The evolution of habitable environments on terrestrial planets: Insights and knowledge gaps from studying the geologic record of Mars

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Main point: We have made enormous strides in determining the *range* of environmental conditions that existed on ancient Mars from *in situ* and orbital observations, but significant new data are needed to understand the *evolution of these environments over Mars history* and the *conditions under which they occured*. These environments are records of broader Mars surface and subsurface conditions, and constraining the boundary conditions for these environments is critical to developing planet-wide models for the evolution of major parts of the Mars system, such as its internal processes (including links to an early dynamo, volcanism, etc.), hydroclimate (including links to atmospheric pressure/composition, surface temperature, etc.), and habitable environments (where/when/for how long?).

Scope: The evolution of early Mars surface and subsurface habitable environments, pending overlap with other white papers. This is not intended to be a mission-focused white paper but will make recommendations for observations and measurements possible from both orbital and surface missions.

Background: The Mars Exploration Program has steadily accumulated evidence for an astounding variety of ancient aqueous surface and subsurface environments at numerous locations across Mars. High-resolution orbital imaging and spectroscopy have enabled a general characterization of the geomorphology, mineralogy, and stratigraphy of many of these locations. In addition, landed missions have provided detailed evidence for a complex history of multiple aqueous environments at nearly every location visited. These results paint a picture of an ancient Mars with habitable environments perhaps as varied as those that have existed on Earth and have fulfilled the basic goal of determining whether or not Mars supported environments capable of hosting life and preserving signs of life. However, the bigger picture still remains frustratingly elusive - *what factors in planetary evolution lead to sustained habitable environments?* Even though we know that these environments existed, we don't have robust constraints on when or for how long, what climate/atmospheric conditions they existed under and how these conditions changed over time, and how they were created or destroyed by other large-scale processes (e.g., dynamo, volcanism, impacts). Resolving these questions is important for understanding the factors that govern habitability in terrestrial planets, both in our solar system and beyond.

Challenges: We haven't yet been able to construct a rigorous timeline of paleoenvironment evolution across Mars because: (a) the sheer complexity of the history of aqueous processes on Mars can make untangling the sequence of events at any given location challenging; (b) the locations where we have a detailed understanding of the specific environments tend to be highly localized, without clear constraints on timing or links to planetary evolution; (c) the origin of many regionally/globally extensive altered units that may provide clearer links to planetary evolution is poorly understood based on orbital data alone.

Knowledge gaps: These challenges have led to specific gaps in knowledge in several areas. This white paper will provide a brief overview of the state of knowledge in these areas and discuss the significance of knowledge gaps relative to big picture questions.

(1) *Timeline* - Timing (relative/absolute), duration, and persistence of surface/subsurface environments
(2) *Distribution* - Regional variations vs. global trends, connectivity, and uniqueness of landing sites
(3) *Diagenesis* - Temporal/vertical/horizontal extent of post-depositional processes
(4) *Water sources* - Source of surface/subsurface fluids and P/T regime
(5) *Geochemistry* - Fluid chemistry (pH, redox, dissolved cations) and sources of solutes
(6) *Hydroclimate* - Links between environmental records and hydroclimate/atmospheric chemistry
(7) *Analogs* - Fundamental processes and limitations of Earth comparisons (modern or ancient)
(8) *Astrobiology* - Impacts of the above factors on habitability/biosignature preservation over time

Recommendations: This white paper will explore the types of data needed to resolve these knowledge gaps and suggest possible approaches for acquiring these datasets from orbit and *in situ*.

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