

A multiproxy approach ($^{87}\text{Sr}/^{86}\text{Sr}$, $\delta^{44}\text{Ca}$, $\delta^{13}\text{C}_{\text{DIC}}$) for tracking seasonal changes in permafrost dynamics

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Global change predictions indicate the warming will be greatest in the high latitudes, where permafrost soils have historically been a large carbon sink. As temperatures increase, the seasonally thawed active layer will extend downward into previously frozen soils, potentially releasing large quantities of greenhouse gases to the atmosphere, thus accelerating the pace of warming. In addition, dramatic changes in the hydrology and biogeochemistry of Arctic landscapes will result. A better understanding of the dynamics of permafrost thaw is needed to gauge the importance of feedbacks between Arctic warming and global climate change. Conventional methods for probing the depth of the active layer are labor intensive and may not address the spatial heterogeneity of Arctic soils. Alternatively, geochemical gradients in permafrost may be harnessed as spatially integrative, natural tracers of the downward movement of the active layer. This study evaluates $^{87}\text{Sr}/^{86}\text{Sr}$, $\delta^{44}\text{Ca}$, and $\delta^{13}\text{C}_{\text{DIC}}$ in stream water as potential tracers of seasonal variations in permafrost thaw.

Surface waters were collected from six watersheds on the North Slope of Alaska between May and October of 2009 and 2010, focusing on early spring thaw through late season freeze-up. All rivers drain continuous permafrost: three drain tussock tundra-dominated watersheds, and three drain bare bedrock catchments with minor tundra influences.

Large interstream variations in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios imply heterogeneity in soil composition across watersheds. However, within individual watersheds, $^{87}\text{Sr}/^{86}\text{Sr}$ ratios vary with changes in discharge, including early season melt, base flow, and large rain events. During periods of high discharge, slightly elevated $^{87}\text{Sr}/^{86}\text{Sr}$ ratios indicate flushing of the shallow soil pool, which has a relatively low carbonate mineral content. $\delta^{44}\text{Ca}$ values in tundra streams decrease during the melt season while $\delta^{44}\text{Ca}$ values in bedrock streams increase. In tundra streams, low $\delta^{13}\text{C}_{\text{DIC}}$ values in the early season indicate silicate weathering. Higher mid- to late-season $\delta^{13}\text{C}_{\text{DIC}}$ values indicate carbonate weathering. Bedrock streams have nearly constant $\delta^{13}\text{C}_{\text{DIC}}$ values and high dissolved sulfate concentrations throughout the year, indicating the significance of sulfuric acid carbonate weathering. In late fall of 2010, $\delta^{13}\text{C}_{\text{DIC}}$ values suggest a shift from sulfuric acid- to carbonic acid-dominated weathering, possibly due to oxygen limitation during active layer freezing. Our initial findings illustrate how seasonal changes in mineral weathering have potential for tracking active layer dynamics.

Model of isotope distribution during water-rock interactions

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Soil particles evolve by contact with weathering agents supplied by meteoritic waters (mainly protons) or produced by the near activity of living organisms (protons, organic acids and ligands). The chemical budget of soil-forming reactions depends primarily on the nature of the parent bedrock but also on the extent and rates of the weathering reactions. The mechanisms and controls of soil particles (trans)formation depend on multi-parametrized and non-linear reactions that are therefore difficult to characterize and even more to model on the basis of chemical composition alone.

In the present study, we developed a general model of isotopic evolution of bulk soil samples in response to progressing weathering reactions. It is based on mass and isotopic budgets and treats the bulk soil evolution as a simple gain-and-loss problem in which soil-forming reactions consist in mineral dissolution (loss) and secondary mineral precipitation (gain) including exchange of matter with the surrounding soil solution. Since dissolution and precipitation reactions have distinct effects on stable isotopic systems (like B, Ca, Li, Mg, Si, and many other metals of intermediate mass), then analyses of bulk soil samples give insights on the degree of soil evolution by comparison with a reference material that can be either the parent bedrock or a deeper soil layer. Adding analyses of the soil solution with knowledge of the water velocity provides additional information on the reaction rates as well as helps distinguishing reactions currently active from those active the past.

Because the water-rock interaction system may rapidly be under-determined, we developed a population-based stochastic search technique based on a modified Particle Swarm Optimization approach (PSO) to solve our system of differential equations. This has the advantage to provide sets of solutions without requiring the precise knowledge of model parameters like isotopic fractionation factors or the relative mass of parent material lost.

The model has been tested with B chemical and isotopic compositions in two soil profiles developed on granitic bedrock from the Strengbach watershed (Vosges Mountains, France) and showing different dissolution/precipitation dynamics. First numerical solutions are consistent with our hydrological and mineralogical knowledge of the two soils. They also clearly show varying intensity of soil-forming reactions with depth in line with the tree roots density or the soil horizons. These results encourage further work coupling isotopes with advanced numerical approaches for investigating water-rock interactions in multi-parametrized systems.