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Multi-scale curvature for automated identification of glaciated mountain landscapes

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ABSTRACT

Erosion by glacial and fluvial processes shapes mountain landscapes in a long-recognized and characteristic way. Upland valleys incised by fluvial processes typically have a V-shaped cross-section with uniform and moderately steep slopes, whereas glacial valleys tend to have a U-shaped profile with a changing slope gradient. We present a novel regional approach to automatically differentiate between fluvial and glacial mountain landscapes based on the relation of multi-scale curvature and drainage area. Sample catchments are delineated and multiple moving window sizes are used to calculate per-cell curvature over a variety of scales ranging from the vicinity of the flow path at the valley bottom to catchment sections fully including valley sides. Single-scale curvature can take similar values for glaciated and non-glaciated catchments but a comparison of multi-scale curvature leads to different results according to the typical cross-sectional shapes. To adapt these differences for automated classification of mountain landscapes into areas with V- and U-shaped valleys, curvature values are correlated with drainage area and a new and simple morphometric parameter, the Difference of Minimum Curvature (*DMC*), is developed. At three study sites in the western United States the *DMC* thresholds determined from catchment analysis are used to automatically identify 5 × 5 km quadrats of glaciated and non-glaciated landscapes and the distinctions are validated by field-based geological and geomorphological maps. Our results demonstrate that *DMC* is a good predictor of glacial imprint, allowing automated delineation of glacially and fluvially incised mountain landscapes.

1. Introduction

The effect of glacial processes on the geometry of mountain landscapes has been studied since the 19th century and large scale features of alpine glaciation like cirques, hanging valleys, and U-shaped valley cross sections have been described and investigated by generations of geologists. The now-conventional interpretation of U-shaped glacial and V-shaped fluvial valleys probably originated in 1872, when Swiss geologist Franz Joseph Kaufmann concluded that round-bottomed valleys owe their form to glacial erosion (Kaufmann, 1872). In North America, Clarance King recognized the cross-sectional U-shape of the upper valleys in the glaciated district of the Uinta Mountains, Utah and the V-shaped profiles below, and attributed these differences to the effect of glacial erosion (King, 1878). William Morris Davis compiled a variety of morphologic attributes of glaciated mountain landscapes and presented hand-drawn illustrations of V-shaped and U-shaped valleys (Davis, 1906). For decades, consensus on this basic distinction between fluvially and glacially carved valleys was primarily based on a plethora of similar qualitative reports, rather than on quantified and measurable attributes.

Quantitative descriptions of valley cross profiles can capture the essence of valley morphology and provide an effective tool to differentiate between valleys formed by different processes (Li et al., 2001). Two principal models are widely used to achieve mathematical approximation of glacial valley transects: a power law adopted by Svensson (1959) and a second-order polynomial first applied by Wheeler (1984). Both approximations show advantages and limitations in depicting valley cross profiles. Power laws have more potential for understanding cross-sectional shape, whereas quadratic equations offer a more robust description (Harbor and Wheeler, 1992; Li et al., 2001).

In geomorphometry, referred to as quantitative land surface analysis based on digital terrain models (Hengl and Reuter, 2009), polynomials are fitted to a regular neighborhood of grid cells (e.g., a kernel of 3 × 3 cells) to calculate land surface parameters (LSPs) like slope and curvature. For curvature calculation, two approaches are widely used. Second order polynomials have been proposed by Evans (1972), and partial fourth order polynomials were adapted by Zevenbergen and Thorne

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(1987). The lower order approach is incorporated in the geographic information system Landserf for multi-scale LSP calculation (Wood, 1996). Although mathematical approximation of valley cross sections by power laws or polynomials is widely used (Graf, 1970; Doornkamp and King, 1971; Augustinus, 1992; James, 1996; Schrott et al., 2003), to our knowledge, quantification of cross-sectional valley shape has never been done based on mathematical approximation of the three dimensional land surface instead of a two dimensional cross section. The advantages of a three dimensional approach would be automation, spatially continuous instead of discrete results, and the potential for automated mapping of glaciated valleys.

Identifying the location of recent and past glaciated areas has been an integrated part of glaciology since Agassiz (1840), and plays a crucial role in understanding climate variations and landscape evolution. Presence and extent of Pleistocene glaciation have been mapped throughout the globe, but knowledge is still incomplete in some regions (Ehlers and Gibbard, 2004; Ehlers et al., 2011), and consensus remains elusive in others (Gualtieri et al., 2000; Grosswald and Hughes, 2002; Owen et al., 2008). In addition, evidence for glacial remains on Mars is extensively investigated, and controversial, in planetary science (Head et al., 2003, 2010). Although the importance of glacial mapping is undoubted, implications of automated approaches are widely lacking and existing investigations reveal several drawbacks. d'Oleire-Oltmanns et al. (2013) developed a simple semantic model for automated delineation of drumlins and tested their approach in Bavaria. Agreements between mapped and reference landforms were satisfactory, but the study area covered only about 40 km^2 and did not include large variations in landform development. Sternai et al. (2011) introduced hypsokyrtomes, a specified derivative of hypsometric curves, to identify the regional glacial imprint of mountain ranges. While their results are promising, *a priori* knowledge about an important variable of glaciation, the mean long-term equilibrium line altitude (ELA), is a prerequisite to apply their approach.

Here we present and test a novel method to automatically identify glaciated mountain landscapes based on digital land surface analysis. We exploit the conventional wisdom of U-shaped and V-shaped valleys to gain simple geomorphometric semantics and identify glacial imprint in three mountain ranges across the western United States. Continuous DTMs are segmented into regular quadrangles of identical size, and finally those quadrangles are classified. We first investigate differences in multi-scale curvature of sample catchments revealing well-established fluvial and glacial morphology to define threshold values for differentiation. We then apply these thresholds to the study areas and validate our results using field mapping from prior studies. Our methodology is designed to identify glaciated valleys in a regional manner and to assign fluvially incised valleys and flat terrain to the general class *non-glaciated*.

2. Study areas

We test our approach in three study areas in the west of the United States: Sawtooth Mountains, southern Sierra Nevada and Olympic Mountains (Fig. 1). These mountain ranges were selected to test the performance of the approach presented below because of: 1) extensive Pleistocene glaciation; 2) no or very limited recent glaciation; 3) presence of proximal fluvially incised terrain not affected by glaciation; and 4) availability of field mapping of LGM extent or glacial remains for validation.

2.1. Sawtooth Mountains and southern Salmon River–Boise Mountains

The Sawtooth Mountains and their western drainages in the southern Salmon River–Boise Mountains area (Fig. 1) primarily consist of Cretaceous biotite granodiorite of the Idaho Batholith and Eocene biotite or hornblende-biotite granite of the Challis magmatic complex. A large block of metamorphic rocks of possible Precambrian age occurs near Stanley Basin (Reid, 1963). Northwest-striking faults of Miocene age and younger caused strong uplift of the rocks underlying the Sawtooth Range. Of these ruptures, only the Sawtooth Fault, an active, range-bounding normal fault on the eastern flank of the Sawtooth Mountains, is known to have had major movement within the last 130 ka (Breckenridge et al., 2003).

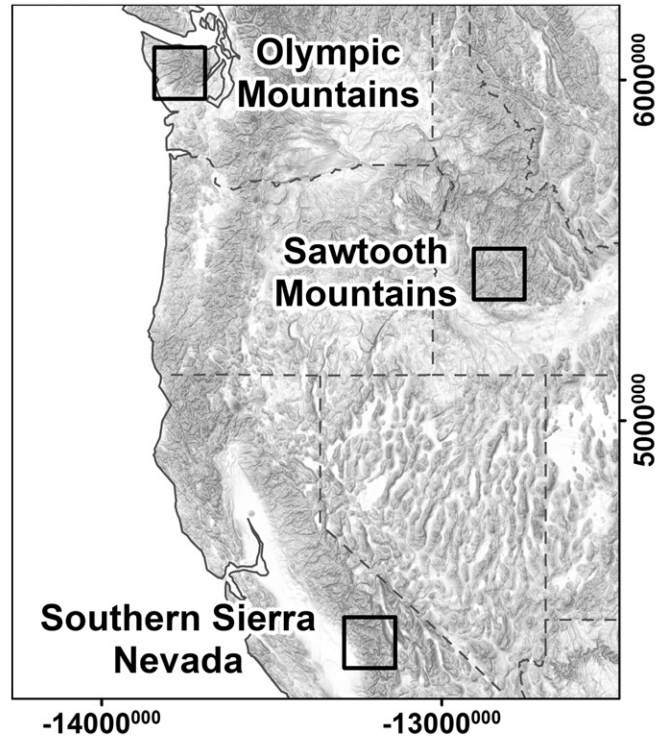

Fig. 1. Location of study areas. Spatial reference: WGS84/World Mercator (EPSG 3395).

Extensive valley glaciers developed in the Sawtooth Range during the Pleistocene, fostered by moist Pacific air masses traversing central Idaho and encountering the mountain barrier (Thackray et al., 2004). Well-developed glacial landforms including deep valley troughs and high jagged peaks are abundant (Reid, 1963; Stanford, 1982; Borgert et al., 1999). However, the western part of the study area has not been affected by glaciers, but shows extensive fluvial relief (Amerson et al., 2008) qualifying for an ideal study site to test our approach. Reconstructed late Pleistocene ELA from Meyer et al. (2004) is used for validation of automated classification results. The ELA rises eastward across the study area from about 2250 to 2650 m. Maps of glacial deposits provide additional validation data (Stanford, 1982; Borgert et al., 1999; Kiilsgard et al., 2001, 2006; Thackray et al., 2004).

2.2. Southern Sierra Nevada

The southern Sierra Nevada study area is located in California; about 150 km from the Nevada border (Fig. 1). It extends east–west from Great Basin to Central Valley and from Kings Canyon in the north to Kern Peak in the south. Large sections of the study area belong to Kings Canyon and Sequoia National Park. The bedrock is dominated by granite of Jurassic–late Cretaceous plutons of the Sierra Nevada Batholith (Moore, 1981; Moore and Sisson, 1985). The physiographic history of the area now occupied by the Sierra Nevada remains controversial. Until recently, consensus was that uplift, mainly caused by westward block tilting of the entire range, occurred in several episodes over the last 10 Ma and produced the present elevation only in the Quaternary Period. Alternatively, recent studies argue that the Sierra Nevada was uplifted in the late Mesozoic and remained high or even subsided in the late Cenozoic (Henry, 2009).

The Sierra Nevada was repeatedly glaciated during the climatic fluctuations of the Pleistocene, and Wahrhaftig and Birman (1965) and