Rocks, fluids, and microorganisms

Probing and modeling mineral interfaces from the laboratory to the field

The chemical transformation of minerals is central to the evolution of the Earth system. Over geologic timescales, rock weathering processes regulate atmospheric CO₂ and climate, drive pedogenesis and generate some bio-essential elements that fuel the development of surface ecosystems. The metabolism of deep biosphere microbial communities is supported by electron transfers at mineral interfaces, while deeper in the lithosphere, fluid confined in nanoporous interfaces exhibits singular properties that can control metasomatism and metamorphic reactions. Common to the understanding of these processes is the need to tackle the functioning of complex fluid-mineral(-microorganism) interfaces by crossing disciplines and scales.

This seminar will highlight three sets of studies conducted in contrasting biogeochemical contexts, investigating the multi-scale properties of reactive mineral interfaces and their effect on rock weathering rates.

First, I will outline results obtained in recent field studies conducted at the soil profile scale at the Watershed Institute (New Jersey) and at the Strengbach catchment critical zone observatory (France). We analyzed the evolution of mineral surface microtopography, in combination with field observations and laboratory experiments, to disentangle the contributions of microorganisms, direct fluid-mineral interactions, and exchange reactions to denudation fluxes. We used high-throughput DNA sequencing methods to identify fungus taxa potentially associated with microbially-driven weathering fluxes.

Moving towards conditions relevant to deeper (hydrothermal) conditions, we investigated the effect of the formation of nm- to µm- thick Si-rich nanoporous layers at fluid-mineral interfaces on the dissolution rates of mm- to cm-scale silicate mineral samples (feldspars). We coupled surface-sensitive synchrotron techniques (X-ray reflectivity and GISAXS) to investigate in situ the textural evolution (porosity, density) of these interfaces and measure their apparent transport properties. The structural evolution of these interfaces was probed in situ using synchrotron pair distribution function analyses. We tested the effect of similar interfacial layers formed at the surface of olivine samples on microbial colonization patterns and microbial weathering by Fe(II)-oxidizing bacteria.

Finally, we used atomic-scale non-equilibrium molecular dynamics simulations to evaluate the transport properties of individual silica nanopores relevant to interfaces observed experimentally. We show that pressure gradients ranging from 0 to 250 MPa, combined with the interaction between salt solutions and nanopore walls, generate electrostatic potential gradients that decrease the apparent permeability of the system, with consequences for transport properties at the porous network scale and for macroscopic dissolution rates.

Overall, our approach and data support emerging efforts to incorporate the effect of interface evolution and microorganisms into reaction transport models, broadly used to evaluate mineral reactivity across scales (µm to km) and disciplines (geosciences, sustainable engineering, environmental science and beyond).