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Landscape response to tipping points in granite weathering: The case of stepped topography in the Southern Sierra Critical Zone Observatory

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ABSTRACT

The dynamics of granitic landscapes are modulated by bimodal weathering, which produces patchy granular soils and expanses of bare rock ranging from meter-scale boulders to mountain-scale domes. We used terrain analysis and with cosmogenic nuclide measurements of erosion rates to quantitatively explore Wahrhaftig's decades-old hypothesis for the development of "stepped topography" by differential weathering of bare and soil-mantled granite. According to Wahrhaftig's hypothesis, bare granite weathers slower than soil-mantled granite; thus random erosional exposure of bare rock leads to an alternating sequence of steep, slowly weathering bedrock "steps" and gently sloped, but rapidly weathering, soil-mantled "treads." Our investigation focused on the terrain surrounding the Southern Sierra Critical Zone Observatory (CZO), which is underlain by granitic bedrock and lies outside the limits of recent glaciation, in the heart of the stepped topography described by Wahrhaftig. Our digital terrain analysis confirms that steep steps often grade into gentle treads, consistent with Wahrhaftig's hypothesis. However, we observe a mix-and-match of soil and bare rock on treads and steps, contrary to one of the hypothesis' major underpinnings – that bare rock should be much more common on steps than on treads. Moreover, the data show that bare rock is not as common as expected at step tops; Wahrhaftig's hypothesis dictates that step tops should act as slowly eroding base levels for the treads above them. The data indicate that, within each landscape class (i.e., the steps and treads), bare rock erodes more slowly than surrounding soil. This suggests that the coupling between soil production and denudation in granitic landscapes harbors a tipping point wherein erosion rates decrease when soils are stripped to bedrock. Although broadly consistent with the differential weathering invoked by Wahrhaftig, the data also show that steps are eroding faster than treads, undermining Wahrhaftig's explanation for the origins of the steps. The revised interpretation proposed here is that the landscape evolves by back-wearing of steps in addition to differential erosion due to differences in weathering of bare and soil-mantled granite.

1. Introduction

Granitic landscapes are often bimodal, with patchy soil and adjacent bare rock ranging in extent from meter-scale boulders to mountain-scale domes. Cosmogenic nuclide data have shown that bare granitic bedrock tends to erode more slowly than the surrounding soil-mantled terrain (e.g., Granger et al., 2001; Small et al., 1999), presumably because of differences in moisture retention (Wahrhaftig, 1965) and biologically driven differences in weathering intensity (e.g., Roering et al., 2010). This suggests that the coupling between soil production and denudation in granite landscapes can harbor a crucial tipping point, such that weathering and erosion are as bimodal as the appearance of the landscape surface (Granger et al., 2001). For example, if soils are stripped to bedrock, weathering rates may decrease, thus restraining soil formation and erosion to the point that bare rock can persist and rise in relief relative to surrounding soil-mantled terrain. To the extent that this mechanism is manifested in landscapes, it has implications for predicting landscape response to climate change, quantifying the sustainability of soils and ecosystems, and modeling landscape evolution.

Although studies have increasingly documented erosion-rate discrepancies between bare and soil-mantled granite (Granger et al., 2001; Small et al., 1999), comparatively few have quantified how such differences factor into shaping landscapes and the ecosystems they support. Nevertheless, in 1965, long before the advent of cosmogenic nuclide methods for measuring erosion rates,

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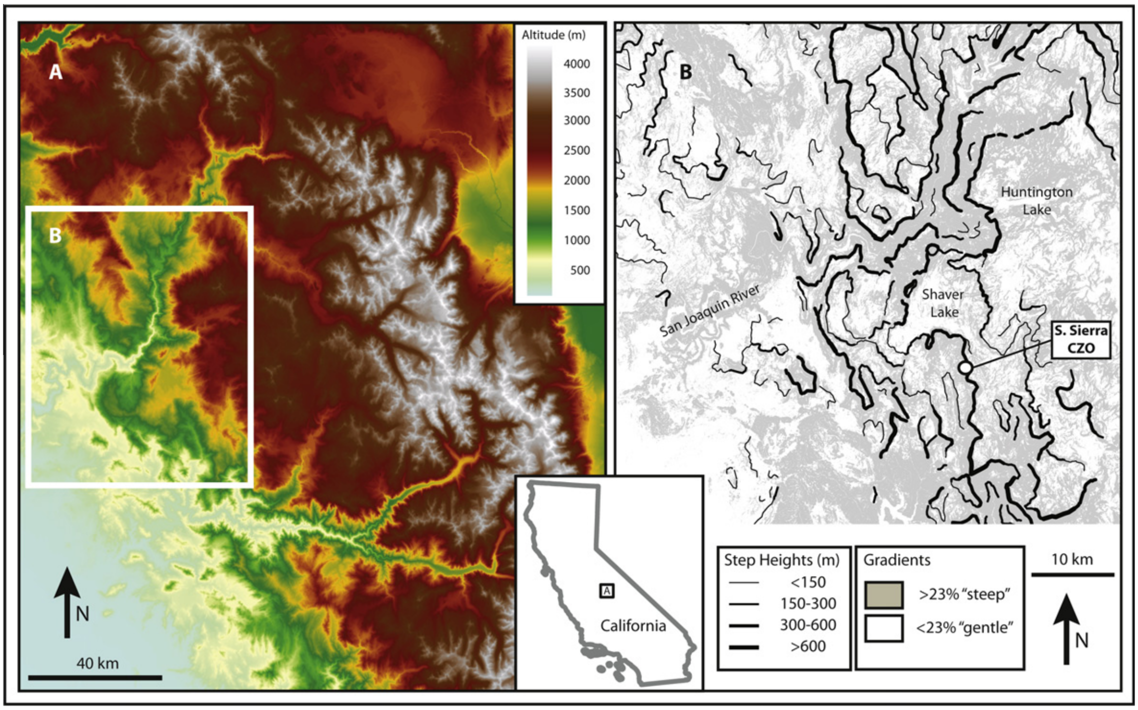

Fig. 1. Study site location map with insets for color-shade topography (A) and distribution of steep and gentle terrain (B). Spatial distribution of steep (gray) and gentle (white) terrain (B) in the area mapped by Wahrhaftig (1965) as the heart of the stepped topography. The distribution of slopes is suggestive of a stepped landscape wherein patches of gentle terrain (or "treads") alternate with bands of steep slopes (or "steps"). Lines are digitized step fronts, as mapped by Wahrhaftig (1965). Variations in thickness correspond to variations in step front height.

Wahrhaftig (1965) proposed that a tipping point in granite weathering might be a first-order regulator of landscape evolution in regions underlain by granitic bedrock. According to Wahrhaftig's (1965) hypothesis, contrasts in erodibility between bare and soil-mantled granite can generate "stepped topography," wherein steep, mostly bare, "steps" alternate with gentle, soil-mantled, "treads." Such steps and treads were attributed by Wahrhaftig (1965) to account for the first ~2000 m of relief in the granitic portions of the southern Sierra Nevada, California.

Although Wahrhaftig's (1965) hypothesis embodies a compelling conceptual model of weathering-driven evolution of mountainous landscapes, it was difficult to test quantitatively in 1965 because it predated cosmogenic nuclide methods and the computational advances needed for systematic terrain analysis. Here we tested several aspects of Wahrhaftig's (1965) hypothesis about how weathering-related tipping points affect landscape evolution using GIS-based terrain analysis and denudation rates inferred from cosmogenic nuclides in stream sediment and exposed rock (e.g., Granger and Riebe, 2007). Our investigation focused on the terrain surrounding the Southern Sierra Critical Zone Observatory (CZO), which is underlain by granitic bedrock, outside the limits of recent glaciation, in the heart of Wahrhaftig's "stepped topography" (Fig. 1). The landscape is loosely organized into range-parallel (i.e., NW-trending) ridges and valleys, with each ridge higher than the next as viewed from SW to NE (perpendicular to the range axis). The observation of range-parallel ridges is one of the foundations of Wahrhaftig's (1965) claim that the landscape is "stepped," with each successive ridgetop representing the leading edge of the next higher "tread."

Based on Wahrhaftig's (1965) hypothesis, we expected several additional observations to emerge from our analysis. Firstly, throughout the study area, the landscape should exhibit a dichotomy of steep and gentle terrain, with roughly range-parallel bands of steep "steps" separating gentle "treads" at many scales (from hundreds of meters to kilometers). Secondly, steep areas should be bare, especially at the tops of step risers, where they transition into gentle treads. According to Wahrhaftig (1965), the bare tops of steps are slowly eroding base levels for adjacent soil-mantled treads. Hence, a third expectation based on Wahrhaftig's (1965) hypothesis for development of stepped topography is that steps should be eroding more slowly than treads and thus act as broad "knick zones" that dominate both the evolution and appearance of the western flank of the range.

2. Results and discussion

2.1. Is the "stepped topography" really stepped?

To distinguish between steps and treads, we divided the landscape into steep and gentle terrain using a threshold slope of 23%, derived from analysis of slopes in areas that Wahrhaftig (1965) designated as representative examples of steps and treads. The resulting distribution of steep and gentle terrain (Fig. 1) is suggestive of a stepped landscape wherein patches of gentle terrain (or "treads") alternate with bands of steep slopes (or "steps") along a trend perpendicular to the range axis.

To gauge the scale of these steps and treads, we used region analysis to group clusters of steep and gentle terrain according to whether adjacent cells hold the same value (either "steep" or "gentle"). The results show that groups of steep and gentle terrain span a range of scales, from hundreds of m^2 to tens of km^2. Thus, overall, the analysis is consistent with a landscape organized into an alternating sequence of steep and gentle terrains across a range of scales.

2.2. Does the stepped topography result from a tipping point in granite weathering?

If Wahrhaftig's (1965) proposed tipping point in weathering is responsible for generating stepped topography, we should see (i)

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that granite outcrops are eroding slower than the surrounding soil, and (ii) that steps are typically bare, especially at step tops, which (according to the hypothesis) act as base levels for the treads above them. To quantify whether step tops are typically bare, we coupled the analysis of slopes (Fig. 1) with an analysis of ground cover (whether it is soil mantled or exposed rock) to estimate the areal distribution of four landscape classes: bare steps, bare treads, soil-mantled steps, and soil-mantled treads. Although preliminary, the results suggest that bare treads are nearly as common as bare steps, contrary to Wahrhaftig's (1965) assertion that bare terrain is concentrated on steep steps. Moreover, bare steps are much rarer than expected given that bare step tops should be acting as erosional base levels for adjacent treads. Indeed, bare rock crops out at the crucial transitions between steps and treads (at step tops) as often as it does elsewhere on the landscape. In other words, the exposure of bare rock appears to be random among the steps and treads – and thus not functionally tied to whether the terrain is steep or gentle. This is inconsistent with Wahrhaftig's (1965) assertions about the occurrence of bare granite on steps and treads.

Cosmogenic nuclide-based erosion rates span more than an order of magnitude across the four landform classes identified above. On both steps and treads, bare rock outcrops erode more slowly than their soil-mantled counterparts, consistent with the working hypothesis that landscape evolution is influenced by the proposed tipping point in granite weathering. However, erosion rates are fastest on soil-mantled steps, and, although erosion rates are similar on bare steps and soil-mantled treads, on average, the steps erode more quickly than treads. Bare treads exhibit the slowest erosion rates of all, eroding more than an order of magnitude slower than the fastest eroding soil-mantled steps. Hence the pattern of erosion rates is one in which steps erode more quickly than treads, in direct contradiction to Wahrhaftig's (1965) hypothesis.

3. Conclusions

Wahrhaftig's (1965) characterization of topography in the southern Sierra Nevada is largely validated by the terrain analysis presented here. The landscape appears to be organized into an alternating sequence of variably scaled steep steps and gentle treads that, overall, account for the first ~2000 m of the relief in the range. However, our analysis thus far fails to confirm Wahrhaftig's (1965) observation that step tops are commonly bare and thus act as erosional base levels for adjacent treads. Moreover, the cosmogenic nuclide data show that, on average, steps erode more quickly than treads, seriously undermining Wahrhaftig's (1965) explanation for the origins of the steps. Rather than acting as stationary erosional base levels for the treads above them, the steps appear to be wearing back into the treads at several tens of meters per million years. Nevertheless, the results also indicate that, within each landscape class (i.e., steps and treads), bare rock erodes more slowly than the surrounding soil. This leads to a revised conceptual model in which the stepped topography of the southern Sierra Nevada evolves by back-wearing of steps (Penck, 1924) in addition to differential erosion due to differences in weathering of bare and soil-mantled granite (Wahrhaftig, 1965).

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