RADIOLYTIC H$_2$ PRODUCTION, TRANSPORT, AND DISSOLUTION ON NOACHIAN MARS. J. D. Tarnas, J. F. Mustard, B. Sherwood Lollar, M. S. Bramble, K. M. Cannon, A. M. Palumbo, A.-C. Plesa, \textsuperscript{1}Brown University, Dept. of Earth, Environmental and Planetary Sciences, Providence RI (jesse.tarnas@brown.edu), \textsuperscript{2}University of Toronto Dept. of Earth Sciences, Toronto ON, \textsuperscript{3}University of Central Florida Dept. of Physics, Orlando FL, \textsuperscript{4}German Aerospace Center Institute of Planetary Research. Planetary Physics, 12489 Berlin.

Introduction: Subsurface microbial communities on Earth obtain energy by facilitating energetically favorable redox reactions. Such ecosystems are prevalent in both the terrestrial [1, 2] and marine [3, 4] crust on Earth, and may have inhabited the subsurface of Noachian Mars in regions with liquid water or brine, temperatures between 0-122 °C [5], and available oxidants and reductants. H$_2$ is a major reductant in terrestrial subsurface communities [1-4, 6, 7] and a building block for reductants of higher molecular complexity such as CH$_4$, HS$^-$, and NH$_4$ [7]. Thus, characterizing the production, transport, and dissolution of H$_2$ in the Noachian crust is key to assessing habitability. Here we demonstrate that radiolysis, which powers subsurface microbial communities on Earth [1-3], likely generated sufficient H$_2$ to support subsurface chemolithotrophic microbial communities on Noachian Mars. We use models of radiolytic H$_2$ production [6], diffusion [8], and dissolution to estimate the availability of dissolved H$_2$ in subsurface fluids within the Noachian crust, which we find to be orders of magnitude more than sufficient to support microbial life (0.349.9 μM). The minimum concentrations of dissolved H$_2$ required for microbially-facilitated SO$_4$ reduction and CH$_4$ formation through CO$_2$ reduction are 1 nM and 13 nM, respectively [9]. As such, dissolved H$_2$ availability in the Noachian crust was likely higher than required for sustaining chemolithotrophic microbial communities, regardless of the background climate or groundwater composition.

Methods: We employ a radiolytic H$_2$ production model which has been applied previously to terrestrial environments [6], Europa [10], and modern Mars [8]. Gamma Ray Spectrometer data were used to obtain concentration maps for radionuclides K and Th [11] that were normalized following [12]. U concentrations were estimated by assuming a Th/U ratio of 3.6 [13]. A half-life decay model was used to estimate K, Th, and U abundances during the Noachian.

We apply the porosity model of [14] assuming 5-15% surface porosity and a porosity decay constant of 4.3 km, which we derive by scaling GRAIL measurements [15] to martian gravity. Surface porosity assumptions agree with values from gravitational analysis of Noachian terrain [16]. We generate a temperature profile for the Noachian crust using geothermal heat flux maps [18] and mean annual surface temperature maps for both warm and cold Noachian climates [17]. This allows us to generate cryosphere depth maps for various climate and heat flux scenarios during the Noachian, assuming different groundwater compositions.

We model steady-state H$_2$ diffusion through the Noachian crust and calculate diffusivity through ice and water following [8]. We derive a solution for H$_2$ solubility as a function of temperature and pressure using data compiled by [19] and then calculate dissolved H$_2$ concentrations in groundwater using the H$_2$ gas concentration profile and solubility function. We compare our model results with required H$_2$ concentrations for terrestrial subsurface life to estimate whether radiolysis could be a sufficient mechanism to support subsurface life on Noachian Mars.

Results: Global H$_2$ production estimates range from $[0.29-1.16] \times 10^{10}$ moles H$_2$ yr$^{-1}$ in the cryosphere and $[0.91-3.88] \times 10^{10}$ moles H$_2$ yr$^{-1}$ in the subcryosphere (Figs. 1 & 2d). H$_2$ gas concentrations range from 0-9.24 mol m$^{-3}$ in cold Noachian climate and from 0-4.43 mol m$^{-3}$ in warm Noachian climate (Fig. 2a). For the cold climate scenario, dissolved H$_2$ concentrations range from 0-349.9 μM. For the warm climate scenario, dissolved H$_2$ concentrations range from 0-282.9 μM (Fig. 2b). Dissolved H$_2$ concentrations are more than sufficient to support a subsurface biosphere in all modeled scenarios, especially when coupled with additional H$_2$ from serpentinization [21].

Discussion: Our results indicate that habitability of the Noachian subsurface was primarily contingent on oxidant availability, as extensive regions with temperatures between 0-122 °C, protection from radiation, and sufficient quantities of dissolved reductants (H$_2$) likely existed in the Noachian crust. We propose that the region immediately beneath the cryosphere—termed the subcryospheric highly-fractured zone (SHZ)—was habitable for hundreds of millions of years, making it the longest-lived habitat on Mars. The proximity of this region to the surface would also increase availability of oxidants from the atmosphere/surface.

Material from the SHZ can be excavated and exposed at the surface in ejecta from craters that penetrate beneath the depth of the Noachian cryosphere on Noachian-aged terrain. Such deposits are thus compelling targets for astrobiological exploration of ancient subsurface Mars. Martian megabreccia blocks and ejecta contain phyllosilicates likely formed by hydrothermal alteration [22-24], either in the
subsurface pre-impact [25], in a primordial supercritical atmosphere [24], or from impact-generated hydrothermal systems [23]. Some megabreccias also contain unaltered megaclasts with their original ultramafic lithologies [22,23], revealing H₂ production potential from serpentinization of this material. These units may contain organic, isotopic, and morphological biosignatures from the SHZ and transient, impact-induced hydrothermal habitats [23].

In the presence of equal amounts of CH₄, the predominantly CO₂ reducing greenhouse atmosphere proposed by [20] to warm the Noachian surface to above 273 K requires \(0.7 \times 10^{20}\) moles H₂ for 2 and 1 bar atmospheres, respectively. Even if 100% of H₂ produced through radiolysis and serpentinization [21] were locked in clathrate hydrates within the cryosphere, \(\sim 10^8\) years would be required for H₂ to build up in sufficient quantities to generate this reducing greenhouse atmosphere upon major cryospheric perturbation. Another mechanism must account for the missing atmospheric H₂, if the transient reducing greenhouse atmosphere did exist.

**Conclusions:** Based on models of H₂ production [6,7], diffusion, and dissolution, we conclude that concentrations of dissolved H₂ in Noachian crustal groundwater were likely more than sufficient to support a subsurface biosphere. Based on temperature gradients and liquid water and nutrient availability, the region immediately beneath the cryosphere—the SHZ—was the longest-lived habitable environment on Mars. Material from this zone can be excavated and exposed at the surface in impact ejecta and central uplifts. This should be considered when selecting future targets for astrobiological exploration of Mars.


![Figure 1](http://example.com/fig1.png)

**Figure 1 | Latitudinal cross section of H₂ production with topography.** Surface H₂ production variations with latitude and longitude displayed on Noachian-age terrain (right) and H₂ production variations with latitude and depth (left) for H₂O groundwater. In the latitudinal cross sections (left), the cryosphere base is indicated as a black line. Topography data for the latitudinal cross sections are from MOLA. H₂ production is maximized at shallower depths where porosity is highest.

![Figure 2](http://example.com/fig2.png)

**Figure 2 | Noachian subsurface habitability model.** Modified after [26]. For cold Noachian climate with H₂O groundwater a) H₂ gas concentrations within the top 10 km of crust. b) Dissolved H₂ concentrations in crust based on solubility model. c) Cross-section of Noachian crust displaying the cryosphere. H₂ from radiolysis and serpentinization, CH₄ associated with serpentinization, CH₂ clathrates, groundwater circulation (which contains dissolved H₂), and a subsurface aquifer-based habitat within the subcryospheric highly fractured zone (SHZ). d) Temperature increase with depth given cold climate [17] and two possible heat fluxes [18] from initial mantle temperatures of 1650 K (60.16 mW/m²) and 1850 K (67.83 mW/m²). e) Radiolytic H₂ production estimates for various assumed surface porosities.