MARS SAMPLE RETURN: THE VALUE OF DEPTH PROFILES

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Introduction: Sample return from Mars offers the promise of data from Martian materials that have previously only been available from meteorites. Return of carefully selected samples may yield more information about the history of water and possible habitability through Martian history. Here we propose that samples collected from Mars should include depth profiles of material across the interface between weathered material on the surface of Mars into unweathered parent rock material. Such profiles have the potential to yield chemical kinetic data that can be used to estimate the duration of water and information about potential habitats on Mars.

Characteristics of depth profiles:

On Earth, soil-forming processes result in distinct horizons and chemical gradients long studied by soil scientists. Soil-forming processes include transformations from one soil component to another; translocations of material laterally or vertically; additions of material; and loss of material, as by leaching. Soil profiles collected on Mars yield the possibility of additional information into similar soil-forming processes on that planet.

In addition, when depth profiles (through soils or through weathering rinds) are characterized by dissolution of a mineral component, these profiles can be used to study weathering kinetics. When soils can be compared to unaltered parent material, elemental and mineralogical changes can be quantified.

Elemental and mineralogical depth profiles are commonly normalized to an assumed immobile element or mineral to account for non-isovolumetric weathering [1]:

$$\tau_{i,j} = \frac{C_{j,w}}{C_{j,p}} \frac{C_{i,p}}{C_{i,w}} - 1 \qquad \text{(Eq. 1)}$$

where $\tau_{i,j}$ is the fraction of mobile element or mineral j lost or gained assuming that element or mineral i is immobile (w and p refer to weathered and parent material respectively) and C is the concentration of the immobile and mobile elements or minerals in the parent and weathered materials. An immobile element can be chosen by using the strain of the profile if bulk density is known. Such a normalized dissolution profile commonly has characteristics shown in the schematic dissolution profile, Figure 1. In two profiles formed on basalt and diabase in Hawaii and Virginia, respectively, such normalized profiles reflect differences in climate and mineralogy (Figure 2). The different meteoric precipitation rates likely play an important role in the difference in depletion of the Na-containing plagioclase mineral (Figure 2).
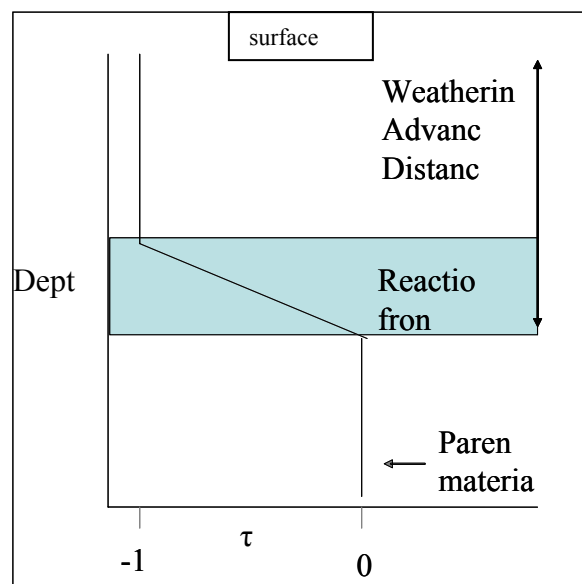

Figure 1. A schematic normalized depth profile from parent material through a weathered surface, showing the reaction front and weathering advance distance.

Kinetic information from depth profiles: Several studies have used chemical/mineral kinetics to study the duration of water on Mars, which is important for the potential habitability of the planet [2-4]. With quantitative chemistry as a function of depth (e.g. Figure 2), information about weathering kinetics can be inferred. Lichtner [5] formulated an analytical solution for the thickness of a reaction front (shown here for a diffusion-dominated front):

$$l = \left(\frac{\phi D}{kA} \right)^{1/2} \qquad \text{(Eq. 2)}$$

where ϕ = porosity, D = diffusivity, k = the reaction rate constant, and A = the mineral-water interfacial area. This equation is strictly true only for weathering of a single-component, single-phase system characterized by linear kinetics [5]. However, it is more generally true that steeper fronts represent slower weathering rates relative to solute transport than shallow fronts.
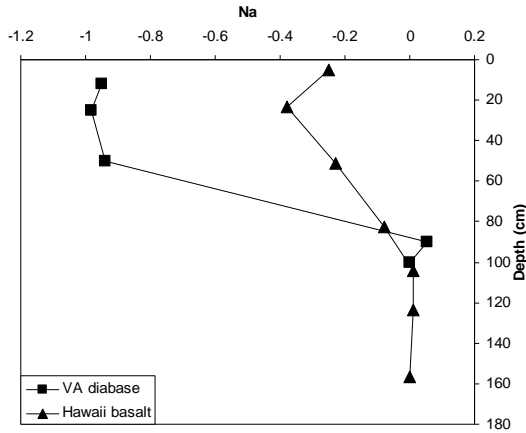
Figure 2. Normalized Na concentrations in soils developed on a diabase in Virginia [6], and a basalt in Hawaii [7]. Na concentrations are normalized to assumed immobile element Ti (Virginia) and Zr (Hawaii). Sodium concentrations are close to parent at depth, and approach a complete loss close to the surface for the Virginia soil, and approximately 40% for the Hawaii soil. These profiles reflect the different climates (MAT=23°C for Hawaii and = 10°C for Virginia, MAP = 180 mm for Hawaii and = 1040mm for Virginia, as well as the different parent materials (diabase for Virginia and basalt for Hawaii). The different precipitation rates likely play a strong role in the different total depletions.

White [8] has used the slope of the weathering gradient (or reaction front) in combination with the weathering advance rate (Figure 1), to calculate surface-area normalized rates from soil profiles using the following equation:

$$R_s = 1000 \frac{\rho_w}{S\beta} \frac{\omega}{b_s} \qquad \text{(Eq. 3)}$$

Here R_s (mol m^{-2}s^{-1}) is the surface-area normalized weathering rate, ρ_w (g cm^{-3}) is the density of weathered material, S (m^2 m^{-3}) is the reactive surface area, β (mol mol^{-1}) is the stoichiometric coefficient for the elemental distribution in a mineral, ω (m s^{-1}) is the weathering advance rate, and b_s (m kg mol^{-1}) is the weathering gradient. If parameters could be sufficiently constrained, such an equation might yield information about the weathering history on Mars.

In addition to analytical solutions such as equations 2 and 3, numerical models CrunchFlow and FLOTRAN have been used to model weathering profiles on Costa Rica basalts [9], California river terraces [10], and Svalbard basalt and the Mars rock Humphrey [4]. Such models, which incorporate geochemical parameters including mineral dissolution rate constants, solubilities, pore water chemistry, parent mineralogy and secondary products, as well as transport, can allow the calculation of duration of weathering [4]. Although such calculations have been performed for one rock on Mars [4], sample collection and return of one or more depth profiles would allow many more parameters to be constrained and different environments studied.

Alteration of the surfaces of Mars rocks analyzed by the Mars Exploration Rovers has occurred over mm scales [11]. Sample return would allow much more detailed characterization of such minimal alteration. Techniques could include Environmental Scanning Electron Microscopy (ESEM), which would allow samples to be observed without coating. Transmission Electron Microscopy (TEM) would yield mineralogical information at the nanoscale, such as the incipient formation of secondary products. Atomic Force Microscopy (AFM) and X-Ray Photoelectron Spectroscopy (XPS) could yield topographic and chemical data of sample surfaces. High-resolution X-ray computed tomography and neutron scattering could be used to study porosity development due to weathering at μm to nm scale on the surfaces of altered Martian rocks returned to Earth.

Stable isotope measurements on secondary products present in the weathering profile may also yield valuable information about the history of water on Mars. For example, oxygen and hydrogen isotopes in phyllosilicates, and oxygen isotopes in carbonates and Fe-oxides have been measured in depth profiles to yield paleoclimatic information on Earth [12-14]. Such measurements could yield valuable information about water interactions and paleoclimate on Mars. In addition, carbon and oxygen isotopes from carbonates and thermal springs have shown to be useful as biosignatures in some terrestrial settings [15].

Conclusions: Depth profiles yield valuable mineral kinetic and chemical flux information on Earth, and, if collected on Mars and returned to Earth could likely yield similarly important information about Mars weathering and habitability. Since weathering on Mars could have occurred under much more water-limited conditions, and potentially for much shorter time-scales than on Earth, weathering profiles and reaction fronts may be much thinner. Sample return may therefore be ideal to measure these fine-scale weathering profiles. Sample return of depth profiles could also yield valuable information about potential habitats and possible biosignatures on Mars.

References:
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