IMPACT GARDENING AS A MECHANISM FOR HYDROTHERMAL ALTERATION AND ATMOSPHERIC EVOLUTION ON NOACHIAN MARS. C. Sanders[1] and R. Wordsworth[1,2], [1]Harvard University Department of Earth and Planetary Sciences, [2]Harvard University John A. Paulson School of Engineering and Applied Sciences.

Introduction: On Noachian Mars, frequent meteor impacts associated with the Late Heavy Bombardment may have led to increased rates of serpentinization and atmospheric evolution. The mechanism is simple: meteor impacts till the planetary crust, filling with it with fractures and effectively increasing the availability of unweathered mafic rock [1, 2, 3]. In the subsurface, fresh rock generated by impacts may interact with fluids from impact-induced melting. Water, pressure, and (Fe,Mg)2SiO4 provide the conditions for serpentinization, a process that generates H_2 and, indirectly, methane[4, 5, 6, 7, 8]. H_2 in turn affects the redox potential of the atmosphere, and can even behave as a greenhouse gas when it is in high enough abundance to collide frequently with background molecules [9, 10].

We present models which test this mechanism, utilizing simple parameterizations of the Martian lithosphere, cryosphere, and atmosphere to demonstrate the possible extent of impact-induced serpentinization and predict the changes in atmospheric chemistry that may have followed. These models consider accepted constraints on Noachian impact rates [11], the depth of the Martian cryosphere [12], and the relationship between impactor size and the mass of shocked material [1]. In addition, we include models for the decay of hydrothermal systems post-impact [13]. Preliminary results suggest that impact-induced serpentinization could not have contributed significantly to the reducing power of the Noachian atmosphere, as impact-generated hydrothermal systems grow dormant too quickly for serpentinization to persist for more than several thousand years. This has implications for early life, not simply because of the melting of large portions of the cryosphere, but because there are extremophilic organisms on Earth who rely on H_2 and other reducing species as a metabolic staple. The possible influences of other impact-induced hydrothermal reactions, as illuminated by impact melt breccias from terrestrial impact sites, are currently under investigation.

Models: $(Fe,Mg)_2SiO_4$ is necessary to produce reduced hydrogen species from H_2O via serpentinization. On Earth, fresh, unweathered iron-magnesium silicates are produced at active mid ocean ridges, so the rate of crustal spreading and the total length of mid ocean ridges limit the rate of serpentinization on geologic time scales [7]. There is a dearth of evidence, however, for plate tectonics in the Martian past, meaning that the active recycling of the crust into the mantle cannot be the source of fresh rock for alteration processes. The Late Heavy Bombardment of the inner solar system by rocky meteors was concurrent with the Noachian on Mars, a time of climatic change and hydrologic activity. We propose that the size distribution and impact frequency of meteors between 4.1 and 3.7 Ga could be analogous to crustal spreading rates on Earth, in that they determine the rate of production of unweathered crust, a limiting reactant for H_2-generating processes like serpentinization, which may have an effect on atmospheric chemistry and climate. Our models utilize the Hartmann's analysis of Martian craters to design a distribution of meteor sizes and size-dependent impact rates that evolve in time [11]. Given this information, we can model the production of fresh, mafic rock in the form of impact-shocked material:

Sleep and Zahnle [1] discuss the implications of higher meteor impact rates in the Earth's past for the global climate from the perspective of carbon cycling, but in doing so they address the heightened weatherability of impact ejecta compared to basaltic oceanic crust, due to shock fracturing. For our purposes, we draw only on their parameterized relationship between the properties of an impactor and the mass of the shocked material that it creates - which we assume to be more easily accessible to oxidizing fluids.

Modeling the Melting Cryosphere: Clifford and Parker discuss the Martian cryosphere extensively in [12], providing a parameterization for the depth of frozen layers within the Martian crust. Their parameterization for cryosphere depth (the extent of frozen soil and rock below the surface) is $z = \kappa_{ave}(T_{mp} - T_{ms})/Q_g$,where z is depth or distance from the surface, κ_{ave} = average thermal conductivity of a column of crust, T_{mp} = melting temperature at base of ice layer, T_{ms} = mean annual surface temperature, and Q_g = heat flux from the planet interior. T_{mp} may be anywhere from 273 K down to 252 K, the melting points of pure water and high-NaCl brine, respectively. κ_{ave} is approximated as 2.0 $Wm^{-1}K^{-1}$. T_{ms} is approximately 218 K at the equator to 154 K at the poles, which describes a profile of the cryosphere depth with latitude. Q_g = 3.00 mW/km^2. Desiccation at the surface extends from several centimeters to 1 km in this simplified view, from the equator moving toward the poles - describing a profile for the top of the permafrost layer with latitude. An impactor of a given size will thus produce locally a certain amount of shocked, weatherable material and liberate a certain amount of liquid water and/or brine.

Serpentinization can be approximated as a buffered redox reaction:

$$3Fe_2SiO_4 + 2H_2O \leftrightarrow 2Fe_3O_4 + 3SiO_2 + 2H_{2(aq)}$$

where a mole of H_2 is generated for every 1.5 moles of iron silicate, or for every 1 mole of water consumed. If 1.5 x (the moles of shocked material generated by the sum of all impactors of all sizes for a given time step) x (the proportion of rock which undergoes serpentinization) is greater than 1 x (the moles of water liberated by the melting of the cryosphere and accessing of the local liquid brine layer), the model establishes that the system is either rock- or water-limited, respectively. The limiting reactant (fresh rock or water) is then used to calculate the total moles H_2 generated following a meteor bombardment event. This H_2 is assumed to escape directly to the atmosphere. We do not consider the poorly understood reactions within the Martian regolith between H_2 and more oxidized species, assuming H_2 alone as a measure of reducing power in the atmosphere.

Modeling Atmospheric Escape: Impact-induced serpentinization, as parameterized above, represents the primary input to our simplified Martian atmosphere. What about the outputs? Without considering reactions between H_2 and materials at the surface or in the atmosphere, we can assume escape to space as the primary loss mechanism for H_2. The rate of escape to space may either be controlled by diffusion through the background gas (assumed to be CO_2), across the homopause, or by the availability of extreme ultraviolet solar radiation at the top of the atmosphere. The diffusion-limited escape flux is a function of the mixing ratio of the escaping gas relative to the background gas.

Alternatively, the energy-limited flux of H_2 molecules across the exobase, to space, will be the high-energy radiation available divided by the kinetic energy necessary of a molecule moving at escape velocity

Our model compares the energy-limited and diffusion-limited escape fluxes for each time step, since the H_2 inputs are evolving with each time step. If the energy-limited flux is smaller than the diffusion-limited flux, the system is energy-limited and this is considered the primary output for that time step. If the diffusion-limited flux is smaller, the system is diffusion-limited.

Modeling Decay of Impact-Induced Hydrothermal Systems: We also incorporate the work of Barnhart et al. [13] , who modeled impact-induced hydrothermal systems for crater structures formed by impactors <90 km in diameter. In their models, liquid water formed by impact melt or liberated from subsurface reservoirs refreezes on a time scale of 103-105 years after the initial impact, with the freezing front advancing from the crater rim to the center. These models also predict that most hydrothermal alteration will be concentrated in the middle of craters, leading to central clay deposits near the surface. These results are generated with an assumption of homogeneous permeability for the host rock, which is unrealistic, but consistent with the level of detail in our own models. Permeability seems to greatly affect the ratio of water to rock for the duration of a given hydrothermal system – but this is determined by other factors in our model (i.e. the water liberated from the local cryosphere and the generation of shocked material based on other groups' models).

Preliminary Results: The inclusion of refreezing [13] and a constrained rate of serpentinization renders all changes to the distribution of impactors inconsequential to the resulting H_2 output of our models. The rate of serpentinization acting on fresh, impact-shocked rock at the site of impact can only proceed so quickly, and H_2 mixing ratios reach an equilibrium well below the abundance necessary to achieve the collisional warming mechanisms described by Ramirez et al. [10]. This suggests that impact-induced serpentinization is a negligible contributor to the reducing power of the Noachian atmosphere. Currently, we are examining the abundance of alteration products in hand samples of impact melt breccias from terrestrial impact sites in Northern Australia to investigate the possibility of atmospheric contributions from other impact-induced hydrothermal processes.

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