RADIOLYTIC H₂ PRODUCTION ON NOACHIAN MARS: IMPLICATIONS FOR SUBSURFACE HABITABILITY. J. D. Tarnas, J. F. Mustard, B. Sherwood Lollar, M. S. Bramble, K. M. Cannon, A. M. Palumbo

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Figure 1 | Noachian subsurface habitability model. After [2]. a) Temperature increase with depth given a surface temperature of -45 °C [12] and two possible heat fluxes [13, 14] from initial mantle temperatures of 1650 K (60.16 mW/m²) and 1850 K (67.83 mW/m²). b) Cross-section of Noachian crust displaying the cryosphere, H₂ from radiolysis and serpentinization, CH₄ from serpentinization/carbonation, CH₄ clathrates, groundwater circulation (which contains dissolved H₂), and two distinct subsurface habitats—one aquifer-based within the subcryospheric highly-fractured zone (SHZ), and one between the depth that hydrothermal processes begin [2] (100 °C, 4.8 km) and the depth that the currently known upper temperature limit for life [26] is reached (122 °C, 5.6 km). c) Permeability decrease with depth based on the model from [16], but assuming a rock density of basalt rather than granite. The blue dotted line indicates the minimum surface permeability for basaltic aquifers in the Oregon Cascades (10⁻¹⁴), while the maximum surface permeability is 10⁻⁵ m² ([16] and sources therein). The red dotted line indicates the maximum permeability at 10 km depth for basaltic aquifers in the Oregon Cascades (10⁻³), while the minimum permeability at this depth is 10⁻¹⁵ m² ([16] and sources therein). d) Radiolytic H₂ production calculated using our model and porosity decay [11] with depth.

Introduction: The subsurface of Mars may have been the planet’s longest-lived continually habitable environment [1,2]. Requirements for subsurface life include above-freezing temperatures, the elements CHNOPS for cell construction, and sufficient concentrations of reducing and oxidizing compounds to drive metabolisms of microbes through biologically facilitated redox reactions that sustain abundant subsurface microbial communities on Earth. H₂ produced through water-rock alteration reactions including radiolysis [3-5] and serpentinization [6, 7] is considered one of the most important reducing compounds feeding such ecosystems on Earth [8]. Here we model H₂ production on Noachian Mars via radiolysis of pore water by α, β, and γ radiation produced through decay of K, Th, and U in the martian crust. We find that the quantity of H₂ is sufficient to have sustained subsurface microbial ecosystems on Mars for hundreds of millions of years during the Noachian. Furthermore, we use geophysical arguments to constrain the probable location of this subsurface habitat, as shown in Figure 1. Biosignature-hosting material from this habitat, termed the subcryospheric highly-fractured zone (SHZ), can be excavated in megabreccia blocks ejected from later impacts that penetrate beneath the depth of the Noachian cryosphere, making this hypothesis testable through future robotic and human exploration of Mars.

Methods: Using the model described by [5] and [9], radiolytic H₂ production during the Noachian is calculated by extrapolating Odyssey’s Gamma Ray Spectrometer (GRS) K and Th elemental maps [10] to Noachian concentrations, obtaining U abundances by assuming a Th/U ratio of 3.6, modeling the spatially resolved cryosphere depth [11] based on Noachian surface temperature [12] and heat flux [13, 14] models, and modeling Mars crustal porosity [11] using parameter values derived from GRAIL [15] scaled to martian gravity. Radiolytic H₂ produced beneath the cryosphere base is biologically useful, as illustrated in Figure 1. Following [16] we model crustal permeability, which we use as a proxy for groundwater activity, indicating the degree to which serpentinization would occur in ultramafic zones of the crust.

Results: For water-filled porosity and an initial mantle temperature of 1650 K (corresponding to the thickest cryosphere produced in our models, shown in Figure 2), the global H₂ production at 4 Ga is [0.72-2.40] × 10⁻¹⁰ moles H₂ yr⁻¹ in the cryosphere, [2.63-6.23] × 10⁻¹⁰ moles H₂ yr⁻¹ in the subcryosphere, with [0.35-1.13] × 10⁻¹⁰ moles H₂ yr⁻¹ generated in the SHZ, assuming a 3 km depth SHZ base and including the estimates for both 10% and 30% surface porosity. These results represent the minimum biologically useful H₂ production under the boundary conditions of this study. These radiolytic H₂ production rates for Noachian Mars are all approximately equal to the H₂ production rate in Earth’s Precambrian crust ([1.6-4.7] × 10⁻¹⁰ moles H₂ yr⁻¹) [3], which covers a similar surface area to the total surface area of Mars (1.06 × 10⁸ km² and 1.44 × 10⁸ km²).
respectively) and has been shown to support abundant chemolithotrophic microbial life in the terrestrial subsurface [3, 17]. Therefore, we propose radiolytic H$_2$ production during the Noachian was sufficient to support microbial life in the martian subsurface, especially when coupled with additional H$_2$ generated by serpentinization. Serpentinization has been estimated to produce approximately 6.83 × 10$^{-10}$ moles H$_2$ yr$^{-1}$ at 4 Gai in the top 12 km of crust [18, 19], which lies within our estimated range of radiolytic H$_2$ production at 4 Gai in the top 10 km of crust [(3.35-8.63) × 10$^{-10}$ moles H$_2$ yr$^{-1}$]. Both radiolysis and serpentinization would therefore supply chemical energy to subsurface microbial ecosystems during the Noachian in roughly equal amounts, though the majority of H$_2$ from serpentinization would be produced in the lower, hotter crust, and may be transported to the SHZ by circulating groundwater.

Radiolysis produces H$_2$ at approximately 0.1-1.3% the rate it was lost to space during the Noachian [20]. In order to have a significant climatic effect, this H$_2$ would need to be locked in H$_2$ clathrates, which are stable at the base of the Noachian cryosphere [21], and released during catastrophic events that perturb the cryosphere. Future investigation will determine whether enough H$_2$ could be stored in the cryosphere to have a significant climatic effect, such as increasing mean annual temperatures above the melting point of H$_2$O.

**Figure 2 | Noachian cryosphere depth.** Modeled depth of an H$_2$O cryosphere 4.1 Gai based on modeled surface temperature [12] (1 bar CO$_2$ atmosphere, 25° obliquity) and heat flux [13, 14] (initial mantle temperature = 1650 K).

**Figure 3 | Radiolytic H$_2$ production maps.** Modeled H$_2$ production via radiolysis in the Noachian subsurface assuming 30% surface porosity, H$_2$O groundwater, and 1650 K (1377 °C) initial mantle temperature.

**Discussion:** By integrating geophysical and geochemical models, we quantify the depth range of the most habitable section of the martian crust during the Noachian—the SHZ. Here, microbial ecosystems could have been sustained for hundreds of millions of years by H$_2$ derived from radiolysis and low temperature serpentinization, combined with H$_2$ and CH$_4$ derived from high temperature serpentinization and transported via groundwater circulation and gas diffusion, as shown in Figure 1.

Later impacts on Noachian or Early Hesperian age terrain that penetrate beneath the depth of the Noachian cryosphere can excavate material from the SHZ, exposing it in ejecta or interior crater deposits. These units are thus compelling targets for astrobiological exploration of the possible ancient subsurface martian biosphere. Megabreccia blocks on Mars commonly contain hydrated minerals such as phyllosilicates formed by hydrothermal alteration [22-24], either in the subsurface before impact [25] or from hydrothermal systems generated by impacts [20]. These units could contain biosignatures from both the SHZ and younger, transient, impact-induced hydrothermal environments [22]. Many megabreccias also contain unaltered megaclasts with their original mafic or ultramafic composition [22-24], revealing the H$_2$ production potential from serpentinization of this precursor material, as this is controlled by composition. Megabreccias that contain both altered and unaltered facies are thus potentially valuable astrobiological targets, as they may contain morphological, organic, and chemical biosignatures from both the SHZ, the longest lived habitable environment on Mars, and possible impact-induced transient hydrothermal habitats.

**Conclusions:** Using models of subsurface energy availability, crustal temperature profiles, and permeability, we quantify the probable location of the longest lived subsurface habitat on Mars, termed the SHZ. Later impacts into Noachian to Early Hesperian age terrain that penetrate beneath the depth of the Noachian cryosphere can excavate material from the SHZ that would contain morphological, organic, and chemical biosignatures if subsurface life did exist on ancient Mars. We postulate that the most valuable astrobiological targets on the martian surface are megabreccia blocks from such impacts that contain both their original unaltered mafic lithologies as well as altered phyllosilicate lithologies generated by both pre-impact subsurface hydrothermal alteration and post-impact hydrothermal alteration, as the former would contain biosignatures from the SHZ and the latter would contain biosignatures from impact-induced transient hydrothermal habitats, if either of these habitats did host life on Noachian Mars. This should be considered in the context of Mars 2020, ExoMars, and future robotic and human exploration of the Red Planet.

**References:**