Geophysical Research Abstracts
Vol. 20, EGU2018-11572, 2018
EGU General Assembly 2018

Co-evolution of weathering and subsurface flow pathways in hillslopes – insights from hydraulic groundwater theory

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The movement of water through a hillslope is both the result of its internal architecture, and one driver of the evolution of that architecture. Here we will draw on simplified models of geochemical weathering and hillslope hydraulics to develop some basic insights into how flow pathways and the internal architecture of weathering landscapes co-evolve. First we will show how the Dupuit assumptions (contrary to common wisdom) can be used to estimate the lateral and vertical components of water flux through hillslope aquifers. These can be combined with the advection-diffusion-reaction equation to predict the spatial organization of solutes and water age. The results demonstrate that under certain conditions the mere presence of lateral flow will not disturb the lateral symmetry of reaction fronts along the hillslope. As a result the reactive transport equation can then be simplified (under appropriate conditions) into a 1-D vertical formulation that accounts for the partitioning to lateral flow implicitly. We also show that a simple second-order model of weathering reactions has an analytical solution, which when combined with the simplified reactive transport equation can be used to estimate the location of weathering fronts within the Dupuit aquifer. Further elaborations of this model are then made to account for the effect of weathering on permeability, which leads to an enhanced partitioning of water laterally in the vicinity of weathering fronts.

The resulting approximate equations provide a quantitative, physically-reasoned basis for recent arguments regarding the co-evolution of hillslope hydraulic and geochemical architecture. Some have suggested that in landscapes that approach a geomorphic steady-state, flow paths evolve toward an arrangement where they remove minerals of different solubilities at just the right rate, such that the entire landscape denudes uniformly. This leads in some cases to a stratification of physical and chemical weathering fronts, with easily-dissolved minerals removed at depth via the slow movement of groundwater, more resistant minerals through dissolution into more rapid lateral interflow perched at the soil-saprolite transition, and most recalcitrant primary and secondary minerals via physical erosion at or near the surface. The analytical results derived here show that in hillslopes with persistent groundwater tables the stratification of weathering fronts arises naturally even in the absence of permeability contrasts. The overall rate of weathering front advance is found to be primarily determined by the component of flow normal to the weathering front, and only significantly accelerated by the lateral component above the weathering front when parent rock permeability is very low. This hypothesis of a co-evolved hydrologic architecture adapted to the dictates of geochemical and geomorphic processes offers hope that the unknown properties of the landscape that control hydrologic function (the storage and release of water to a stream) are explicable, and potentially predictable, in terms of the long-term evolution of the system.