Exploring links between vadose zone hydrology and chemical weathering in the Boulder Creek critical zone observatory

Abigail L. Langston, Gregory E. Tucker, Robert S. Anderson, Suzanne P. Anderson

Department of Geological Sciences and Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado, Boulder, CO 80309, USA
Institute for Arctic and Alpine Research (INSTAAR) and Department of Geological Sciences, University of Colorado, Boulder, USA
Institute for Arctic and Alpine Research (INSTAAR) and Department of Geography, University of Colorado, Boulder, USA

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ABSTRACT

Understanding the relationship between subsurface flow paths on hillslopes and chemical weathering of bedrock is fundamental to understanding the timing and mechanisms that weather bedrock to saprolite. The link between chemical weathering of bedrock and contact time with reactive water along flow paths motivates this study. Water drives the chemical alteration of rock into saprolite, yet connected porosity generally declines with depth into the weathered profile. Saprolite formation, therefore, reflects coupled weathering and permeability development over time. This study uses numerical modeling and soil–moisture monitoring to explore the hydrology of the unsaturated zone and the influence of fracture density, hillslope gradient, and permeability contrasts within the saprolite development horizon on saprolite development.

1. Background

This study focuses on the saprolite formation in the Boulder Creek watershed, Colorado, USA, a 1160 km² area which reaches from the Continental Divide to the Great Plains and ranges in elevation from 4120 m to 1480 m. Three smaller instrumented watersheds within the Boulder Creek watershed represent three different environments in the larger basin: a high alpine watershed, a sub-alpine watershed, and a watershed influenced by the incision of Boulder Canyon. The Boulder Creek watershed is underlain by fractured Precambrian granodiorite and metamorphic rocks. Saprolite, bedrock that has been chemically altered but not moved, represents a transition phase between fresh bedrock and soil. The thickness of the saprolite in the Boulder Creek watershed ranges from zero to tens of meters. The mechanisms and rate of saprolite development have an impact on soil thickness, critical zone hydrology, and the distribution and mobility of regolith on hillslopes. Understanding the spatial and temporal development of saprolite will not only provide insight into the future of critical zone processes, but may provide a view of saprolite formation throughout the recent geologic history of the Boulder Creek watershed.

2. Results

In an attempt to understand the role of hydrology in saprolite development, 2D numerical calculations of flow were performed in the vadose zone of an idealized pair of hillslopes whose topography and subsurface properties are typical of hillslopes in the Boulder Creek drainage basin. The US Geological Survey numerical model VS2DT computes the water content and flux in the unsaturated zone in response to a sequence of recharge events, representing spring snowmelt pulses. The model hillslopes are covered with a layer of relatively high hydraulic conductivity soil and underlain by lower hydraulic conductivity saprolite which is cut through by representative cracks. The model hillslopes were subjected to varying hydrologic conditions which represented a north-facing slope and a south-facing slope in a sub-alpine watershed: repeated, small snow melt events on the south-facing slope and a single large, sustained melt of the seasonal snow pack on the north-facing slope.

The goal of these calculations was to determine under which circumstances water reaches saprolite deep below the surface, in an effort to identify the necessary and sufficient conditions for forming the deep pockets of saprolite that are observed at road cuts throughout the watershed. The calculations imply that the timing of precipitation strongly affects the routing of the water at the soil–saprolite interface. Small precipitation events result in vertical flow into the hillslope; however, as the soil nears saturation, lateral water flow along the soil–saprolite interface becomes
the dominant flow path. Volumetric moisture content (VMC) in the saprolite increases along this interface, but the largest increase in VMC in the saprolite occurs at the base of fractures imposed on the saprolite and at the convergence of the two hillslopes, below the stream channel.

3. Discussion and conclusions

The timing and rate of precipitation on hillslopes seems to control vertical flow paths into the soil or lateral flow paths within the soil on the soil–saprolite interface. This suggests that both climate and aspect are factors in saprolite development. Repeated small snow melt events followed by periods of evapotranspiration over the snow season leads to less water at depth in the saprolite, regardless of the aspect of the hillslope.

The results of the model calculations suggest that fracture networks in saprolite and bedrock are important avenues for moving water from the surface into rock. Where fracture networks are dense or have larger than average apertures, a significant amount of water can be routed into deep bedrock. This implies that blocks of bedrock bounded by fractures may chemically weather at a faster rate than areas with fewer fractures. The prediction of saturated bedrock below stream channels does not come as a surprise, but viewed in the light of water as a chemical reactant, it suggests that weathering rates in the saprolite below stream channels may be faster than elsewhere on the hillslope. This finding points to a need to couple hydrologic models with reactive-transport models to better understand the space–time distribution of chemical weathering intensity.

The importance of fractures on the routing of water and development of saprolite in the unsaturated zone will be explored further through chemical analyses of selected samples of soil, saprolite, and bedrock collected along road cuts. These analyses will determine whether the weathering rate increases systematically with fracture density and fracture aperture.