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Control of topography gradients on residence time distributions, mixing dynamics and reactive hotspot development

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Topography-driven subsurface flows are thought to play a central role in determining solute turnover and biogeochemical processes at different scales in the critical zone, including river-hyporheic zone exchanges, hillslope solute transport and reactions, and catchment biogeochemical cycles. Hydraulic head gradients, induced by topography gradients at different scales, generate a distribution of streamlines at depth, dictating the spatial distribution of redox sensitive species, the magnitude of surface water – ground water exchanges and ultimately the source/sink function of the subsurface. Flow velocities generally decrease with depth, leading to broad residence time distributions, which have been shown to affect river chemistry and geochemical reactions in catchments. In this presentation, we discuss the impact of topography-driven flows on mixing processes and the formation of localized reactive hotspots. For this, we solve analytically the coupled flow, mixing and reaction equations in two-dimensional vertical cross-sections of subsurface domains with different topography gradients.
For a given topography gradient, we derive the spatial distribution of subsurface velocities, the rates of solute mixing accross streamlines and the induced kinetics of redox, precipitation and dissolution reactions using a Lagrangian approach (Le Borgne et al. 2014). We demonstrate that vertical velocity profiles driven by topography variations, act effectively as shear flows, hence stretching continuously the mixing fronts between recently infiltrated and resident water (Bandopadhyay et al. 2017). We thus derive analytical expressions for residence time distributions, mixing rates and kinetics of chemical reactions as a function of the topography gradients. We show that the rates dissolution and precipitation reactions are significantly enhanced by the existence of vertical velocity gradients and that reaction rates reach a maximum in a localized subsurface reactive layer, whose location and intensity depends on topography gradients. As a consequence of these findings, we discuss the links between topography variations, subsurface velocity gradients and biogeochemical processes in the critical zone.

References:
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