Quantifying the Intermittency of Mars Surface Habitability

Habitable-zone planets such as Mars host natural origin-of-life experiments whose results are archived in the sedimentary record. To relate Mars biosignature presence or absence to the times and timescales of the emergence of life requires quantifying the intermittency of habitable surface conditions [1-3]. We will do this by analyzing recently-completed orbiter surveys and integrating the results with stochastic climate-evolution and landscape-evolution models.

Rovers show that at some times and in some places early Mars could have supported microbial life [4], but habitability could not have been both long-lasting and global because early Mars terrains lack deep weathering and erosion [5-7]. Defining the intermittency and patchiness of habitability sets the origin-of-life agenda for sample-caching rover landing site selection: do <3.7 Ga deltas and lake deposits [8-10] record the waning of a billion years of continuous habitability? In that case, these deposits sample the maximum time available for biogenesis (Fig 1a). Or did >0.1 Gyr pulses of surface sterilization lead to the biological isolation (quarantine) of late, briefly habitable oases from the extremely early era of bolide organics delivery, possible oceans, and thick (potentially H_2-rich) atmospheres [11-16]? If so, sending rovers to >>3.7 Ga rocks would maximize the probability of finding a second origin (and the information content of a null result) (Fig 1b). A key consideration in either case is whether a late burst of habitability could rescue viable spores preserved from an earlier more-habitable epoch. To quantify stress on spores and possible sterilization, we must quantify UV, cosmic radiation, and oxidative stress [17-19] during uninhabitable periods, and possible subsurface refugia. The key datasets for this work are the largely complete (but little-analyzed) MRO and MEX orbiter surveys of high-resolution topography and stratigraphy, plus isotopic constraints on early atmospheric evolution from meteorites, as input to a hierarchy of models.

Objective 1. Post-3.7 Ga deposits place strong geologic constraints on the time-integrated spatial distribution of surface liquid water (e.g. [12, 20-22], Fig. 2). We will use these to select habitability-versus-time trajectories, using a stochastic forward model coupling atmospheric evolution, weather, the carbon cycle, and the water cycle (Fig. 3) [1, 23]. Mars undergoes large-amplitude chaotic orbital changes which affect surface runoff and we will marginalize over these using an ensemble of 10^3 3.7 Gyr orbital histories weighted by the geologic observations [24]. Three-dimensional models of the Mars water cycle show snow/ice pile-up where sublimation rates are low, which allows snow/melt to be allotted in postprocessing with no need for precipitation tracking [1, 23]. This speed-up allows a dense grid of 1° spatial resolution, 1 hr time resolution global atmospheric circulation model runs. Results from these runs populate a look-up table for the mean and variability of surface runoff for all possible climate forcings. We will use the model to track reversible atmospheric collapse, carbonate formation, and atmospheric escape (constrained by MAVEN measurements scaled to stellar wind and UV flux versus time from astrosphere measurements and spectroscopy of young solar analogs) [25-26]. Ours will be the first spatially-resolved climate evolution model for Mars, the first orbital-ensemble stochastic climate evolution model for Mars, and will generate testable predictions for the concentration and isotopic composition of carbon (and the isotopic composition of hydrogen) versus stratigraphic elevation at Aeolis Mons / Mt. Sharp.

Objective 2. Data on **pre-3.7 Ga deposits** have not yet been integrated to produce geologic constraints. Ancient-crater modification suggests wet conditions, but neither the forcing climate nor the timing of erosion are known, because crater-age dating cannot distinguish the ages of these old deposits [27]. We will attack this problem in a novel way: by analysis and simulation of relative erosion for pairs and triplets of ancient craters whose relative timing is constrained, followed by statistical reconstruction of the erosion time series (time units of crater density) using simple landscape-evolution models [28-29]. A single spike of erosion might suggest an isolated burst of habitability (Fig. 1b): prolonged degradation would indicate a long origin-of-life experiment (Fig. 1a). We will also use anisotropies in erosion [30-31] to determine the relative importance of snowmelt, which will be more aspect-dependent than rainfall in early erosion. Because Mars is a surviving embryo with a young Hf-W age, surface geology extends back to extremely early times, so we will compare our erosion models to dynamical simulations (including possible giant-planet migration) that incorporate climate-changing eccentricity excursions during or shortly after disk dispersal [32-33].

Objective 3. To **determine if dry spells would have been sterilizing** we will quantify the UV fluxes, cosmic radiation, oxidative stresses, and thermal (impact) stresses during globally-dry intervals (during which we assume spores are globally distributed but cannot reproduce), taking into account constraints on the Martian dynamo [34]. This will involve photochemical modeling of atmospheric composition, UV modeling (considering O_2 abundances both above and below the present-day 1 Pa level) [16, 35], and radiation modeling, for varying solar luminosities. A refugium of particular interest is evaporite deposits [36-37]. Our results will determine whether viable spores could survive to inoculate Recurring Slope Lineae [38], and will identify minimum thresholds for future terraforming. Finally, we will determine if surface-interior exchange or meteorite self-fertilization could rescue a once-sterilized surface environment. Revitalization of the surface may occur if warm/wet surface conditions last long enough to melt the permafrost capping subsurface refugia, or in the aftermath of a chaos-forming event [39-40] or impact [41].

Timeline/milestones. The objectives laid out in this proposal can be interpreted chronologically. We anticipate hiring a postdoc in Year 1, and Kite and Simons will collaborate on Tasks 1 and 2 during this year and the two following years. This first postdoc will devote most of their time to Task 1. A second postdoc (to be hired in Year 3) will carry out the bulk of Task 2 and assist with Task 3. Kite and Onstott will collaborate on Task 3. As professors our salary is covered, except for 1 month/year summer salary that is requested for PI Kite. In total, we request $110,000 /yr for five years. This will cover 100% of a postdoc's salary possibly to be divided over 2 people per year (our work is clearly in the interests of NASA's Mars Program, and we anticipate future funding from that source, which could be leveraged through progress on Objective 1 or 2).

Summary of Accomplishments. PI Edwin Kite (PhD 2011) is expert on Mars geology and has written 21 papers on Super-Earths, astrobiology, and Mars. Co-I Frederik Simons (PhD 2002) is expert on statistical climate reconstruction from noisy proxy data [42-43]. Co-I Tullis Onstott (PhD 1980) is expert on astrobiology and extremophile survival [44]. He was a member of the Science Definition Team for the Mars 2020 rover, led the Indiana-Princeton-Tennessee Astrobiology Institute, led the discovery of a long-term biosustainable deep subsurface biome, and is on NASA's Planetary Protection advisory committee.

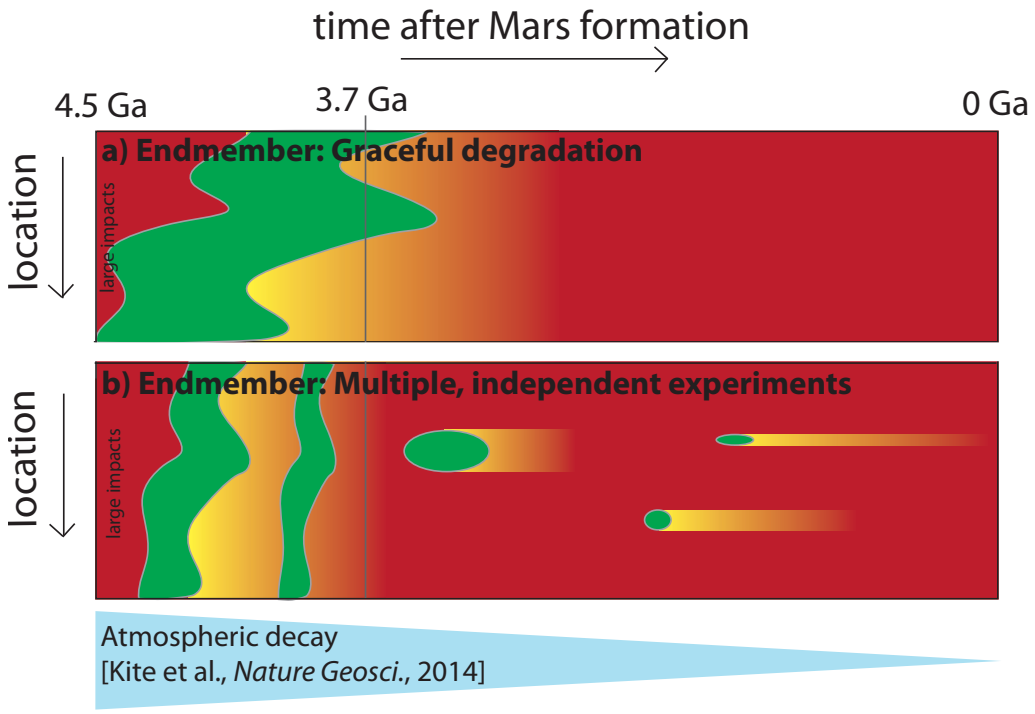

Fig 1. Does Mars record one or several origin-of-life experiments? Green: habitable region. Red: Sterile region. Yellow-orange: Spores accumulating DNA damage which progressively inhibits reproductive viability (wind will disperse spores).

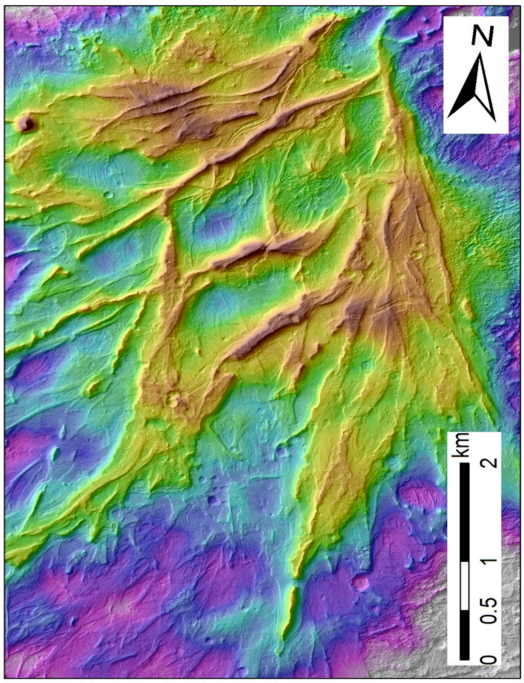

Fig. 2. Inverted channels on a wind-eroded alluvial fan. This is direct evidence for <3.7 Ga surface runoff at this location (154°E, 5°S). Relative timing is constrained by crosscutting relationships [14].

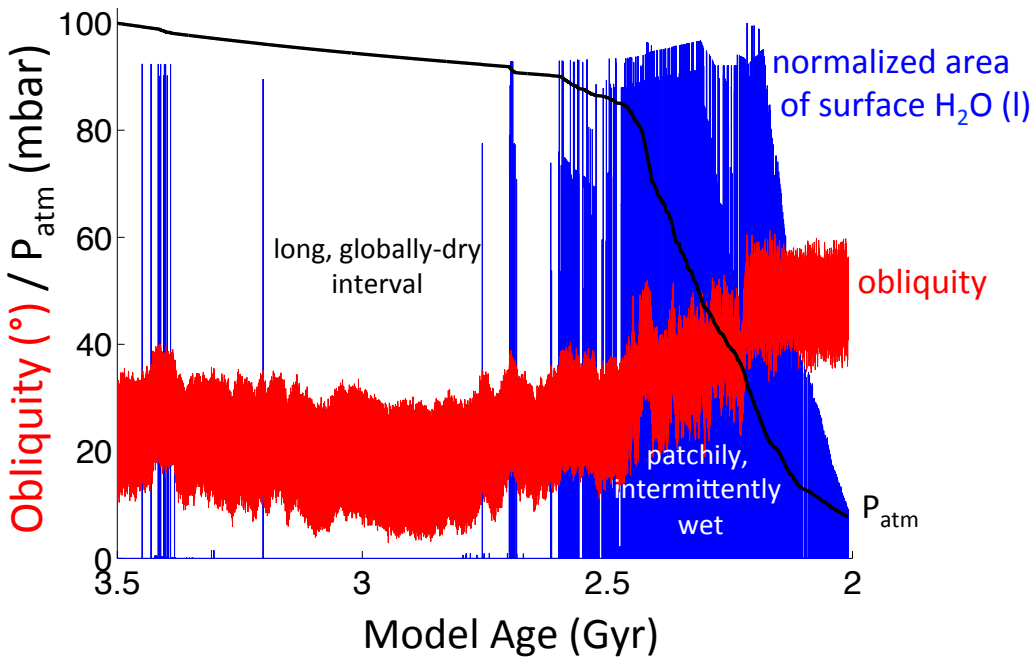

Fig. 3. One example from an ensemble of runs of our long-term, orbitally integrated, spatially resolved Mars climate evolution model [45]. Results shown are global integrals, and we can drill down to 1-hour time resolution and 1° spatial resolution.

References.

[1] **Kite et al., *Icarus* 2013 ("Seasonal melting …").** [2] Summons et al., *Astrobiology* 2011. [3] Grotzinger & Milliken, chapter in *Sedimentary Rocks of Early Mars*, SEPM Press. [4] Grotzinger et al., *Science* 2014. [5] Ehlmann et al., *Nature* 2011. [6] Fassett & Head, *Icarus* 2011. [7] Aharonson et al., *Proc. Nat. Acad. Sci.* 2002. [8] Malin & Edgett, *Science* 2003. [9] Irwin et al., *Science* 2002. [10] Ehlmann et al., *Nature Geoscience* 2008. [11] **Kite et al., *Nature Geoscience* 2014.** [11] Ramirez et al., *Nature Geoscience* 2014. [13] Perron et al., *Nature* 2007. [14] Lunine et al., *Icarus* 2003. [15] **Kite et al., in review.** [16] Zahnle et al., *J. Geophys. Res. - Planets* 2008. [17] Diaz & Schulze-Makuch, *Astrobiology* 2006. [18] Slade & Radman, *Microbiol. Mol. Biol. Rev.* 2011. [19] Pavlov et al., *Geophys. Res. Lett*. 2012. [20] Williams et al., *Science* 2013. [21] Morgan et al., *Icarus* 2014. [22] **Kite et al., *Icarus* 2013 ("Pacing early Mars river activity")** [23] Forget et al., *Icarus* 2013. [24] J.W. Head et al., *LPSC* 2009**.** [25] Claire et al., *Astrophys. J.* 2012. [26] Linksy & Wood, chapter in *The Sun and the Heliosphere as an Integrated System*, Kluwer Academic Publishers. [27] Irwin et al. *J. Geophys. Res – Planets* 2013. [28] Howard, *Geomorphology* 2007. [29] **Kite et al., *Geology* 2013.** [30] Kreslavsky & Head, *Geophys. Res. Lett.* 2003. [31] S.A. Wilson et al., *LPSC* 2013. [32] Agnor & Lin, *Astrophys. J.* 2012. [33] Morbidelli et al., *Astron. J.* 2007. [34] Lillis et al., *J. Geophys. Res. - Planets* 2013. [35] Lanza et al., *Geophys. Res. Lett.* in press. [36] Osterloo et al., *Science* 2008. [37] Ziolkowski et al., *Astrobiology* 2013. [38] McEwen et al., *Nature Geoscience* 2014. [39] **Kite et al., *J. Geophys. Res. - Planets* 2011 a.** [40] **Kite et al., *J. Geophys. Res. - Planets* 2011 b.** [41] **Mangold, Kite et al., *Icarus* 2012.** [42] **Kopp, Simons et al., *Nature* 2009.** [43] **Simons & Olhede, *Geophys. J. Int.* 2013**. [44] **A.P. Johnson et al. (last author Onstott), *Icarus* 2011.** [45] **Kite et al., *LPSC* 2014.**