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Quantifying regolith production rates with Uranium-series isotopes at Shale Hills Critical Zone Observatory: implications for chemical weathering and landscape evolution

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Quantifying regolith production rates is essential in understanding many important Earth's surface processes such as nutrient cycling, carbon sequestration, erosion, and acid rain mitigation. Over the long term, the rates of weathering and erosion also combine to control the evolution of surface landscapes. Uranium-series isotopes offer a powerful tool to investigate regolith production rates and weathering timescales within a weathering system because of their well-documented fractionation behavior during chemical weathering and transport by water. To quantify regolith formation rates on shale lithology, we measured U-series isotopes (^{238}U, ^{234}U, and ^{230}Th) in three weathering soil profiles along a planar north-facing hillslope at the Susquehanna Shale Hills Observatory (SSHO) in central Pennsylvania. All regolith samples show significant U-series disequilibrium: (^{234}U/^{238}U) and (^{230}Th/^{238}U) activity ratios range from 0.934 to 1.072 and from 0.903 to 1.096, respectively. These values display depth trends that are consistent with fractionation of U-series isotopes during chemical weathering, i.e., the relative mobility decreases in the order ^{234}U $>$ ^{238}U $>>$ ^{230}Th. The activity ratios observed in the soils are explained by i) loss of U-series isotopes during water-rock interactions and ii) re-precipitation of ^{234}U and ^{238}U downslope.

Regolith production rates calculated with U-series isotopes for these soil profiles decrease systematically with increasing distance from the ridge: from $\sim$45 m/Myr at the ridge top, the highest point along the hillslope, to $\sim$26 m/Myr at the middle slope site, and to $\sim$15 m/Myr at the valley floor. Soil weathering timescales within these profiles range from 7 kyr to 45 kyr, increasing from the ridge to the valley floor. Given that the SSHO experienced peri-glacial climate $\sim$15 ky ago, we conclude that the hillslope retains regolith formed before that glacial period and that the hillslope is not at geomorphological steady state. The regolith production rates at Shale Hills vary as an exponential function of soil thickness. With the local regolith production function at Shale Hills, a hillslope soil transport model is used to predict the landscape evolution and change of soil thickness along the planar transect. The simulation suggests that both the landscape and soil thickness along the planar hillscope at Shale Hills are currently at a transient state.

This research documents that U-series isotopes are powerful tools to constrain the time scales of chemical weathering and to quantify regolith production rates. Regolith production rates at the SSHO should be useful as a reference value for future work at other shale weathering localities. Furthermore, this study also enhances our understanding of the response of regolith production to climate perturbations, and the landscape evolution for this first-order catchment.