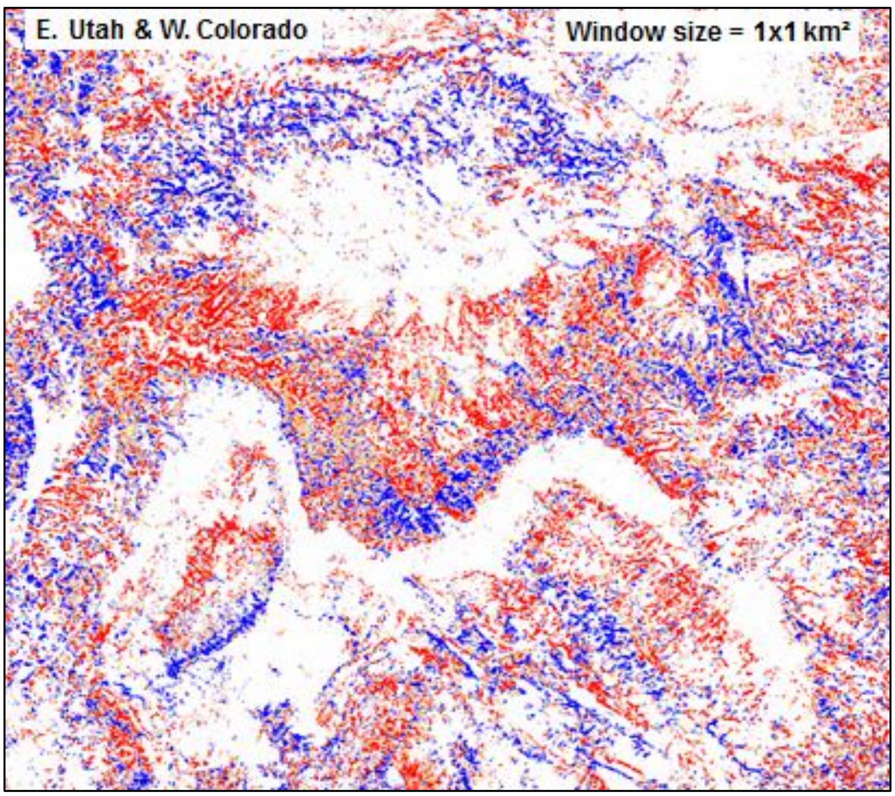

Figure A.2. Resulting map for the window size test using a 1x1 km² window size.

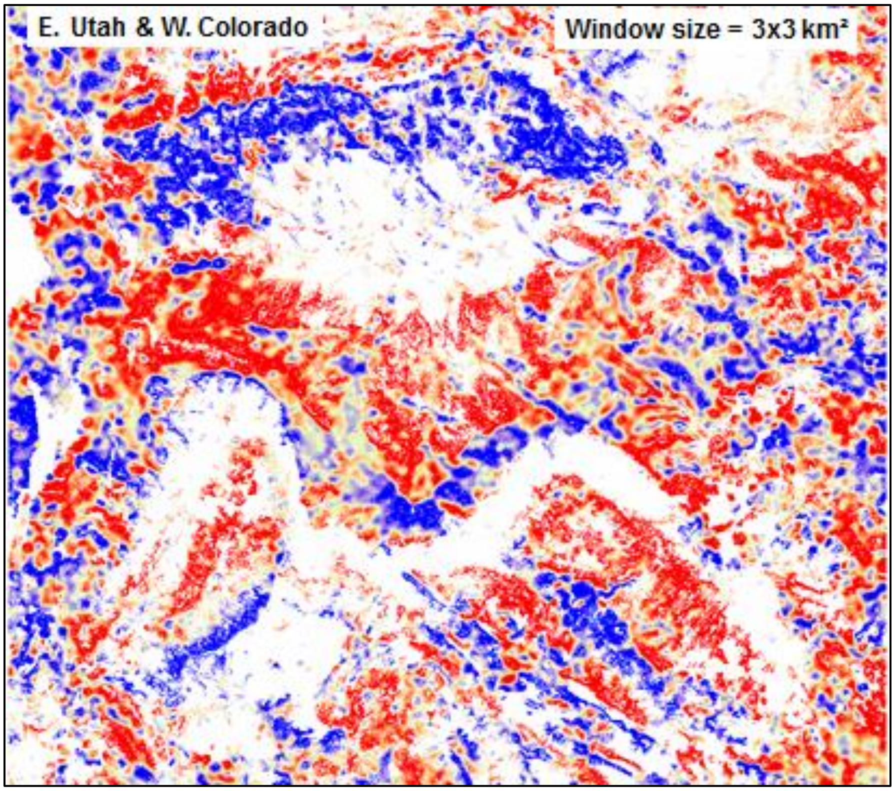

Figure A.3. Resulting map for the window size test using a 3x3 km² window size.

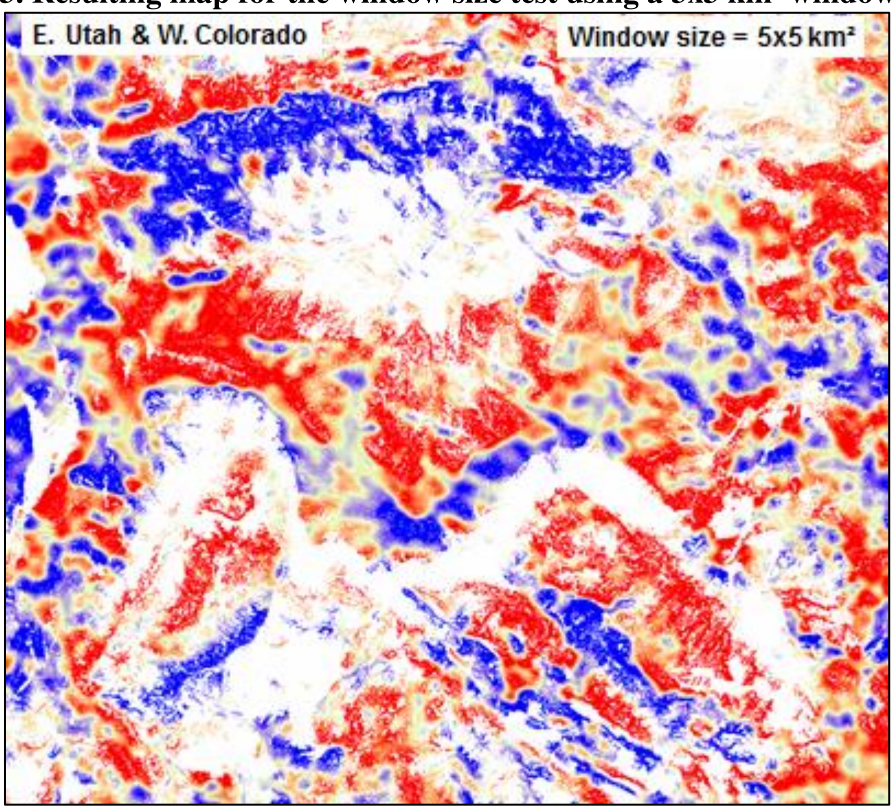

Figure A.4. Resulting map for the window size test using a 5x5 km² window size.

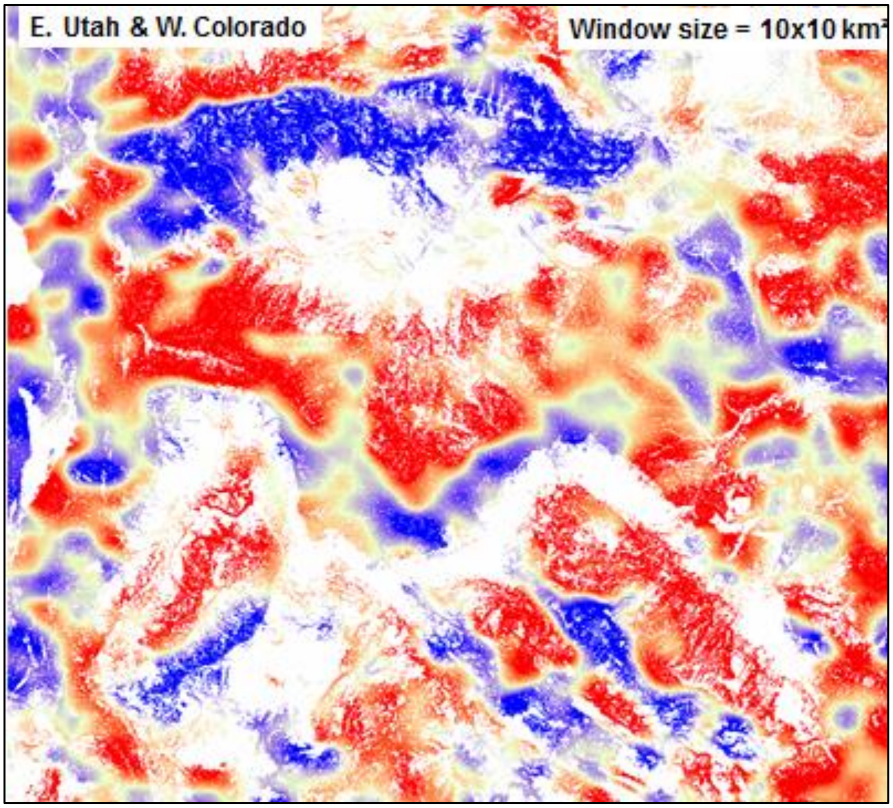

Figure A.5. Resulting map for the window size test using a 10x10 km² window size.

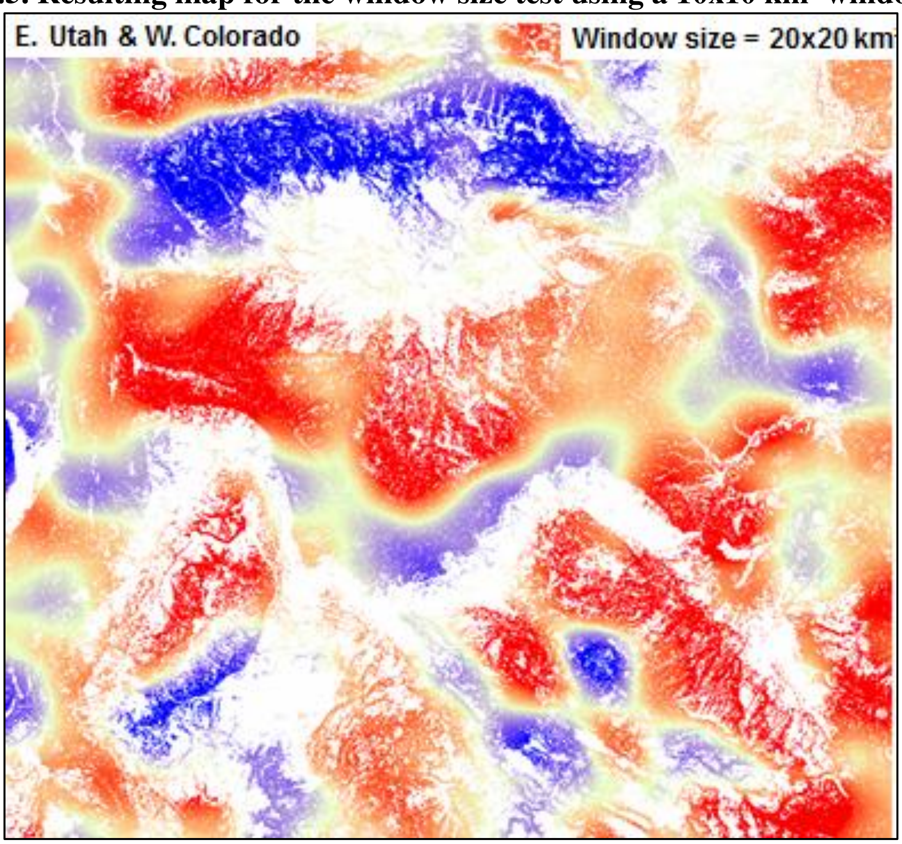

Figure A.6. Resulting map for the window size test using a 20x20 km² window size.

<u>Minimum Slope Parameter Test</u>

This parameter test involved changing the minimum slope parameter to 1, 5, 10, and 15°. The results are shown in the following four figures. The other mapping parameters were held constant at:

- Window size = 5x5 km²
- Aspect window width = 90°
- Minimum data = 1%
- Dem Resolution = 90 m

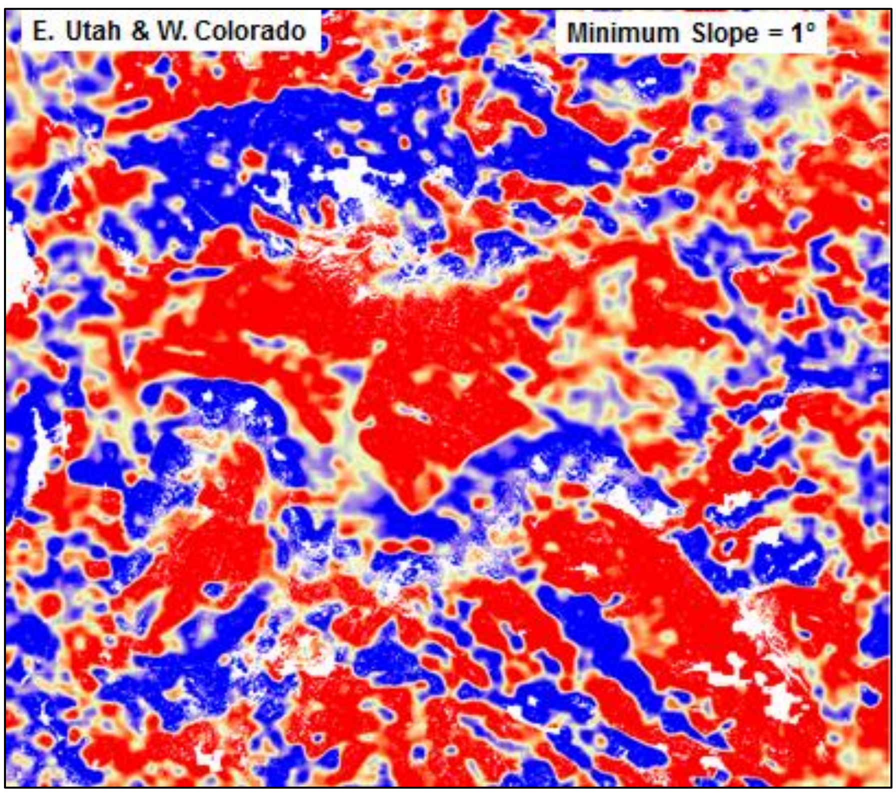

Figure A.7. Resulting map for parameter test using a 1° minimum slope.

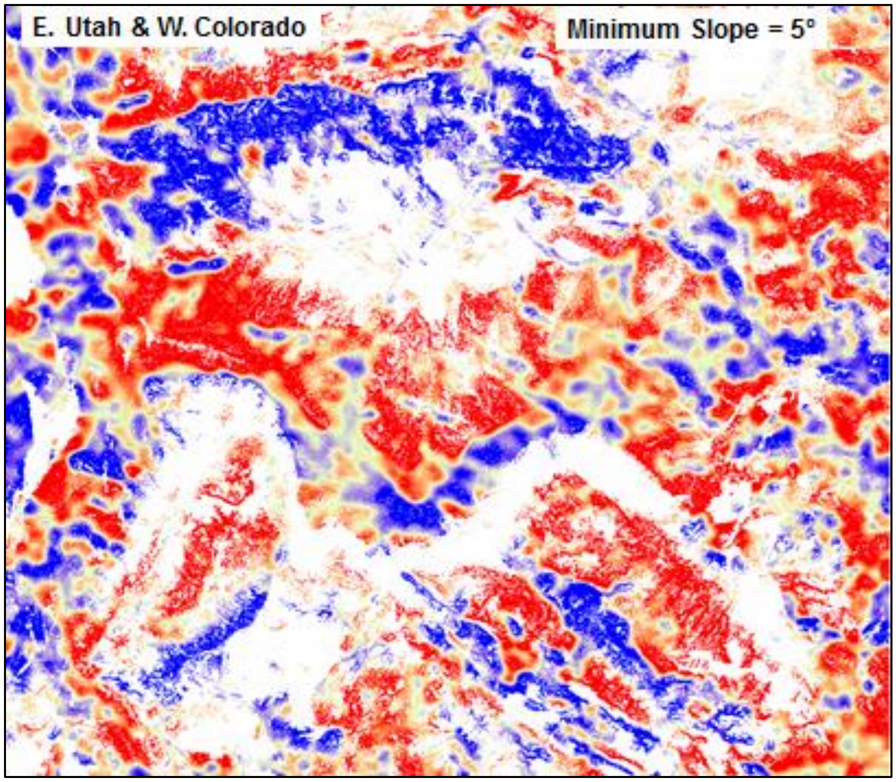

Figure A.8. Resulting map for parameter test using a 5° minimum slope.

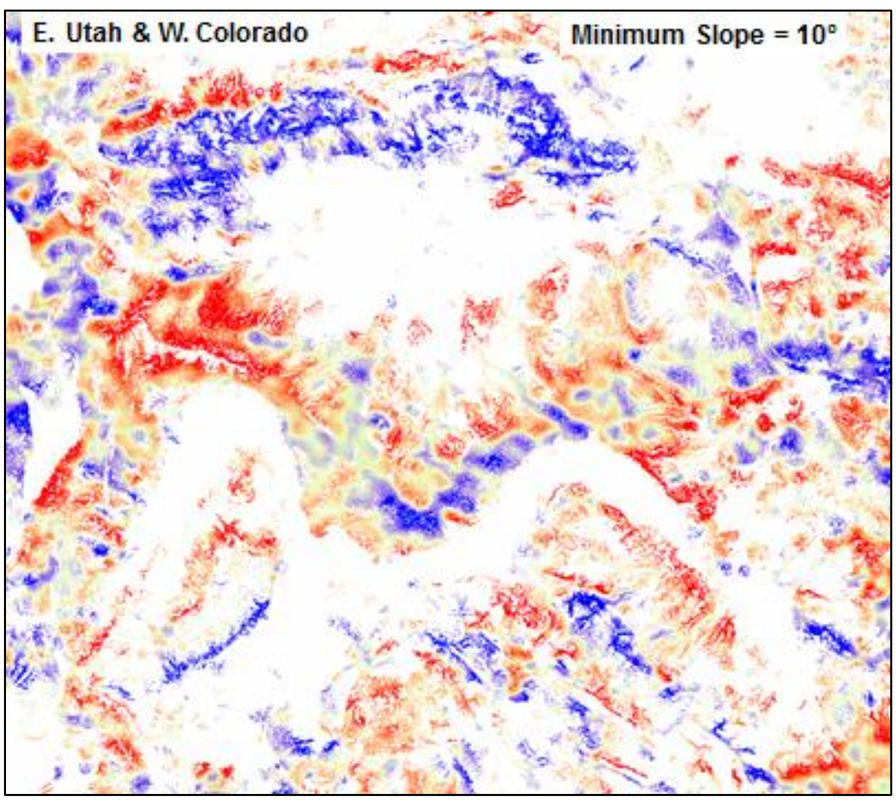

Figure A.9. Resulting map for parameter test using a 10° minimum slope.

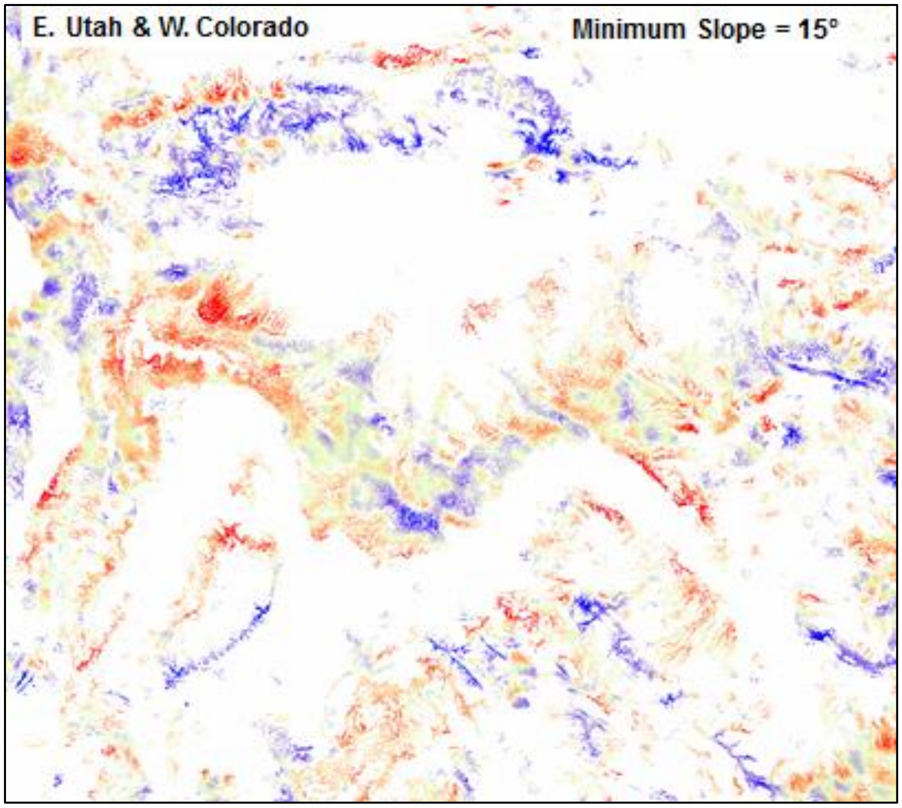

Figure A.10. Resulting map for parameter test using a 15° minimum slope.

Minimum Data Parameter Test

This parameter test compares maps created using minimum data parameters of 1, 5, and 10% (e.g., at least 1, 5, or 10% of the data within each window must represent either aspect being compared). The resulting maps are shown in the next three figures. The other parameters were held constant at:

- Window size = 5x5 km²
- Aspect window width = 90°
- Minimum slope = 5°
- Dem Resolution = 90 m

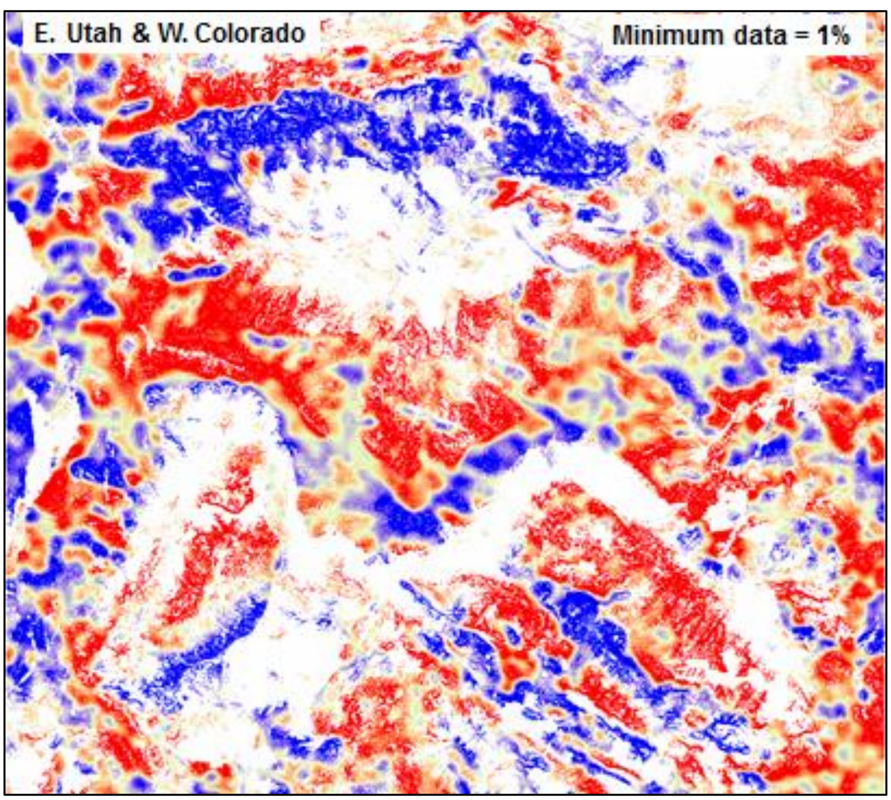

Figure A.11. Resulting map for test using a 1% minimum data parameter.

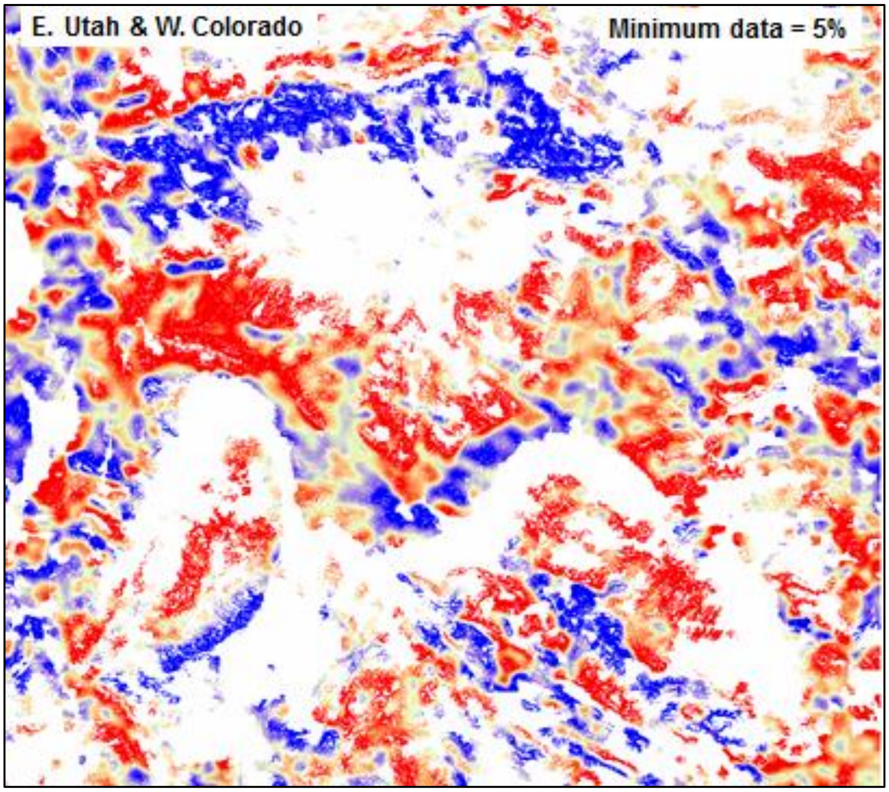

Figure A.12. Resulting map for test using a 5% minimum data parameter.

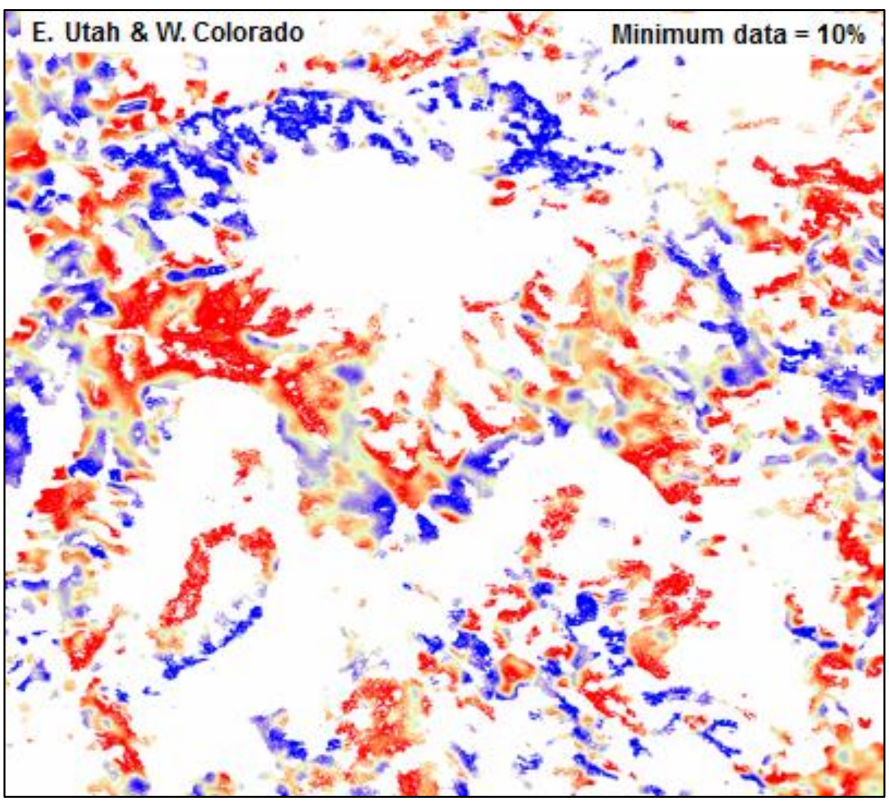

Figure A.13. Resulting map for test using a 10% minimum data parameter.

Aspect-Bin Width Test

This parameter test compared maps created using aspect-bin widths of 30, 60, 90, 120, and 150°. Bins were always centered over a cardinal direction (e.g., north, east, south, or west). The resulting maps are shown in Figures A.14 through A.18. The other parameters were held constant at:

- Window size = 5x5 km²
- Minimum data = 1%
- Minimum slope = 5°
- Dem Resolution = 90 m

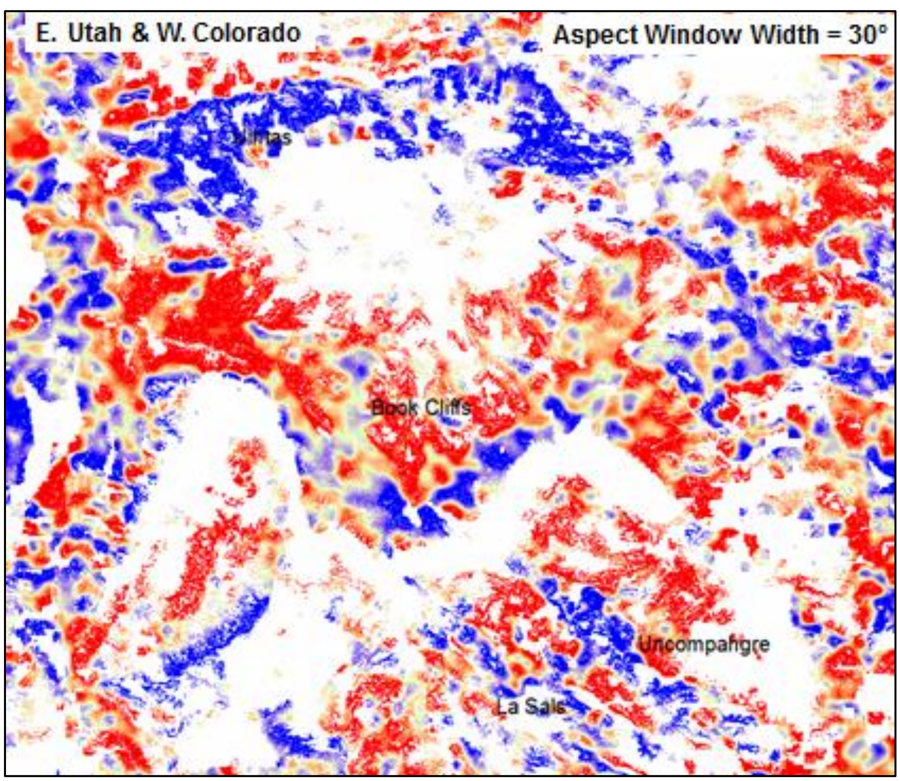

Figure A.14. Resulting map for test using an aspect-bin width of 30°.

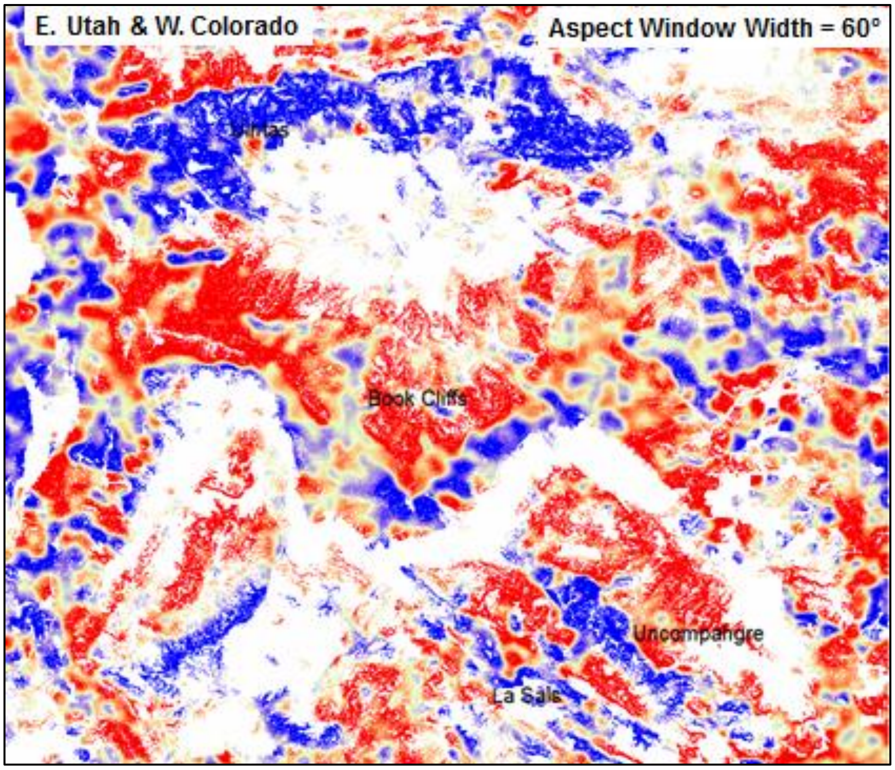

Figure A.15. Resulting map for test using an aspect-bin width of 60°.

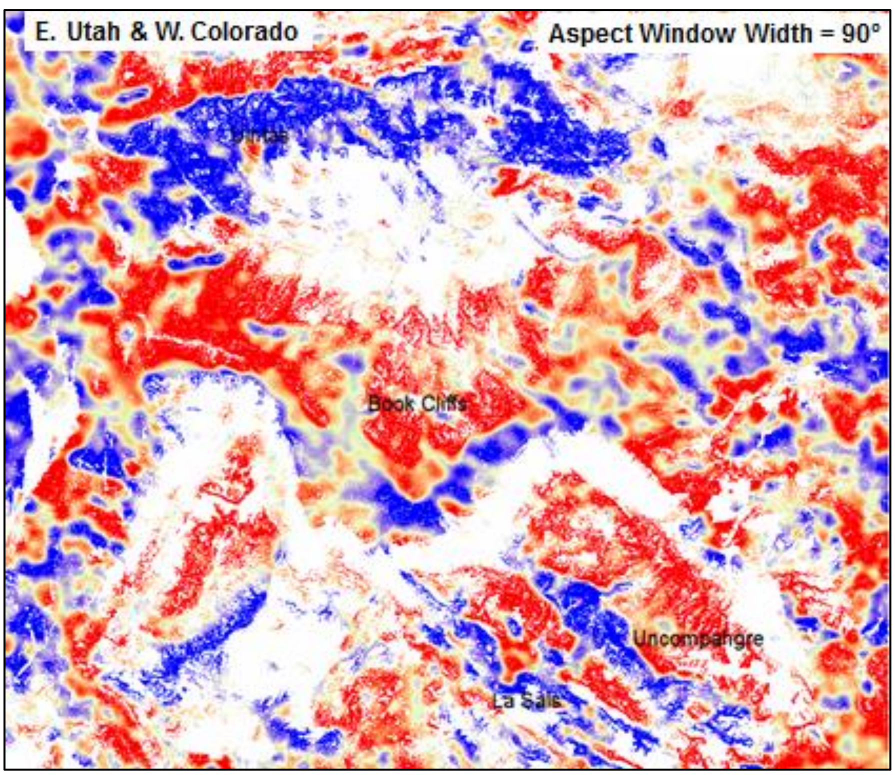

Figure A.16. Resulting map for test using an aspect-bin width of 90°.

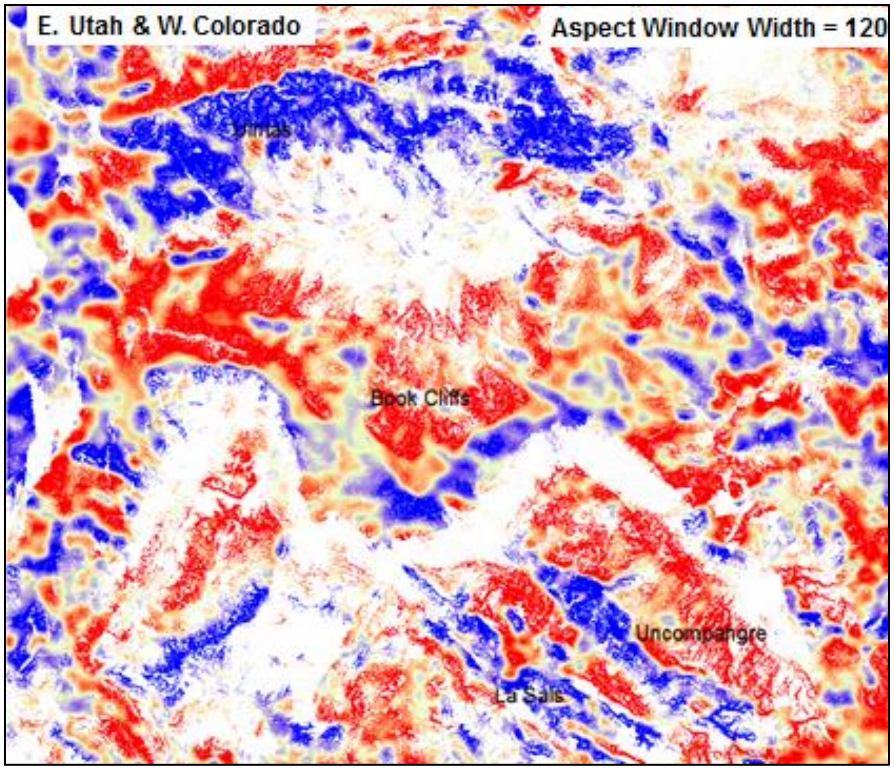

Figure A.17. Resulting map for test using an aspect-bin width of 120°.

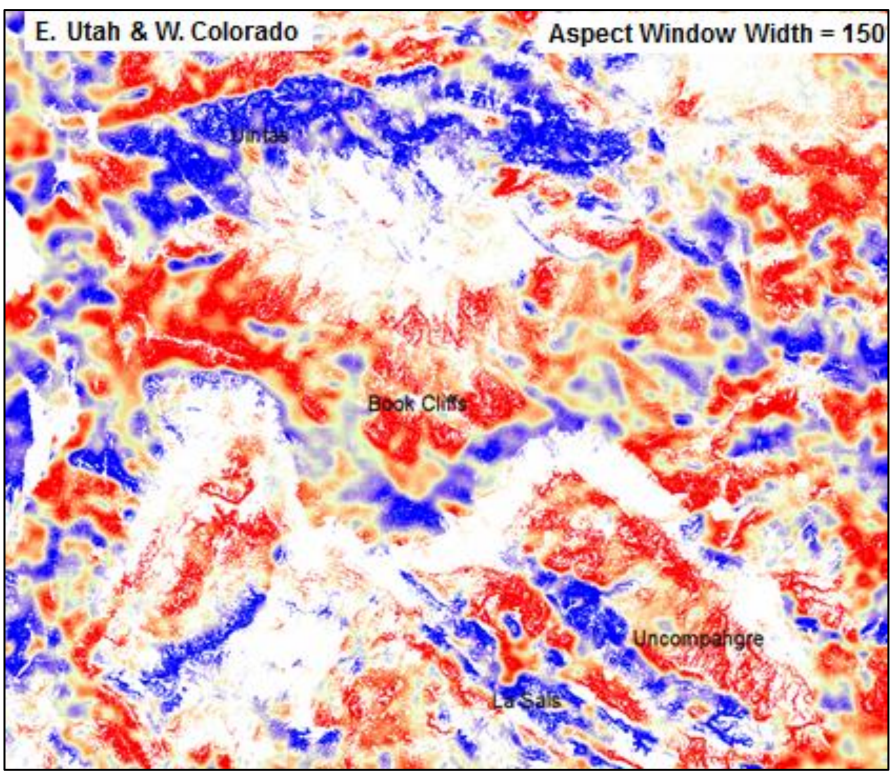

Figure A.18. Resulting map for test using an aspect-bin width of 150°.

Dicussion of Parameter Tests

None of the -arameters appear to alter the broad-scale spatial patterns evident within this geologically, climatically, and ecologically diverse region. This is important because it suggests that the broader-scale spatial patterns evident within the hillslope asymmetry maps do not depend on parameter selection. In other words, the fundamental results assessed in this study (i.e., broad-scale patterns) are not biased by choice of parameters. That said, changing the mapping parameters appears to affect the map extent (e.g., the size of colored areas), HA magnitudes, and the minimum scale of hillslope asymmetry variability mapped. The effects of the individual parameters are discussed below.

Changing the size of the measurement window appears to most strongly affect the minimum-scale of variability expressed in the hillslope asymmetry maps. Smaller windows capture more smaller-scale variability. Using a larger window effectively smooths the data and makes broader scale trends more evident.

Both minimum data and minimum slope parameters appear to affect the extent of the mapped area. Using more conservative (higher) values crops the data away from the edges of large valleys. In the case of slope angles, the terrain near the margins of large valleys (e.g. foothills) is relatively gentle and less of this terrain fulfills the minimum slope parameter as it is increased. With regard to the minimum data parameter, the measurement window overlaps valleys when positioned near valley margins, and this causes relatively few pixels within the window to fulfill the minimum slope parameter. This causes the data fulfilling the parameters to be relatively scarce in these areas, and increasing the minimum data requirement progressively crops these valley-margin areas from the analysis (i.e., they are mapped as white, or grayscale if draped over a hillshade).

Changing the aspect-bin width appears to affect the magnitude of asymmetry values. Wider aspect-bins yield lower hillslope asymmetry magnitudes, but increases the abundance of data for either aspect being compared. For example, north-south asymmetry magnitudes are likely subdued using aspect-bins wider than ~90° because this includes slopes facing more east or west than north or south in the analysis, which might subdue the north-south contrast of interest. Narrower aspect-bins yield higher hillslope asymmetry magnitudes, but this decreases the data representing either aspect being compared, effectively reducing the mapped extent in some areas.

APPENDIX B

Resolution Comparisons

In addition to the comparison of median slope angles for each aspect-bin using DEM resolutions ranging from 250 to 1 m resolution (Figure 2), the influence of source DEM resolution on the mapping method was further investigated by assessing the ability of coarser resolution DEMs to capture hillslope and valley topography. This assessment involved comparing the hillshades, slope angles, and hillslope asymmetry maps derived from 250, 90, and 30 m resolution data. The other mapping parameters were held constant (window size = 5x5 km²; minimum data = 1%; minimum slope = 5°; aspect window width = 90°).

Hillshades provide a visual representation of the topography in the source-DEMs, and act as a metric of the ability of the unaltered source data to capture hillslope and valley form. Because 250 m pixels are large relative to many hillslopes within valleys, it is important to assess whether the source data actually captures the landforms of interest.

Slope angle grids provide a visual representation of the landscape based on the same 8-directional algorithms used to derive the slope and aspect data used by the hillslope asymmetry mapping method. This algorithm estimates the geometry of a point on the landscape by comparing the elevation of each pixel to the 8 surrounding pixels. Slope and aspect are effectively measured over scales ~2-3 times the scale of a pixel in the source-DEM. For 250 m resolution DEMs, this means the minimum scale of topography discernible should be on the order of 500 to 750 m. It is important to assess the hillslope and valley forms captured by the 8-directional algorithms using various resolution source data to ensure that method is actually comparing the landforms of interest (i.e., comparing the oppositely facing slopes within valleys).

Hillslope asymmetry maps derived from each resolution allow us to visually compare how resolution affects the end-results. If different resolutions dramatically affect the mapped results, then this represents an uncertainty. However, if changing the resolution does not change the results, then it increases our certainty that the mapped results are not biased by the resolution of the source DEM.

The results of this assessment are shown in Figures B.1 through B.34. Each figure is labeled with the source-DEM resolution and type of dataset (raw elevation, hillshade, slope, and hillslope asymmetry). DEM resolution limits the minimum scale of features discernible within the landscape. In higher elevation mountainous landscapes, valleys are typically sufficiently wide to be captured by all resolutions. However, in terrain along valley margins, which is relatively low-gradient and has lower-order drainages, the largest valleys are narrow relative to larger pixel sizes, and 250 m resolution DEMs failed to capture these valley landforms. However, the minimum data and slope parameters prevented the calculation of hillslope asymmetry values in such scenarios, and simply reduced the extent of the mapped area away from these areas. Interestingly, broader scale spatial patterns were similar for all resolutions, perhaps suggesting that this hillslope asymmetry is reflected in both the larger and smaller-scale landforms. DEM resolution does not appear to affect the broad scale patterns of interest, but 90 and 30 m data capture more valley landforms and are preferrable for their greater certainty.

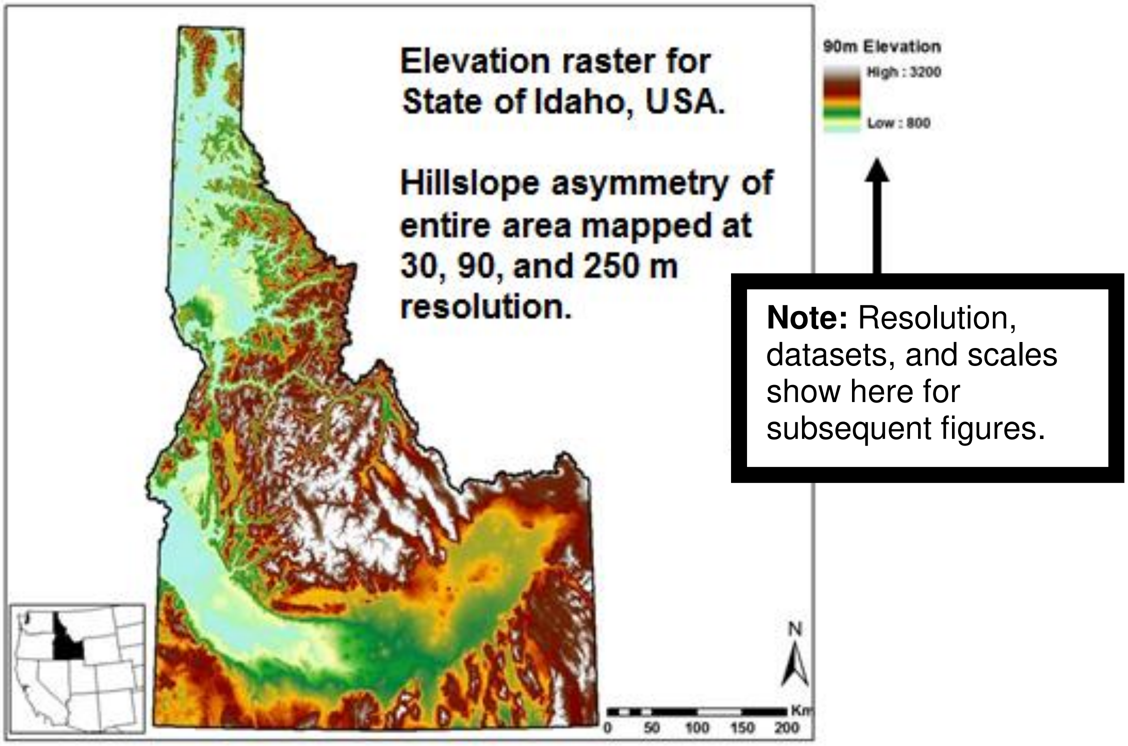

Figure B.1. Overview map of Idaho showing elevation and topography.

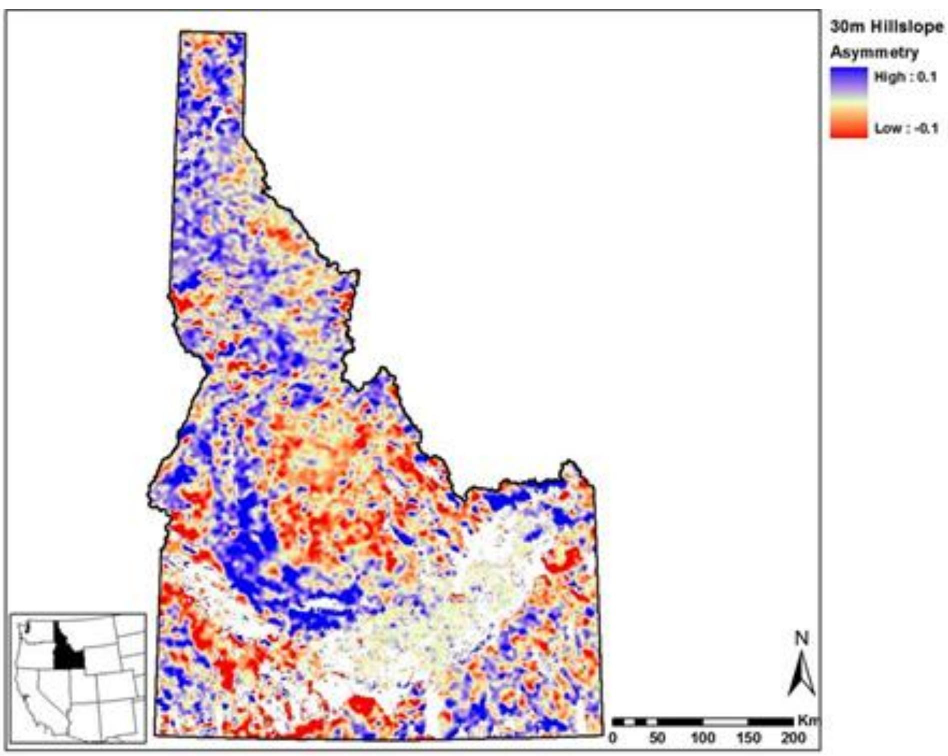

Figure B.2. Hillslope asymmetry map at 30 m resolution for Idaho, USA.

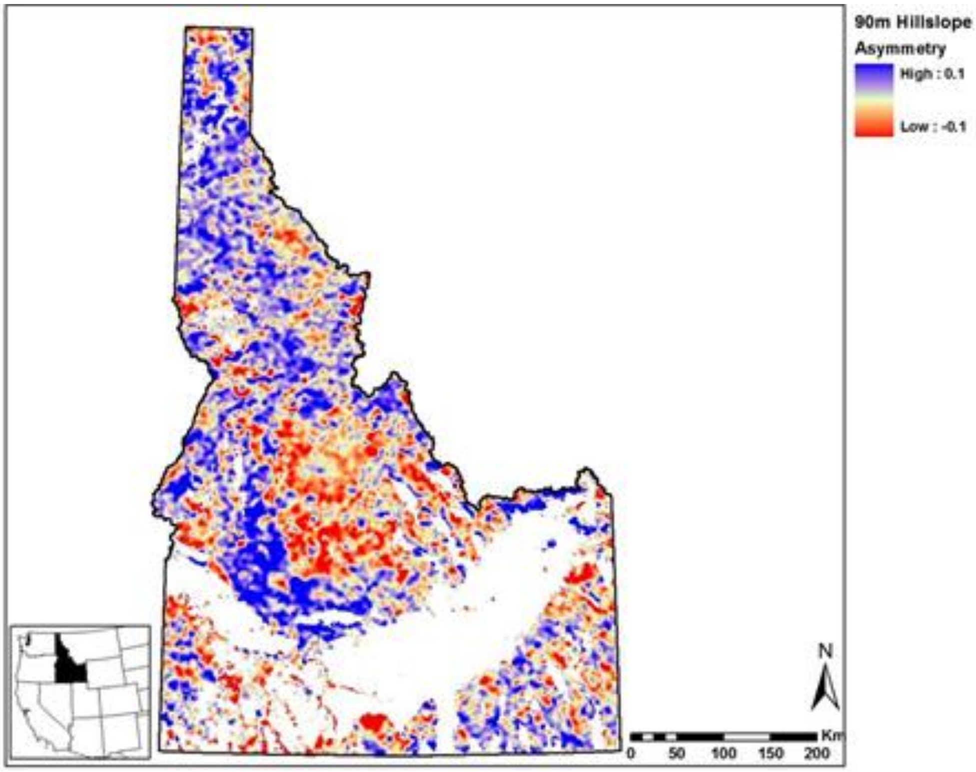

Figure B.3. Hillslope asymmetry map at 90 m resoltion for Idaho, USA.

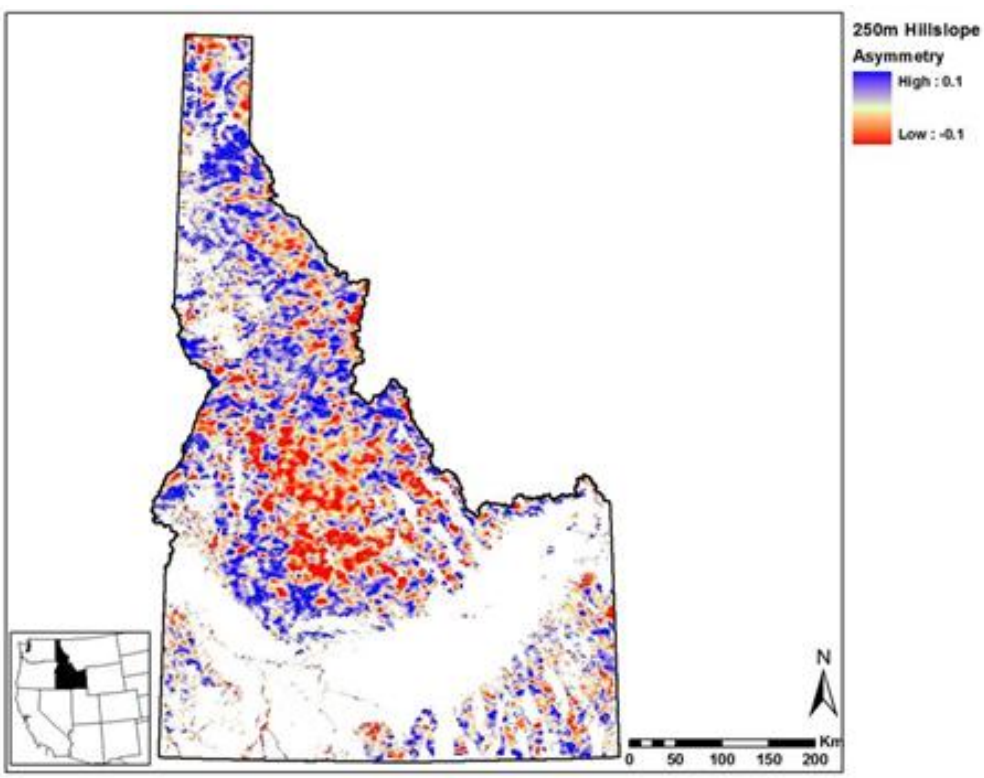

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Figure B.4. Hillslope asymmetry map at 250 m resoltion for Idaho, USA.

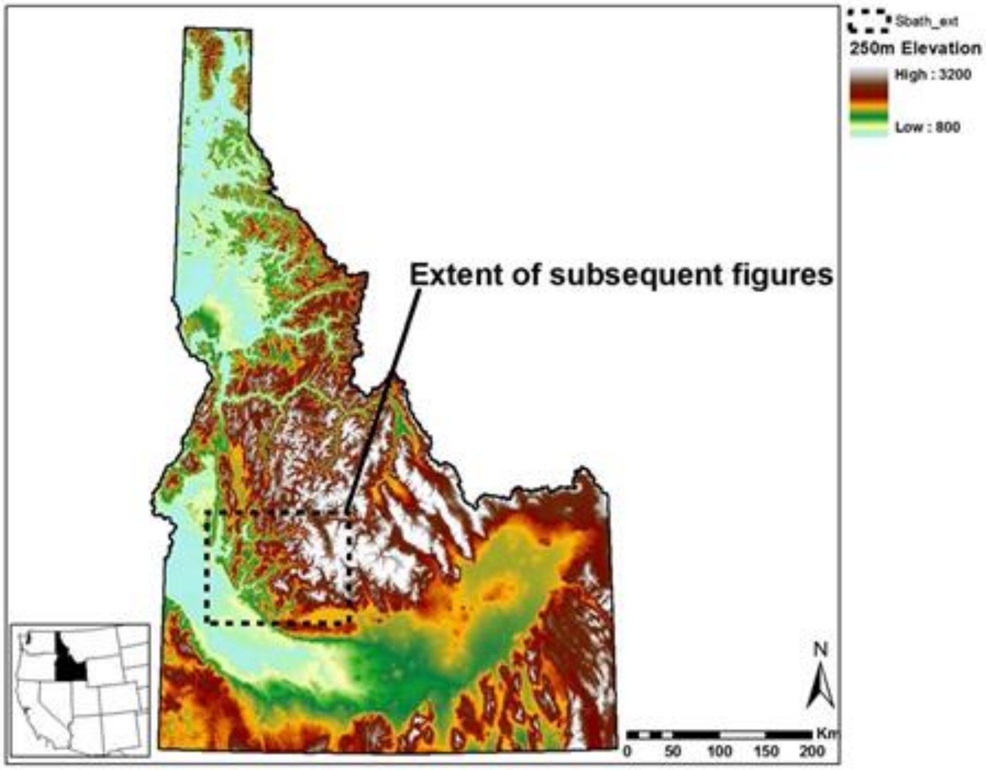

Figure B.5. Overview map of Idaho showing location of next nine figures.

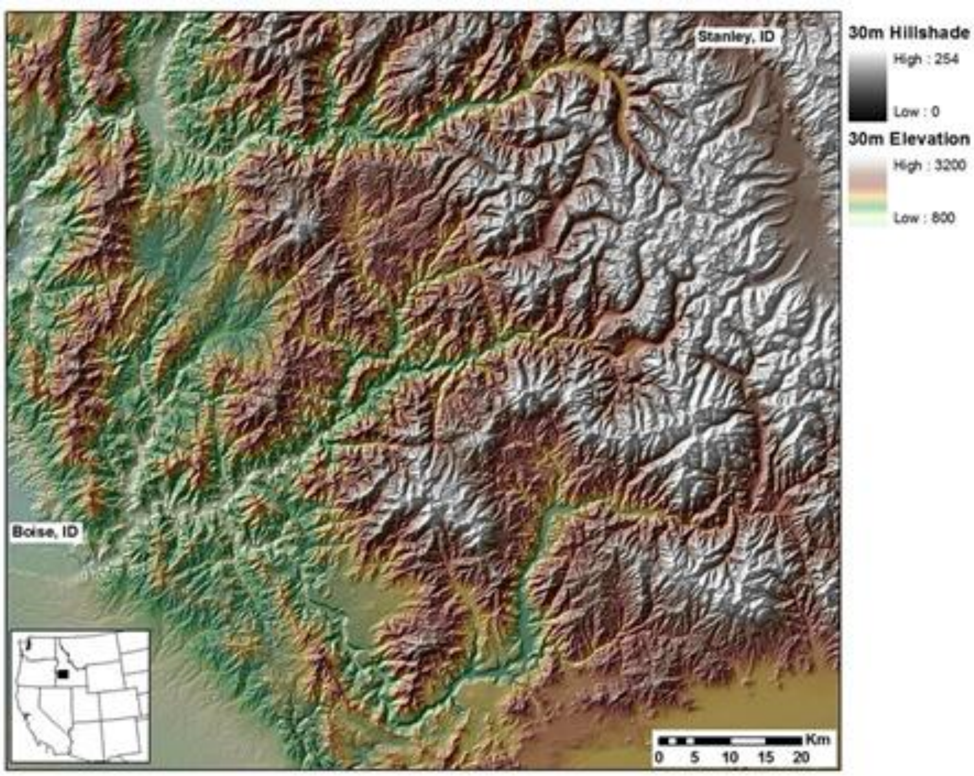

Figure B.6. Elevation draped hillshade at 30 m for the Idaho Batholith.

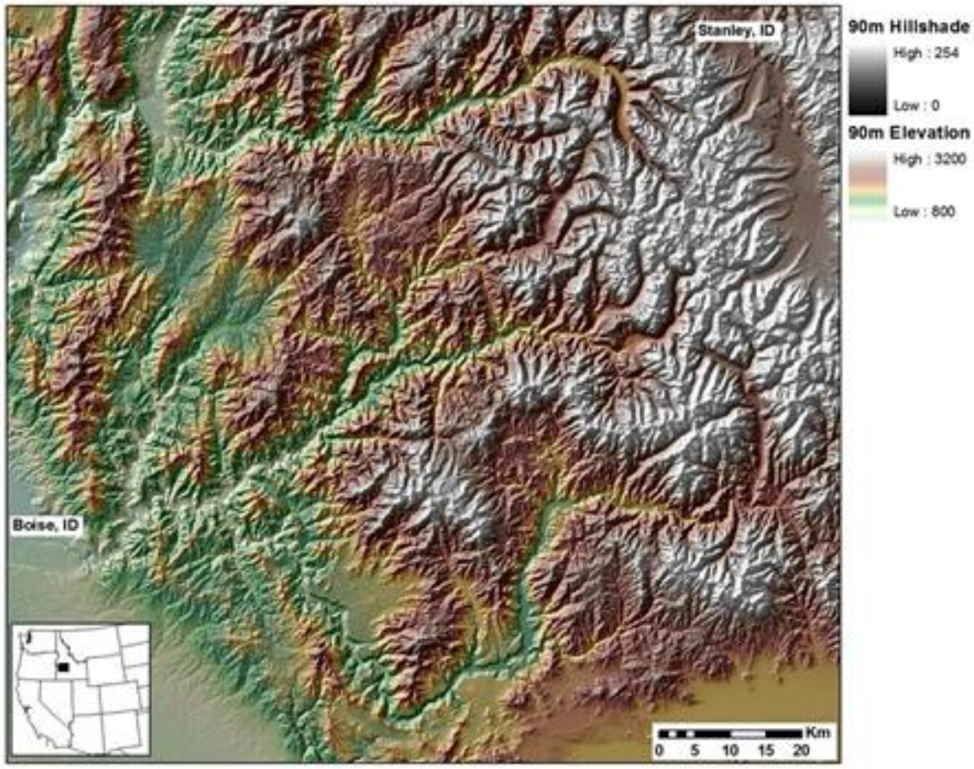

Figure B.7. Elevation draped hillshade at 90 m for the Idaho Batholith.

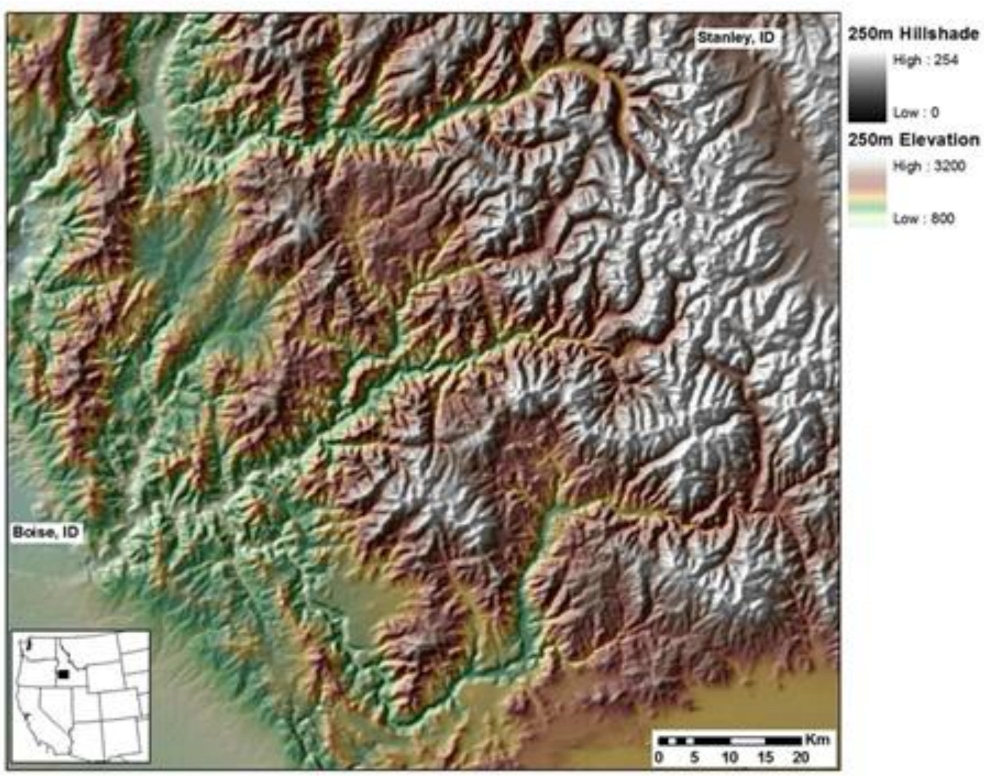

Figure B.8. Elevation draped hillshade at 250 m for the Idaho Batholith.

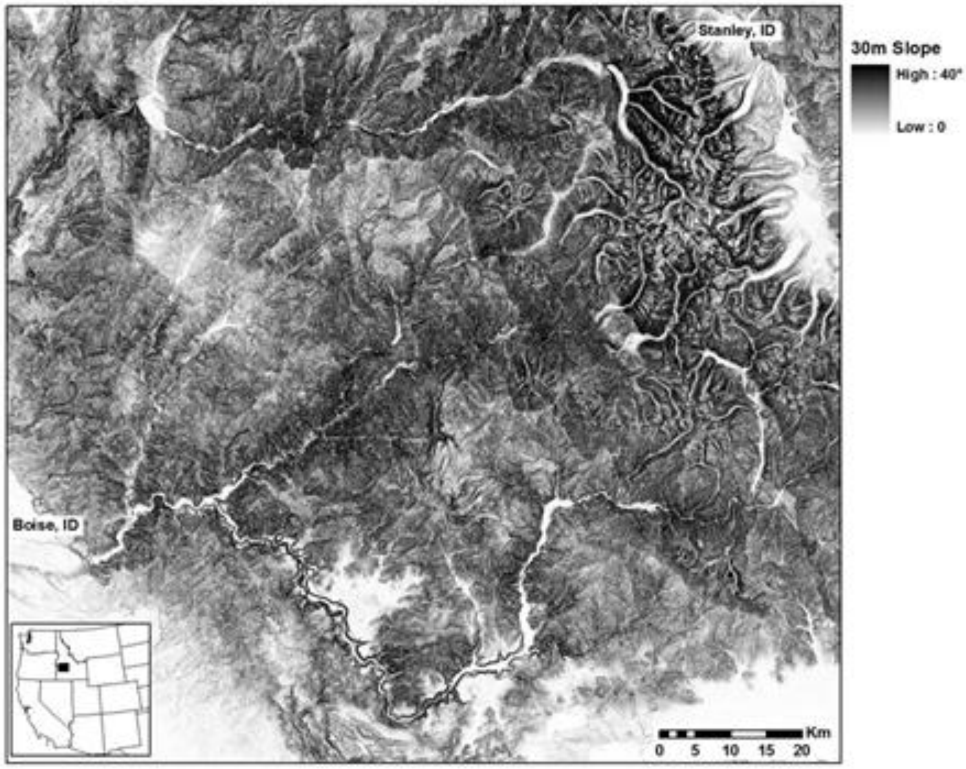

Figure B.9. Slope-shaded raster at 30 m resolution for the Idaho Batholith.

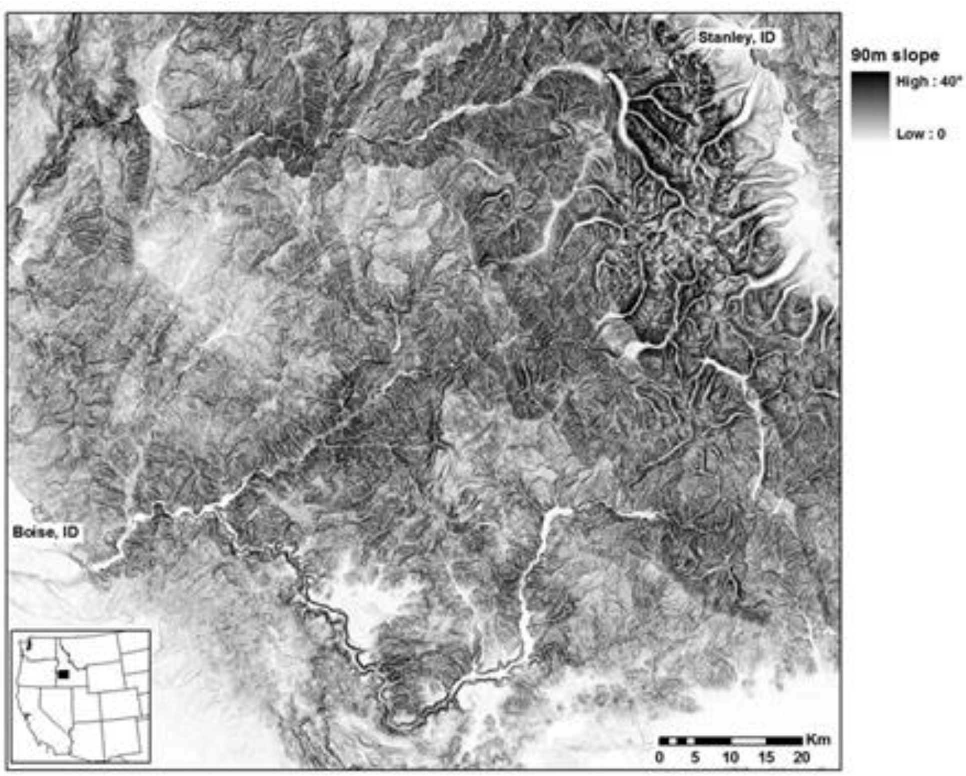

Figure B.10. Slope-shaded raster at 90 m resolution for the Idaho Batholith.

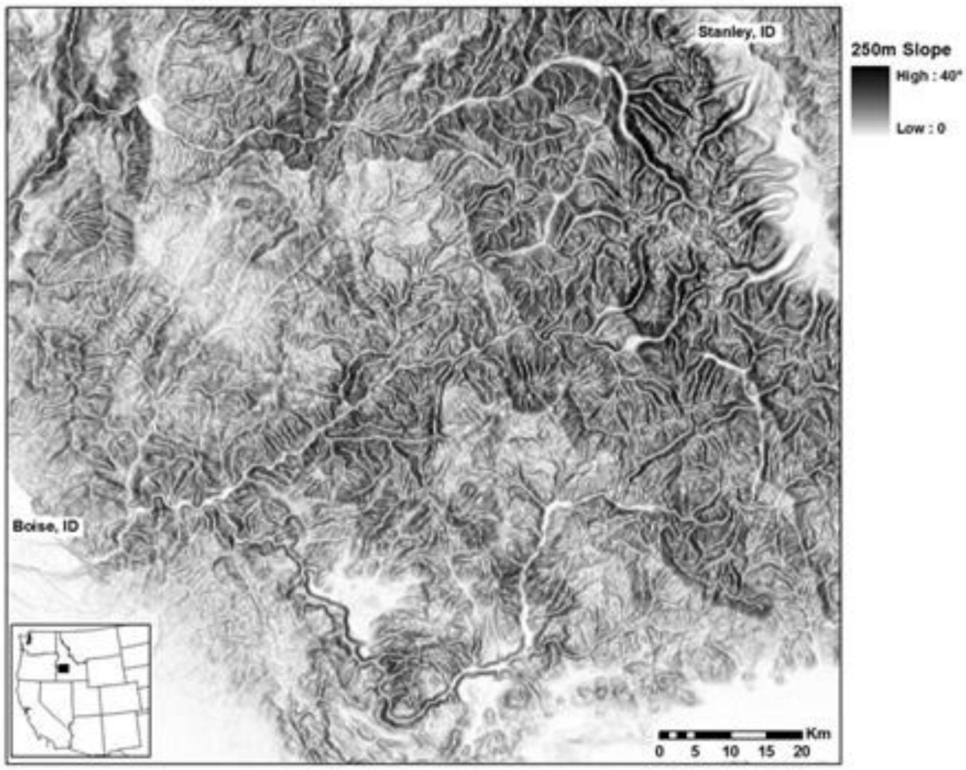

Figure B.11. Slope-shaded raster at 250 m resolution for the Idaho Batholith.

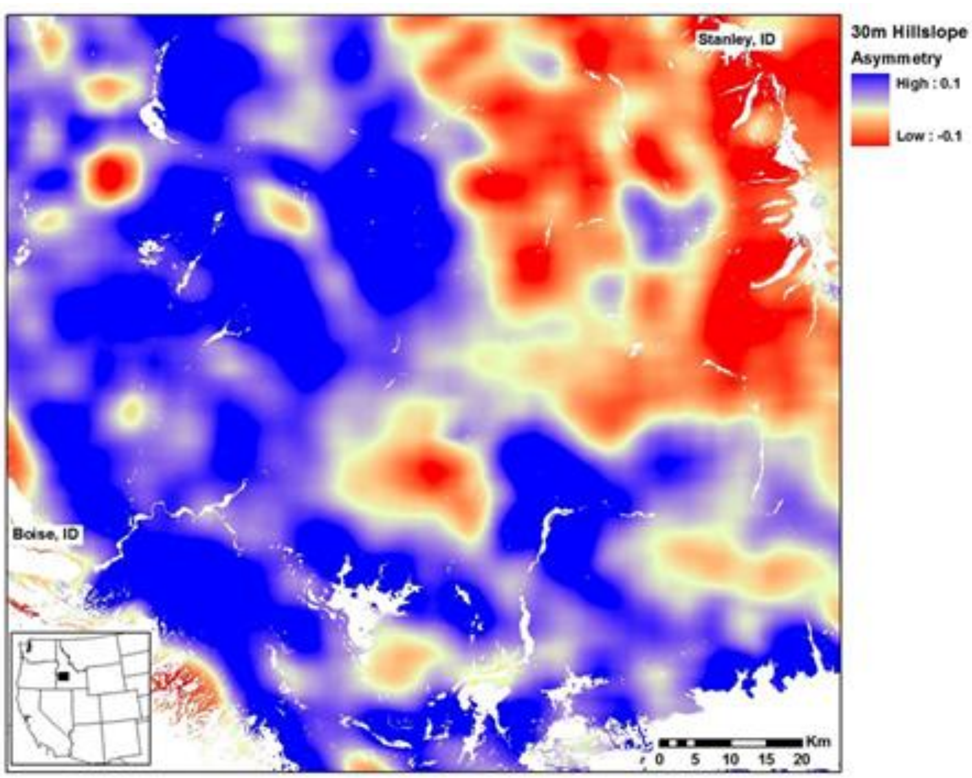

Figure B.12. Hillslope asymmetry map at 30 m for the Idaho Batholith.

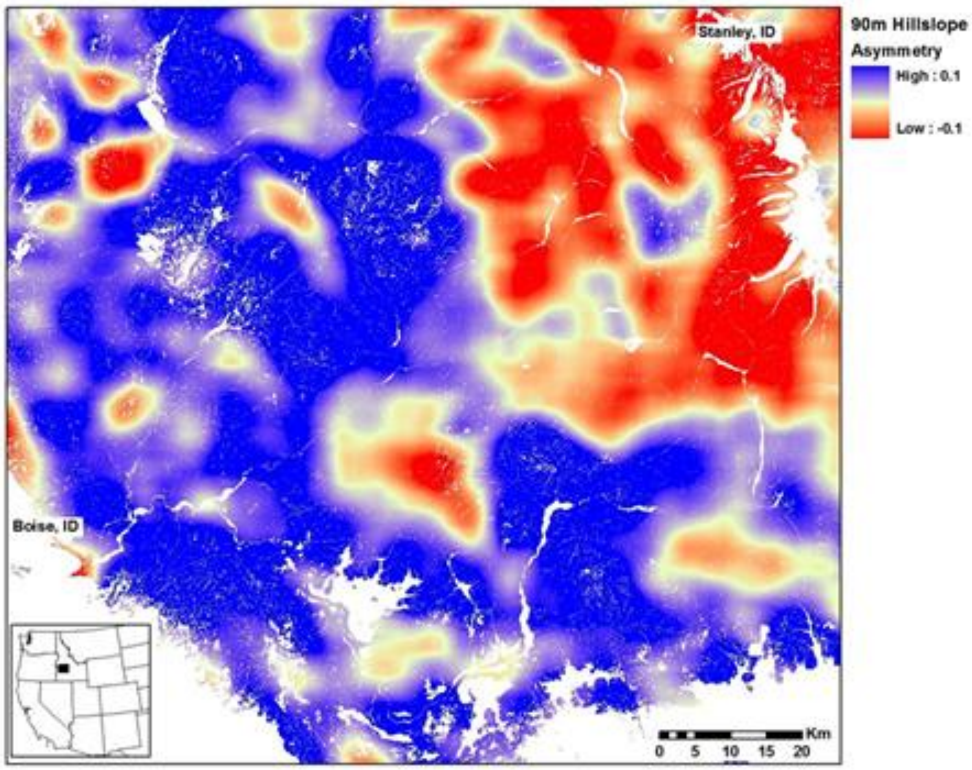

Figure B.13. Hillslope asymmetry map at 90 m for the Idaho Batholith.

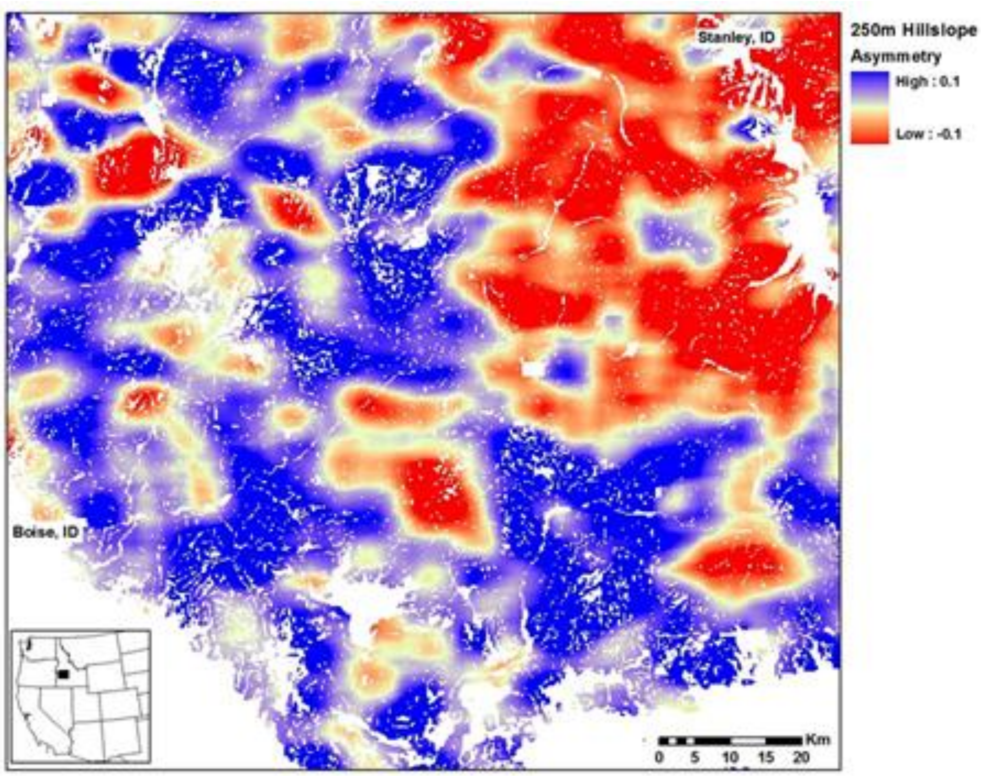

Figure B.14. Hillslope asymmetry map at 250 m for the Idaho Batholith.

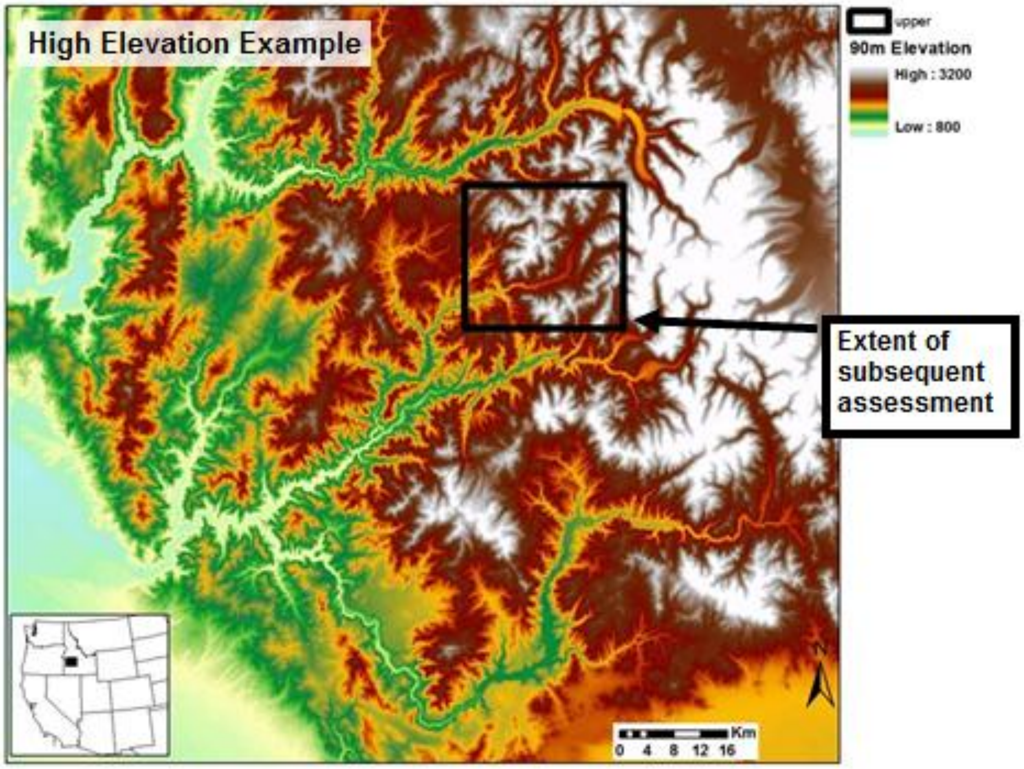

Figure B.15. Location of next nine figures in the S. Idaho Batholith.

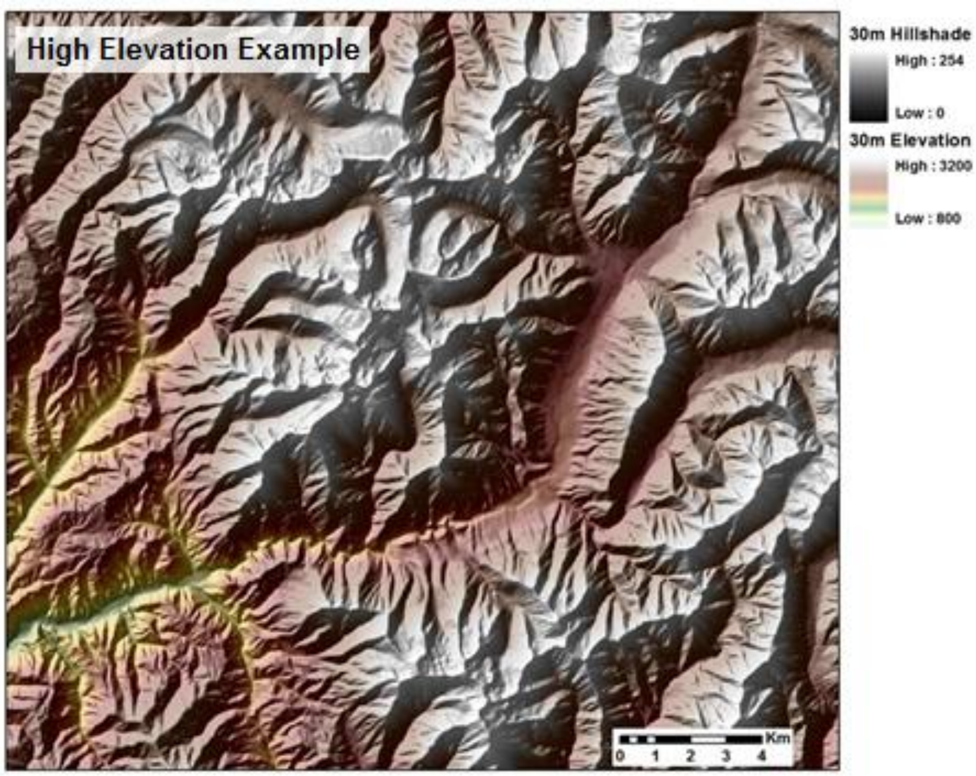

Figure B.16. Elevation draped hillshade at 30 m for high elevations.

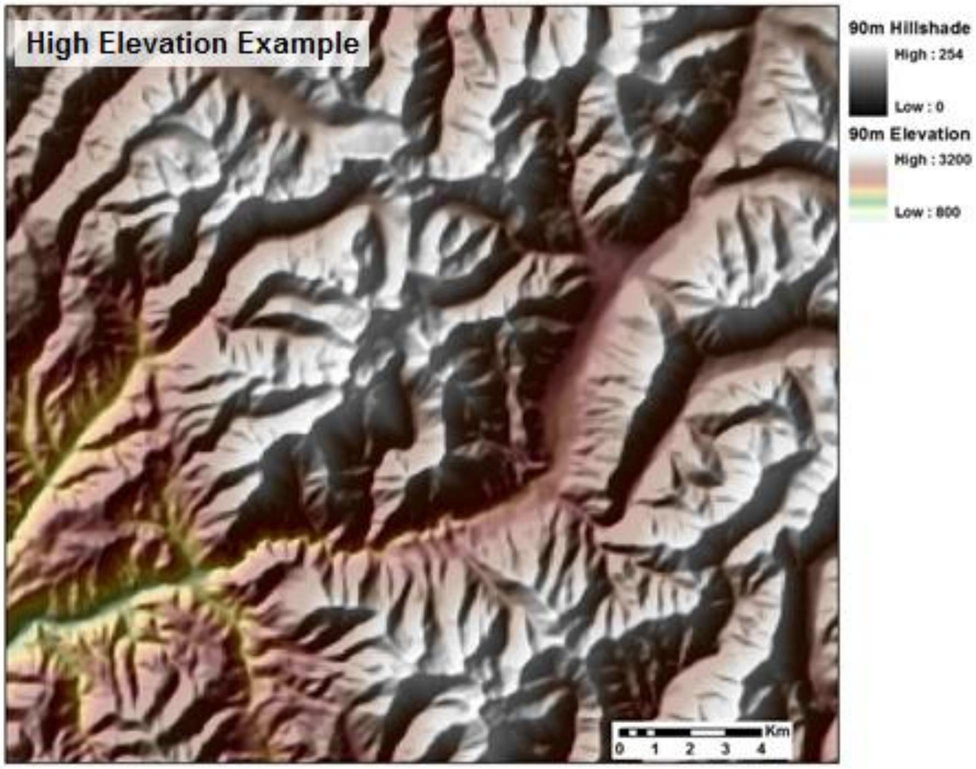

Figure B.17. Elevation draped hillshade at 90 m for high elevations.

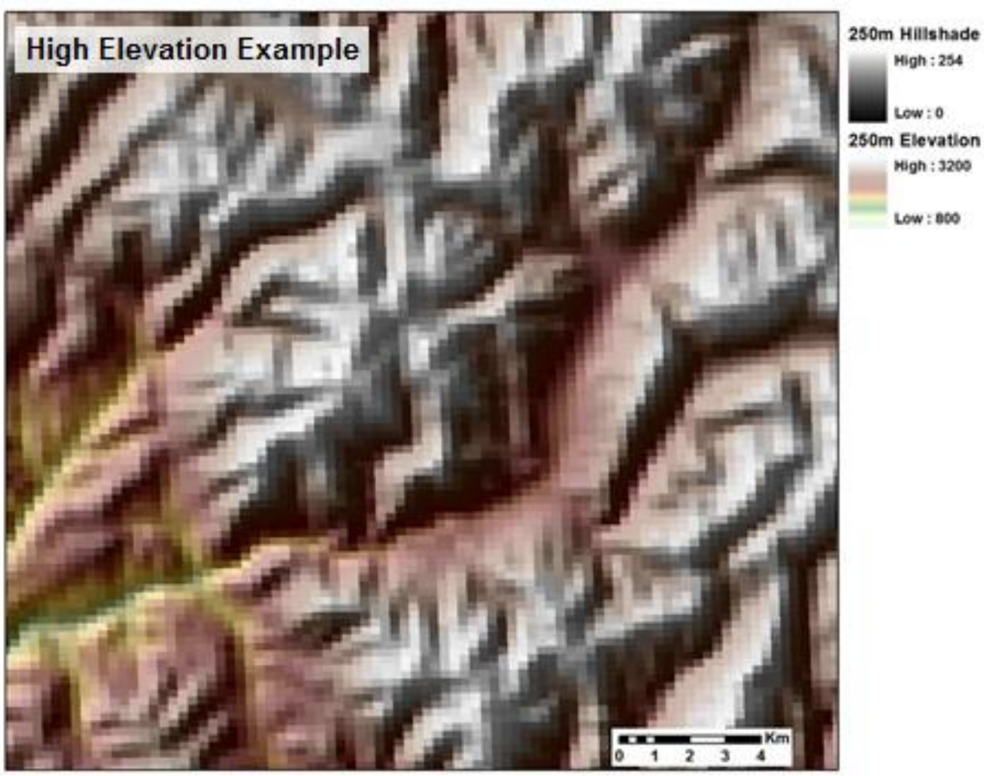

Figure B.18. Elevation draped hillshade at 250 m for high elevations.

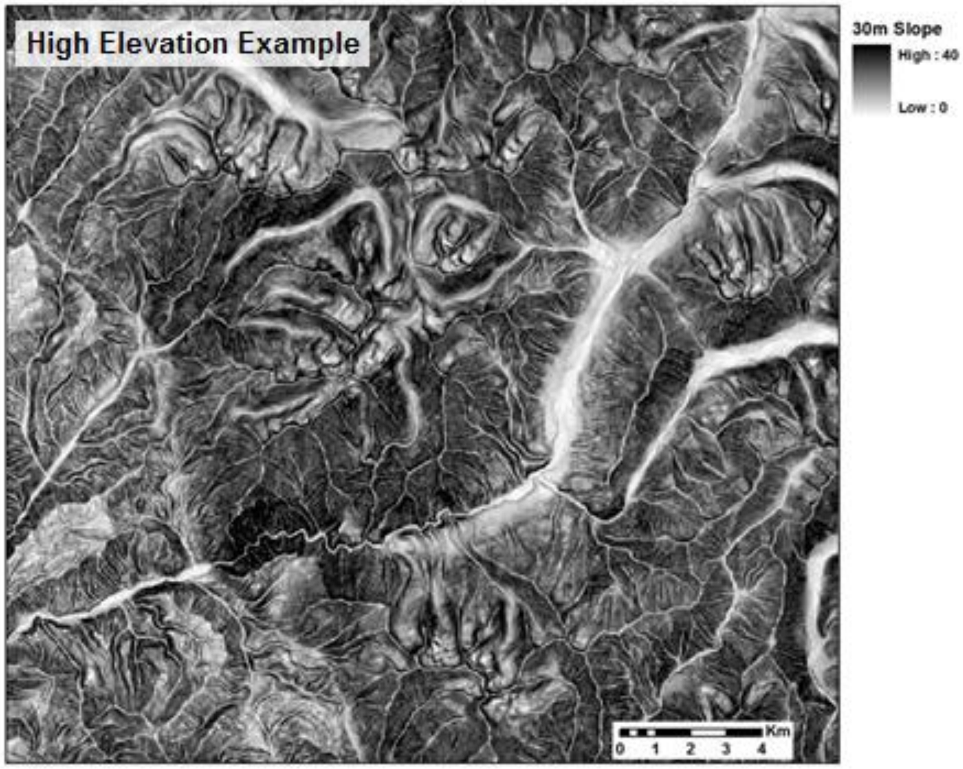

Figure B.19. Slope-shaded raster at 30 m resolution for high elevations.

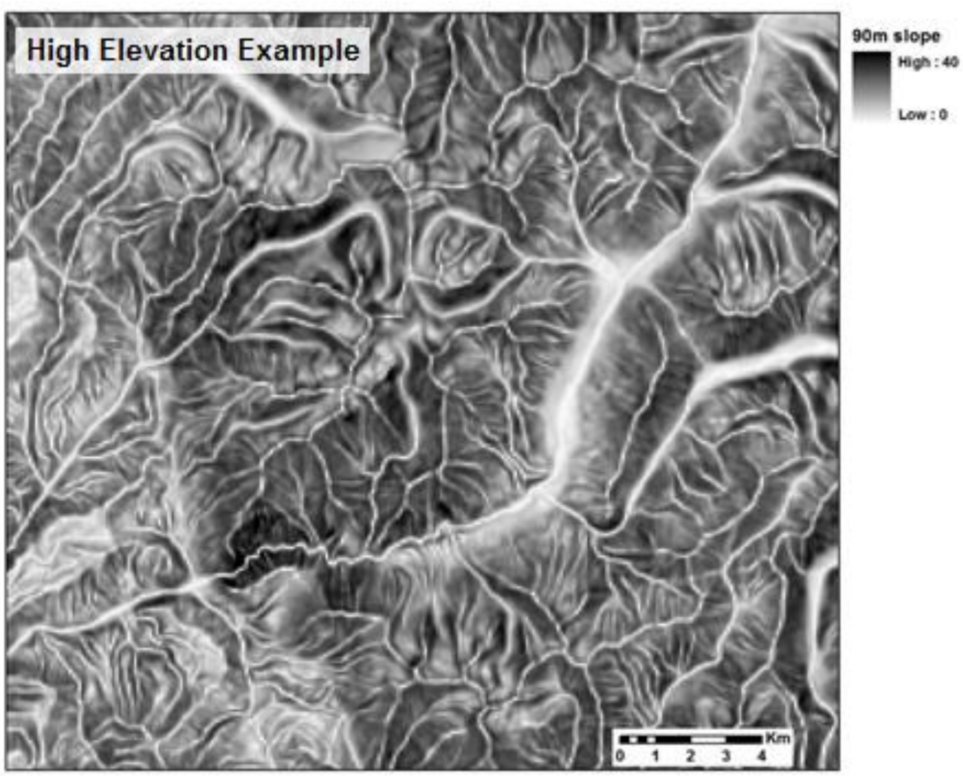

Figure B.20. Slope-shaded raster at 90 m resolution for high elevations.

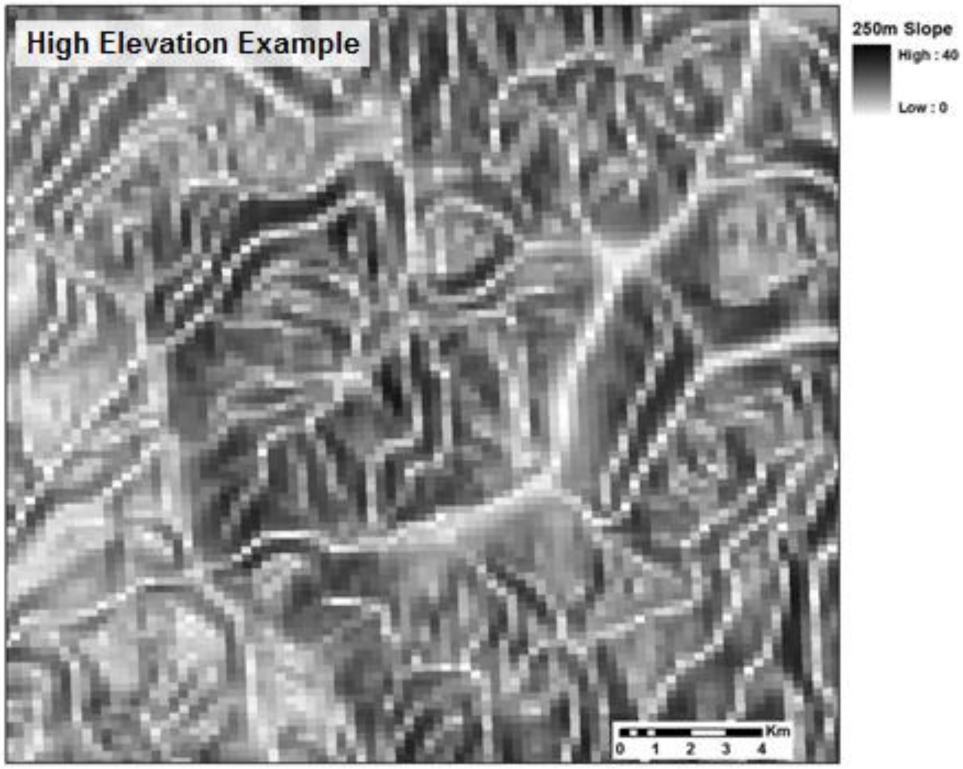

Figure B.21. Slope-shaded raster at 250 m resolution for high elevations.

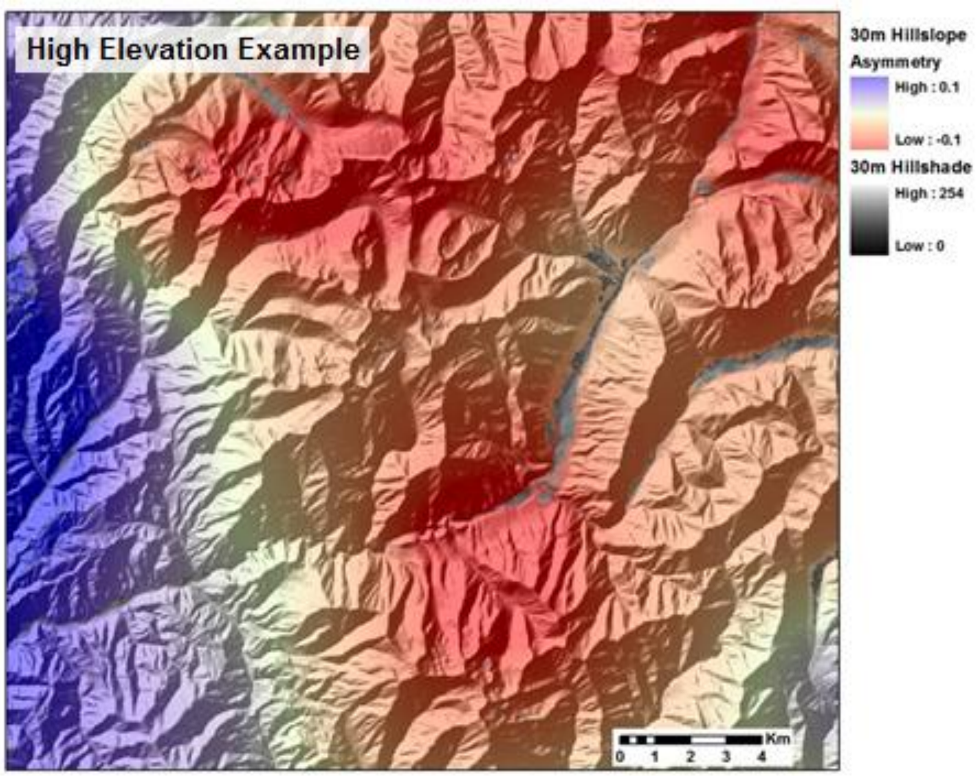

Figure B.22 Hillslope asymmetry map over hillshade at 30 m for high elev.

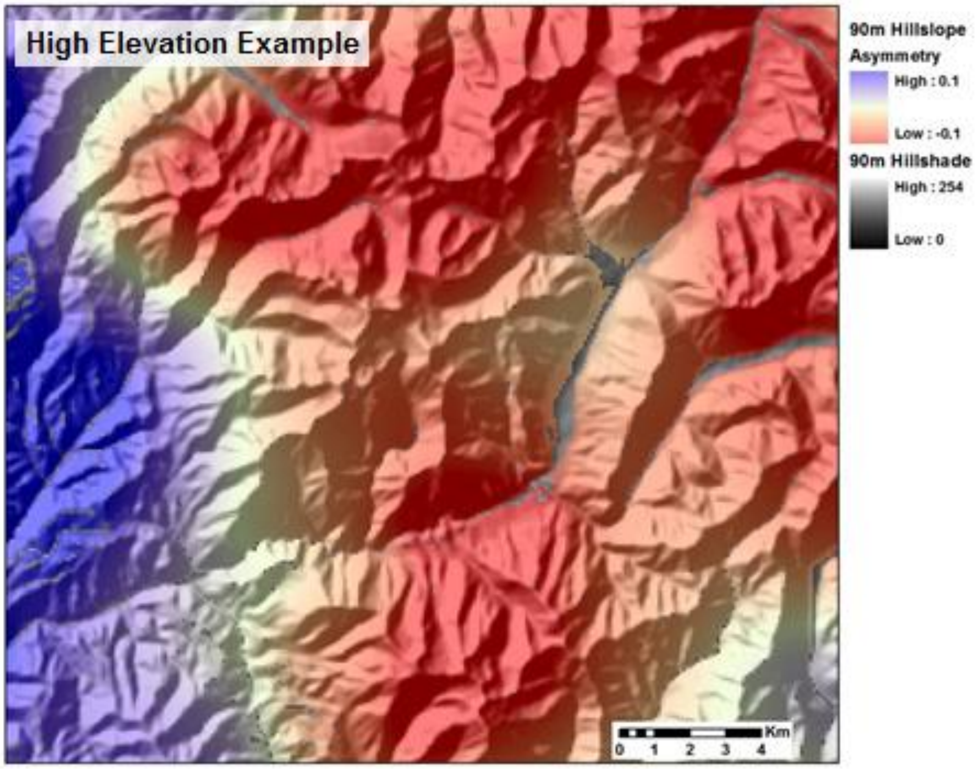

Figure B.23. Hillslope asymmetry map over hillshade at 90 m for high elev.

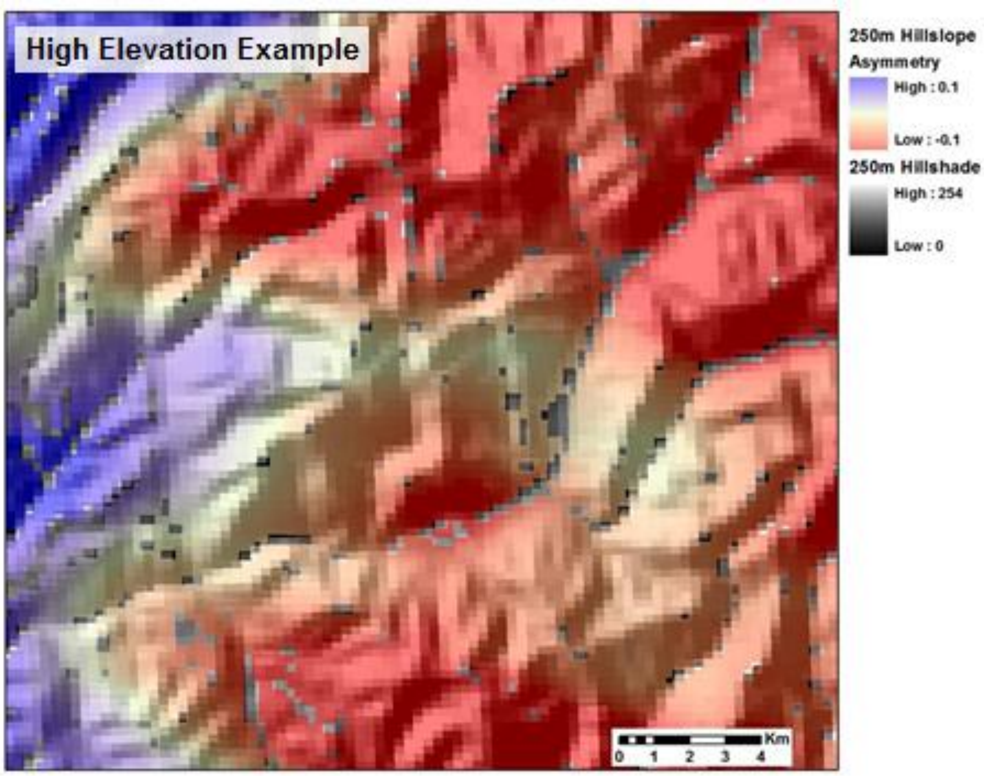

Figure B.24. Hillslope asymmetry map over hillshade at 250 m for high elev.

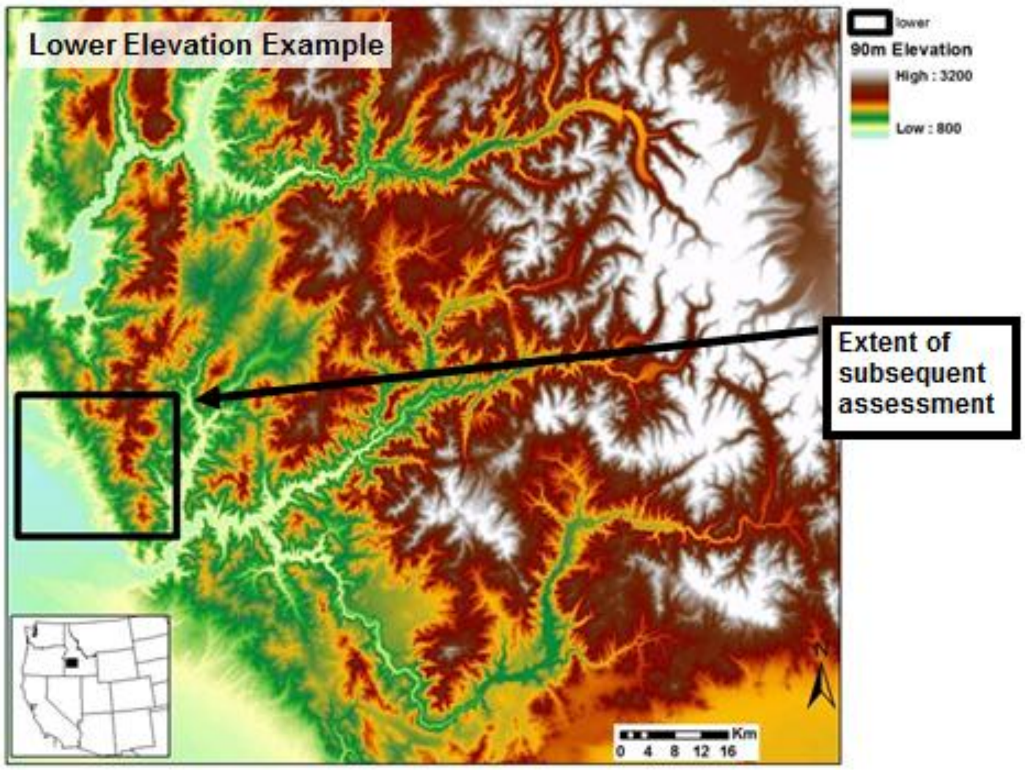

Figure B.25. Location of subsequent nine figures in the Idaho Batholith.

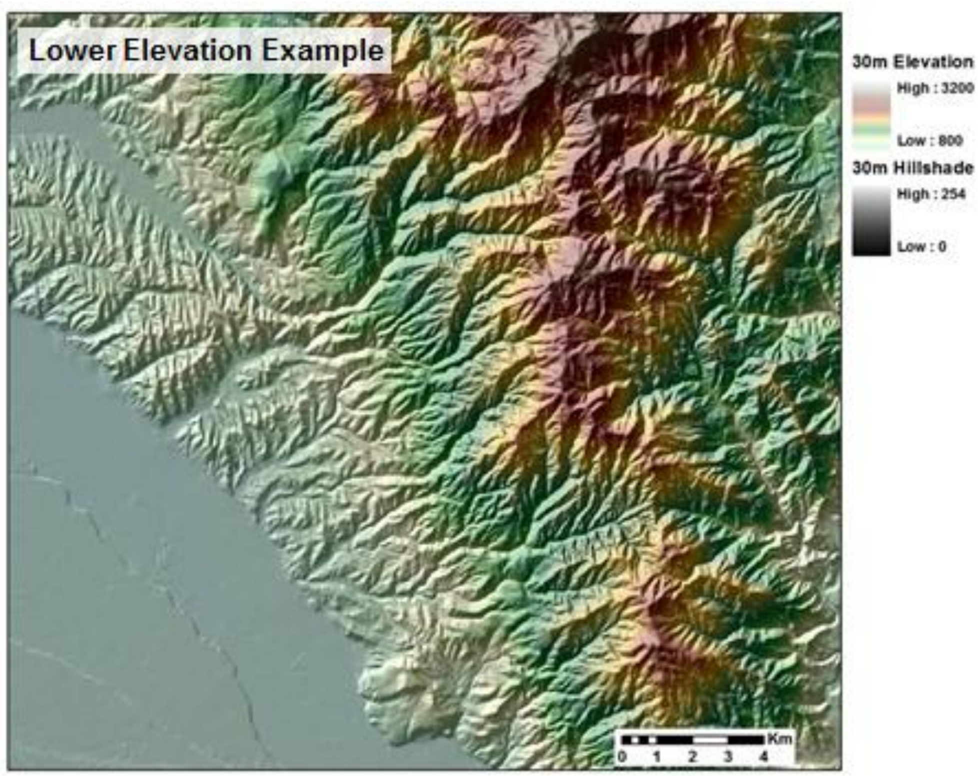

Figure B.26. Elevation draped hillshade at 30 m for low elevations.

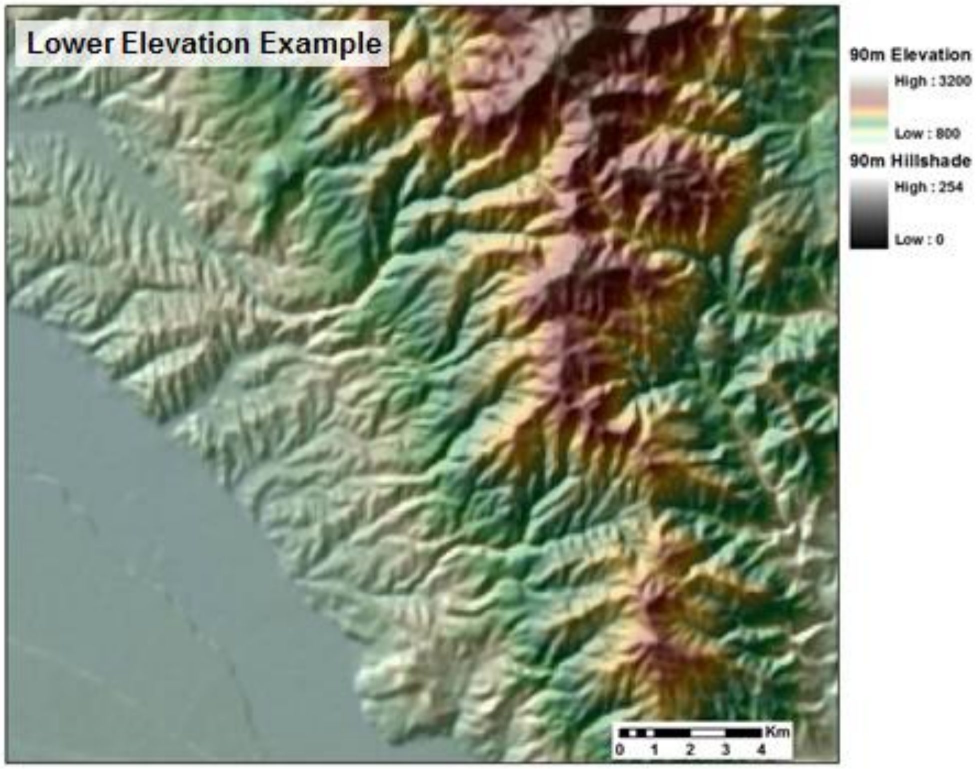

Figure B.27. Elevation draped hillshade at 90 m for low elevations.

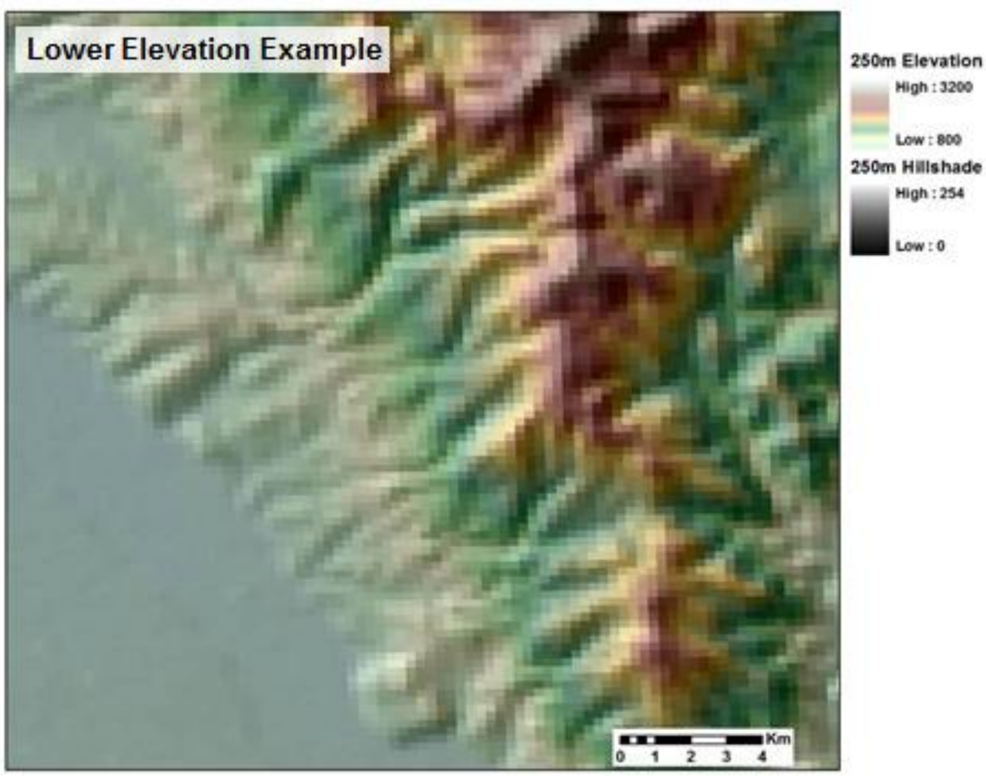

Figure B.28. Elevation draped hillshade at 250 m for low elevations.

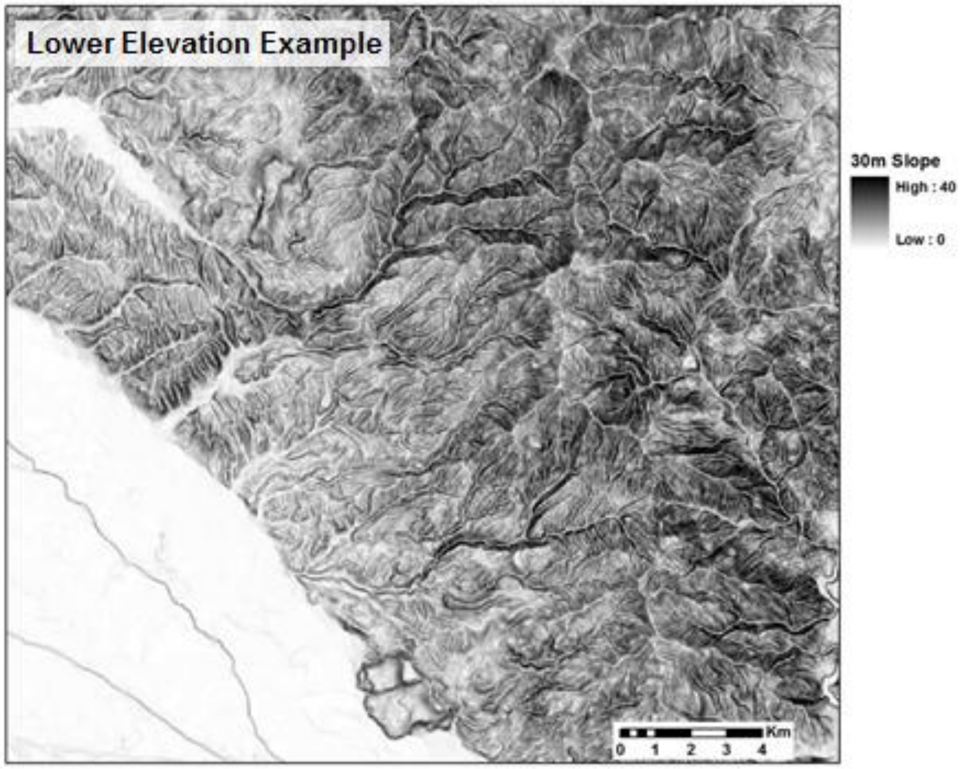

Figure B.29. Slope-shaded raster at 30 m for low elevations.

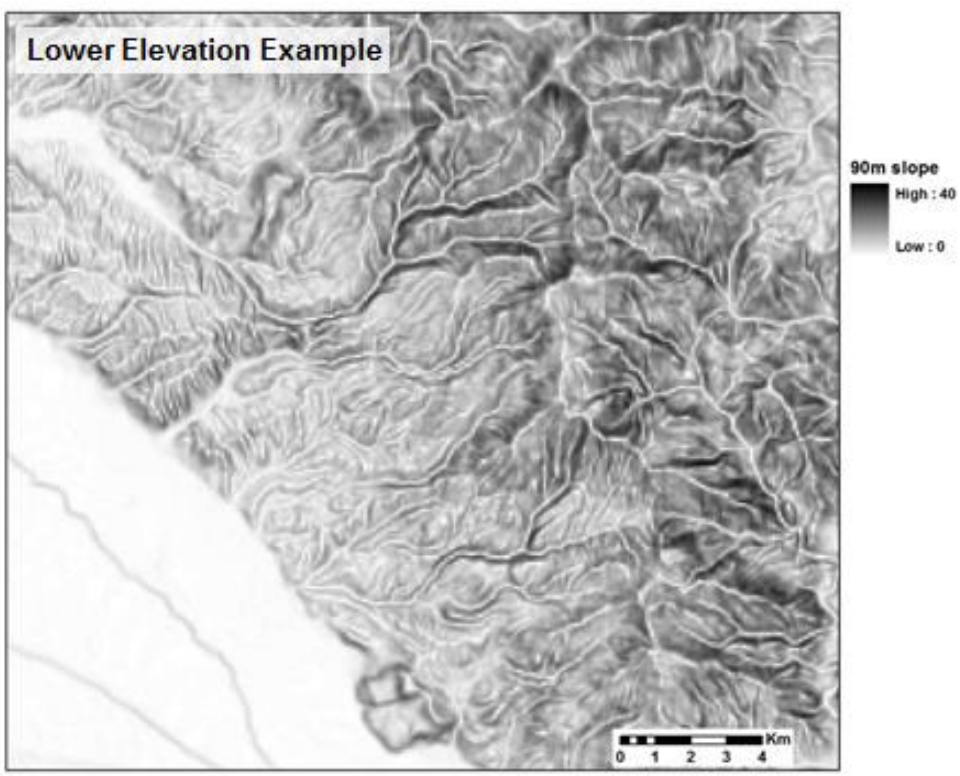

Figure B.30. Slope-shaded raster at 90 m for low elevations.

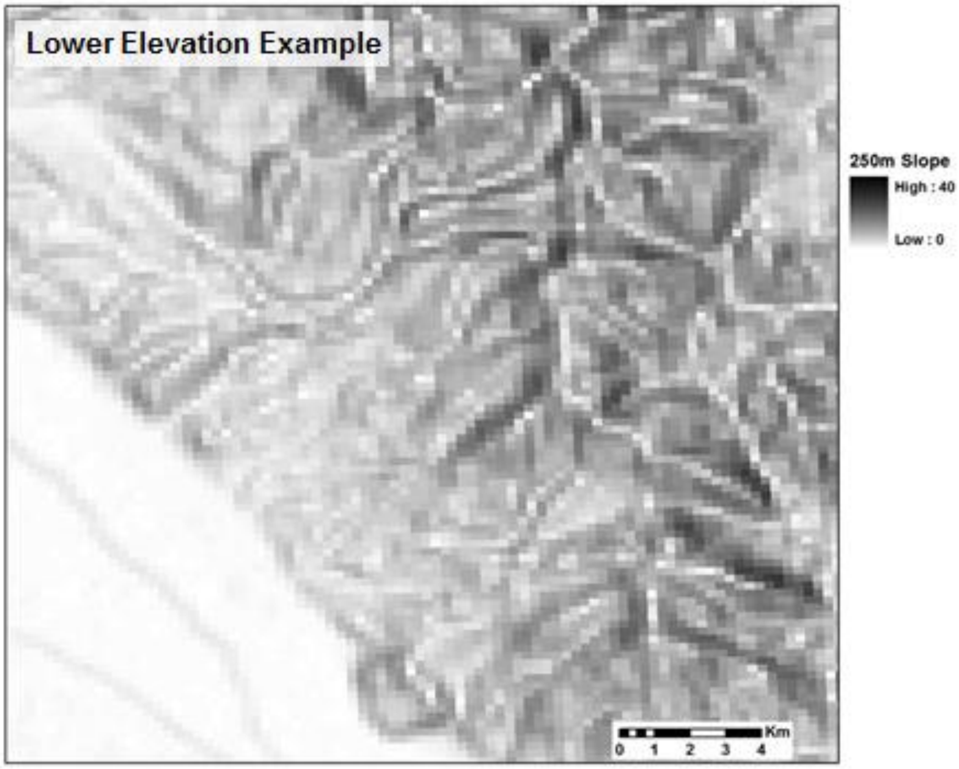

Figure B.31. Slope-shaded raster at 250 m for low elevations.

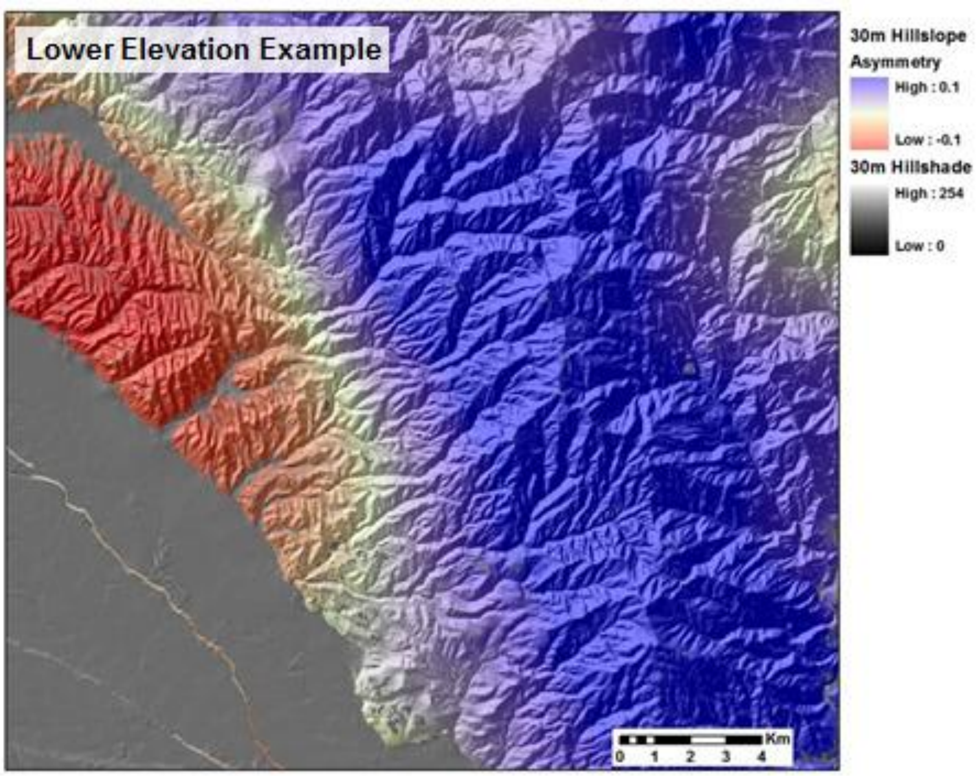

Figure B.32. Hillslope asymmetry map over hillshade at 30 m for low elev.

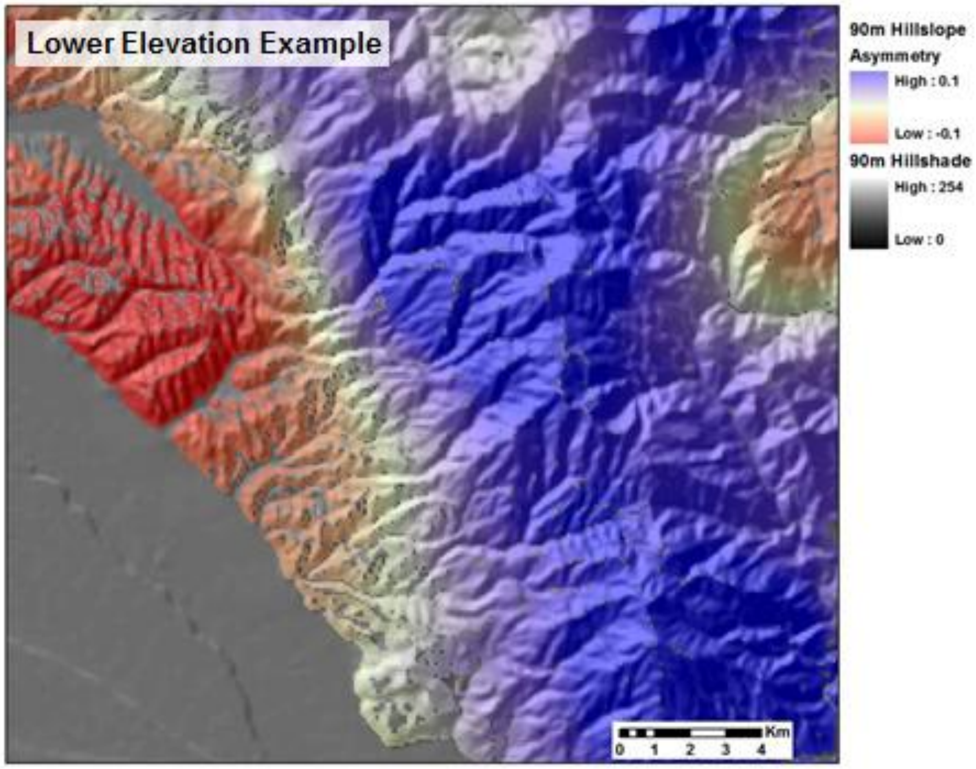

Figure B.33. Hillslope asymmetry map over hillshade at 90 m for low elev.

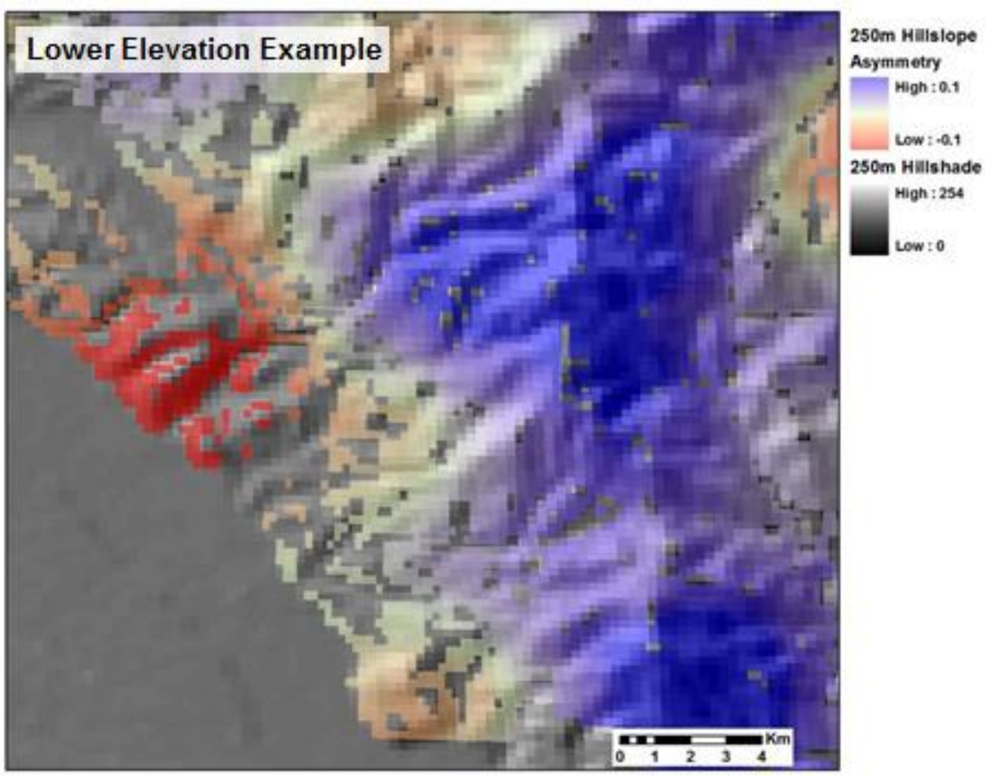

Figure B.34. Hillslope asymmetry map over hillshade at 250 m for low elev.