The Dynamic Habitability of Mars: Key Findings and Needed Measurements

B. L. Ehlmann , *University of Colorado, USA (Bethany.Ehlmann@colorado.edu)*, **R. Wordsworth**, *Harvard University, USA*.

Introduction: The 2023-2032 Decadal Survey highlights the importance of "dynamic habitability" in understanding the distribution of life in the universe (1). Of the 5 characteristics required for habitability (1-3), Mars definitively has two, the building blocks of biochemistry and energy sources that support metabolism. The availability of liquid water as a solvent for chemical reactions and tolerable physical/chemical conditions (e.g., temperature, pH, water activity) for sufficient duration remain priority areas of study.

We recently reviewed geological and climate data acquired over the last decades of exploration and discuss how Mars represents a key example of a planet with intermittent habitability throughout its history (4). Mars has been cold and dry but also warmer and wetter in punctuated 10,000-1,000,000 year intervals throughout its history. This created dynamic habitable environments in the past and likely continues to create such habitats today (Table 1). Only a few of these environments have so far been explored. We highlight four key findings (or controversies) that should drive the prioritization of future Mars missions and measurements for understanding planetary habitability and the search for life.

Key Finding 1. At least 2 billion years of large-scale, intermittent liquid water on the surface

It has been longstanding that the Noachian and Hesperian featured ground and surface waters, at least intermittently, until about 3 billion years ago. The last 5-10 years of exploration have highlighted how waters continued intermittently on the surface and subsurface through the Amazonian or until 1-2 billion years ago(Fig. 1). Fans in craters show long term alluvial activity (e.g., 5, 6). Jarosite at Gale formed in the middle Amazonian (7). Silica formed associated with some fans even into the last ~1 Ga (8). Finally, chlorides were deposited in river valleys carved into Amazonian lavas, flowing over 10's of killometers and leaving behind playa deposits (9).

What causes this episodic Amazonian water availability is not yet clear. The nature of the topography of the chlorides requires an upstream, non-groundwater source. This implies snowmelt. Obliquity change and/or release of greenhouse gases are the most likely candidates for creating a climate different to that observed today that enables melt.

Recommended measurements While the broad outlines are now clear, how chemical alteration, volcanism, impacts, and obliquity generated sustained a warmer climate and its hydrologic cycle remains fundamental to astrobiology on Mars and our ability to predict habitable worlds in other solar systems. Additional texture, chemistry, mineralogy and isotopic data at small scale in altered rocks, hydrothermal minerals, sedimentary rocks are needed to constrain climate and geochemical models and understand the factors creating ephemeral habitats of each of the types (Table 1). The major open question of cold or hydrothermal surface and groundwaters will await techniques such as stable and clumped isotope analysis in returned Mars samples.

Table 1. Habitable environment on Mars and whether they have been investigated in situ.

Habitat setting	Indications of environment	In situ measurements?
Ancient – surface (10,11)	deep neutral/alkaline lakes with clays and/or carbonates, primary igneous basin sediments	Curiosity@Gale, Perseverance@Jezero
	shallow chloride-rich playas	
	shallow acid-Fe sulfate playas,	Opportunity@Meridiani
	lakes of varied depths with silica precipitation	
	basins with large-scale Mg, Ca-sulfate sediments	*(future?) Curiosity@Gale*
Ancient-subsurface (10, 12-16)	silica fumaroles and/or springs	Spirit@Columbia Hills, Gusev; Curiosity@Gale (tridymite deposit)
	ground/surface waters to form Fe/Mg smectites in sedimentary and volcanic aquifers	Opportunity@Endeavour rim; *(future?) Perserverance at Jezero*
	alunite/jarosite-forming focused acid groundwater springs	
	reducing, high pH serpentinization of ultramafic rocks	*(?) Perserverance at Jezero*
	ground or surface alkaline waters causing zeolitization	
	low-grade metamorphism/ hydrothermalism at temperatures of 200-400°C to form prehnite/chlorite	
Modern (17)	Mid-latitude ice/snow-dominated deposits	
	Frost/ice, residual salts in sediments	Spirit@Columbia Hills, Gusev
	(?) Deep groundwaters	

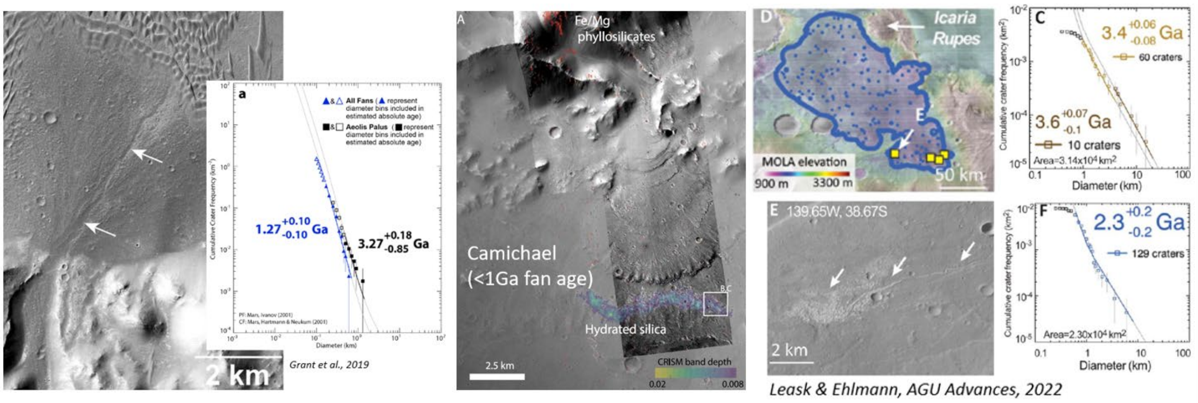

Figure 1. Intermittent Surface Waters. (A) Dirty snow (Case I) provides possibilities for melting at temperatures above the triple point, due to solid state greenhouse effects, as well as a depth zone where light is sufficient for photosynthesis but UV radiation is mitigated. (B) Ice-filled permafrost also, for some latitudes, reaches temperatures greater than a theoretical limit of habitability.

Key Finding 2. Water-rock reactions drove Mars climate change.

New data on modern atmospheric loss rates, the concentrations of minerals in the crust, and isotopes of C, H, N and noble gases in the atmosphere and rock record (18,19) show how the composition and mass of Mars' early atmosphere produce a climate consistent with the geologic evidence. A synthesis of self-consistent models suggests 0.5-1.8 bar CO_2, 0.1-0.5 bar N_2, and 100-1500 m global equivalent water in the climate system in the late Noachian (18-22). Such moderately thicker ancient atmospheres would have increased greenhouse warming by tens of degrees K, facilitating seasonal melt.

Over time, and at greater rates in the wetter Noachian and Hesperian, large volumes of carbonates (0.5-2 bar; 20, 23) and H_2O (100-1500 m global equivalent water; 22) were lost out of the climate system to the crust in water-rock reactions to form aqueous minerals. Thus, the very markers of habitable environments contributed to their decline by irreversible chemical weathering (22). Comparable proportions of carbon dioxide and 10s of meters of H_2O were also lost to space by a range of atmospheric loss processes (18).

The loss of water as hydrogen to space changed the redox chemistry of Mars in tandem with its climate, leaving behind oxygen and ultimately producing its reddish, oxidized surface as this interacted with the surface. The relative importance of the past magnetic field and its effect on escape rates remains uncertain. What is clear is that geologic activity of terrestrial planets – weathering and the production of new crust -- is critical in setting habitability. The drawdown of atmospheric carbon dioxide and water made Mars more arid and the creation of melt more challenging (20-22). But it may have generated reduced gases that warmed the climate (22, 24-26). Mars demonstrates that the balance between volcanic degassing flux, chemical weathering, and atmospheric escape is critical for long-term planetary-scale habitability, requiring consideration at multiple timescales. Superimposed periodic variation in climate system boundary conditions (e.g., obliquity) induce habitability dynamically even when climate averages suggest habitability challenges.

Recommended measurements The atmosphere's losses to the crust and space are fundamental secular drivers of the diminishment in Mars' planetary-scale surface habitability and are now coarsely quantified, thanks to decades of research, but timing and time-pacing of change remains an active subject. Additional isotopic data from secondary minerals from in situ measurements or returned samples are needed to pin down composition, pressure, and changes over time precisely (particularly for the hitherto under-examined Noachian geologic record), Having accurate radiometric dates to understand the pacing and drivers of change is essential. Accurate age dates from rock strata with returned samples are required to quantify timescales of habitability and rates of contributing processes. Determining early atmospheric composition through analyses of returned samples is critical for future progress, and direct atmospheric or fluid samples may be found in volcanic- or impact-melt inclusions or precipitated minerals.

Key Finding 3. Detected snow and probable snowmelt

Promising places to search for extant life include the upper meter of snowpacks, pore-filling ices (Figure 2), and recent salt deposits such as those in hollows uncovered by the Spirit rover (17).

In the last 5 years, it has become clear that "pasted-on terrains" on crater walls do, in multiple cases, represent dust-covered snow (27,28). Furthermore, global climate modeling shows that at 12 mbar pressures at ϕ>~35°, last experienced ~500kyr ago, all areas from 50N to 70S experience some days above water's triple point except the highest-elevation volcanoes. Predicted locations of snowmelt are consistent with gully distribution (29).

Mars' buried snow deposits are thus promising from a habitability perspective; because of their

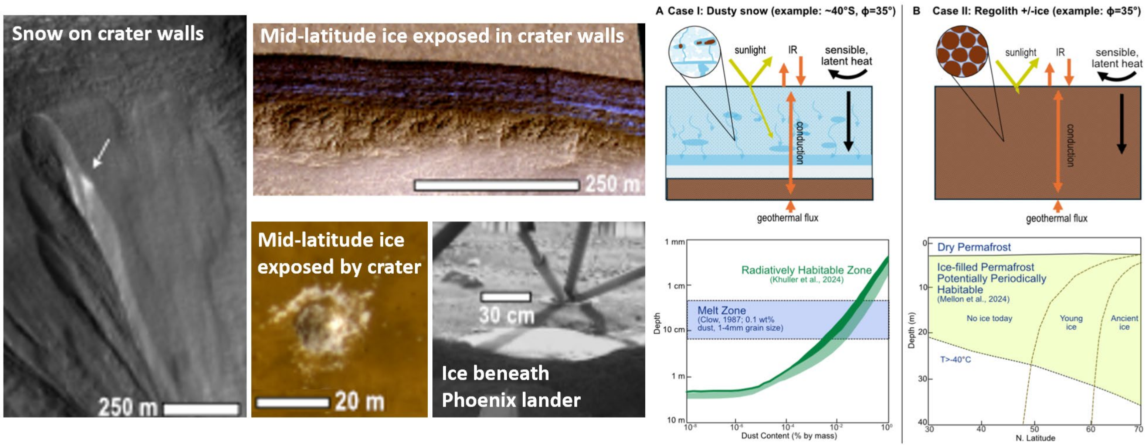

Figure 2. Habitability of Modern Ice. Snow and ice on Mars. Dirty snow (Case I) provides possibilities for melting at temperatures above the triple point, due to solid state greenhouse effects, as well as a depth zone where light is sufficient for photosynthesis but UV radiation is mitigated. Ice-filled permafrost (Case II), for some latitudes, reaches temperatures greater than a theoretical limit of habitability.

transparency, they create a warmer, solid-state greenhouse where ice can melt (30) and this overlaps with the radiatively habitable zone, shielded from UV-C but receiving visible light radiation sufficient for metabolism (31) (Figure 2; Case I). Even in other locales where sediment instead dominates the system (Case II), ices are still potentially of interest as habitats. (32)'s calculations show that $\boldsymbol{\phi}$>~35°, the upper 40 cm of pore-filling ice regolith is within a -40°C theoretical temperature limit of habitability (Figure 2; Case II), although probably not to -15 to -20° C, where on Earth metabolic activity has been observed in both ice and dry permafrost with only interfacial water (33).

Recommended measurements. While models predict potential ice habitability, actual ice physical properties, temperature, temperature history, and water activity are the chief question for whether the snow and ice deposits are habitable or even host life. Higher resolution orbital measurements of ice distribution and physical properties like those of the recent orbiter SAG (34) would allow better classifying these deposits. Finding small snow deposits where melt is likely, e.g., on crater walls is another priority. In situ, measurements like the 4 objectives of the Planetary Decadal Survey's Concept Mars Life Explorer (1) that would search for biosignatures and examine ice and climate properties will be key at the most promising deposits.

Key Finding 4. Modern activity and the question of deep groundwater.

Intriguingly, clustering of Mars earthquakes observed by InSight from 2018-2023 near the young volcanoes and outflow channels of Cerberus Fossae suggests subsurface volcanism/magma movement that could melt ice, if such were present (35). South polar subsurface waters have also been proposed to explain some radar measurements but contested due to requirements on heat flow and the possibility of rock properties instead explaining (e.g., 36, including comment and reply and refs therein). Subsurface geophysical observations acquired so far cannot yet unambiguously distinguish wet, icy, and dry regions underground—water is permitted but not required (e.g., 27).

Recommended measurements. Resolving the question requires different geophysical investigations of the subsurface for water, including different techniques like electromagnetic sounding from landers.

Conclusions: Mars is a key example for understanding planetary habitability in the absence of a continuous hydrosphere and where habitability was intermittent in time and space. Key measurements are still outstanding to understand the drivers of its planetary climate. Sample return plays a critical role, and there are also a rich set of in situ targets, as yet unexplored, for missions of the next decade.

References: (1) NASEM, 2022, *Plan Sci & Astrobio Decadal Survey* (2) Hoehler, 2007, Astrobio (3) Cockell, 2016, Astrobio, (4) Ehlmann & Wordsworth, Science, in revision (5) Grant et al., 2011, GRL (6) Grant and Wilson, 2019, GRL (7) Martin et al., 2017 (8) Pan et al., 2021, PSS (9) Ehlmann & Leask, 2022, AGU Adv (10) Ehlmann et al., 2011, Nature (11) Michalski et al 2022, Nature Astro (12) Skok et al., 2010 (13) Leask et al., 2024, JGR (14) Ehlmann et al., 2010, GRL (15) Ruff et al, 2020, Astrobio (16) Yen et al, 2021, JGR (17) Wang et al, 2006, JGR (18) Jakosky et al., 2018, Icarus (19) Mahaffey et al., 2013, Science, (20) Hu et al., 2015, Nat. Comm (21) Thomas et al., 2023, PSJ (22) Scheller et al., 2021, Science (23) Edwards and Ehlmann, 2015, Geology (24) Wordsworth et al., 2017 (25) Wordsworth et al., 2021, Nat Geo (26) Adams et al., 2025, Nat Geosci (27) Christensen, 2023, Nature (28) Khuller & Christensen, 2021, JGR (29) Dickson et al., 2023, Science (30) Clow, 1987, Icarus (31) Khuller et al., 2024, Nature Comm Earth & Enviro (32) Mellon et al., 2024, Icarus (33) Wood et al al., 2024, ISME Comm (34) I-MIM mission definition team final report, 2023 (35) Stahler et al., 2022, Nat Astro (36) Lauro et al., 2021, Nature (37) Wright et al., 2024, PNAS