THE CASE FOR PALEOCLIMATE SCIENCE FROM A NEXT-GENERATION MARS HELICOPTER.

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Introduction: Ancient habitable climates are the biggest discovery of the Mars Exploration Program. To determine the nature of those climates (warm and wet, or cold and icy?) will require exploring 10^2 km from sediment source to sink: this is enabled by a Mars Science Helicopter.

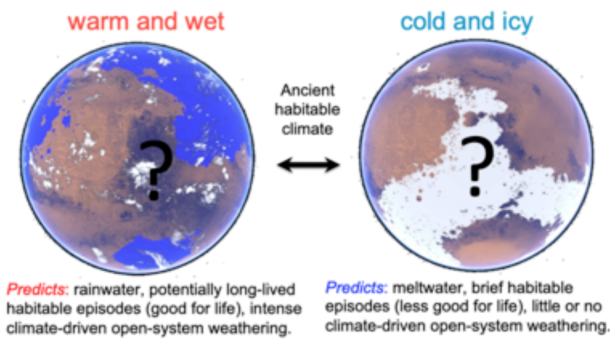

Fig. 1. *Was Early Mars warm and wet, or cold and icy? (Image credit: R. Wordsworth).*

Mars' Early Habitable Era – Opportunity to Test Models of Long-Term Planetary Habitability: What does a habitable planet look like? With JWST data about to arrive, Mars offers a unique opportunity to study – up close – another world that once had a habitable surface [1-2]. However, the triggers, intensity (rain vs. ice-melt), and duration of habitable past climates are all poorly constrained [3-8]. Existing data, and even data we can hope to get from Mars sample return, cannot paint a full picture of Mars' habitability history. In particular, we are missing observations from alluvial fan-forming habitable episodes, which offer some of the strongest constraints on climate models [8].

Three Tests To Determine If Early Mars Was Warm and Wet, or Cold and Icy: *Ingenuity*'s success serves as a pathfinder for a more capable Mars Science Helicopter [9-10]. Equipped with capable cameras, a multispectral imager, and an APXS, a Mars Science Helicopter-based HOPPER (Helicopter Observer for Paleoclimate and Post-habitable Evolution on the Red planet) mission can carry out three tests to determine whether Early Mars was warm and wet vs cold and icy. None can be accomplished with existing missions. (1) *Paleohydrology*. High runoff production (kg/m^2/hr) implies storm rainfall in a warm climate. This runoff production is recorded by river sediments [11-13]. However, to apply this test, we must study a small catchment. This is preferred to big catchments like Jezero [13] that dilute strong storm discharge and mute possible signals of storm rainfall. Furthermore, we must know river width, paleoslope, and (most importantly) bed grain size. We have not yet obtained all those data for Mars, and so today paleorunoff production has 300× uncertainty [13-14]. (2) *Timescale*. The lifetime of individual paleolakes decisively discriminates between different models of climate and of climate evolution [8]. However, new techniques are needed, because crater chronology is too crude, terrestrial analogy is insufficient, and (due to intermittency) radiogenic dating can only give upper limits. (3) *Extent of open-system weathering, and associated mineralogy* can be good climate proxies [15-17]. However, to apply these proxies with confidence, measurements of both source and sink rock composition are needed. Fluvio-lacustrine source rocks on Mars are typically ~10^2 km away from sink rocks, so helicopter mobility enables this test.

How Mars Science Helicopter Enables This Science Mission: Carrying out these tests requires specific geologic systems. The necessary conditions include small catchment areas, access to both source and sink rocks, and relatively recent sedimentary deposits (tail end of Mars' habitable era). None of these conditions are met by existing data or surface assets.

The helicopter's most important asset is range. In addition, hopping over hazards could allow multiple fluvial systems to be profiled from source to sink. Additionally, the helicopter would be able to capture imagery and spectra even during hops when traversing terrain where landing is not possible.

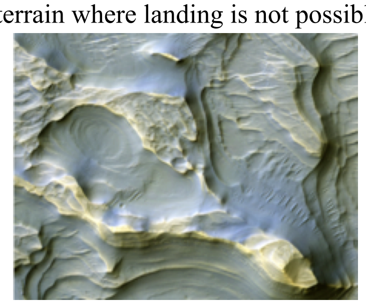

Fig. 2. *Layered alluvial fan deposits exposed by wind erosion at Saheki crater. Image is 500 m across. From [18].*

The instrument payload for the HOPPER must include cameras (for in-flight and landed use, with sub-cm resolution at 10-meter distance to measure deposit dimensions, grain size, and layer thicknesses, multispectral capabilities for VNIR mineral identification, and an APXS). This payload allows measuring source-to-sink changes in grain size, channel width, and chemistry with mineralogical-assessment support. Total payload mass < 3 kg is achievable with instruments currently at TRL 6-9, well within planned Mars Science Helicopter capabilities.

Where To Fly: Mars has ≥6 science sites + landing zones that encourage the mission concept presented here (based on CTX DTM slopes, HiRISE DTM slopes, elevations, total traverse lengths, etc.). For example, in Saheki crater (Fig. 2) [18], alluvial fans drain small catchments small enough to capture the rainstorm runoff signal on a warm and wet Mars (paleodischarge). Paleodischarge (m^3/s) for small catchment of known area (m^2) gives runoff production *R* (mm/hr). These steepland areas also expose the source rock for the entire sedimentary system, where composition can be measured using VNIR spectroscopy and APXS.

Within source-to-sink systems, HOPPER would use multiple measurements to set up to three independent lower limits on how long rivers flowed on Mars. For example, HOPPER would use sediment flux (m^3/s) [19] for fans of known volume (m^3), obtained from paleodischarge, to estimate the timescale of habitable-era sedimentation. Embedded (synsedimentary) impact craters and unconformities would provide additional constraints. All these timescales are important not only for constraining Early Mars climate models, but also for understanding how favorable Early Mars was for the survival of microbes.

Saheki also features flat-lying lake deposits where mineralogy and major element chemistry of sink rocks can be measured and compared to source rocks to quantify the effect of climate-driven weathering on the sedimentary system, especially for fine-gained materials [17]. Aqueous geochemical conditions are recorded by altered primary materials and secondary phyllosilicates, oxides, and salts. Detectable and quantifiable relative mobilities of elements and secondary mineralogy therefore reflect ancient pH, Eh, temperature, and other geological conditions.

Traverses: Many safe landing sites enable HOPPER science [20], including S. Holden, Runanga, and Saheki craters. The paleochannels and alluvial fans needed for HOPPER's science objectives are also conducive to helicopter exploration, with gentle slopes suitable for hopping along the full source to sink system. HiRISE DTM analysis shows that wind eroded fans have plenty of suitable hop sites for a helicopter, including "lily pads" at different elevations throughout the fan stratigraphy which would enable HOPPER to trace changes through time. Maximum flight length is <3 km (to fly over the host crater rim). Peak elevations for several candidate traverses are < -1 km. Total traverse distances, including flying from flat landing sites into the crater of interest, are < 200 km. Depending on target, extended mission opportunities could include Noachian crustal science at Valles Marineris.

Take-Home: HOPPER would carry out 3 tests not possible with existing data or mobile assets to answer the question: Was Early Mars warm and wet or cold and icy? HOPPER would also address questions of programmatic interest, providing:

- The first ground-truthing of paleohydrological and sedimentological techniques applied to Mars using orbital data.
- Constraints on the timescale and intermittency of habitable climates at the time in Mars history that is most difficult to match using existing climate models.
- Observations of younger sedimentary deposits for comparison with the sedimentary units in Gale Crater to identify differences in lacustrine and fluvial environments on Mars on different spatial and temporal scales.
- An opportunity to test how well mineralogy and major element composition record climate-driven chemical weathering in an environment less affected by diagenesis.

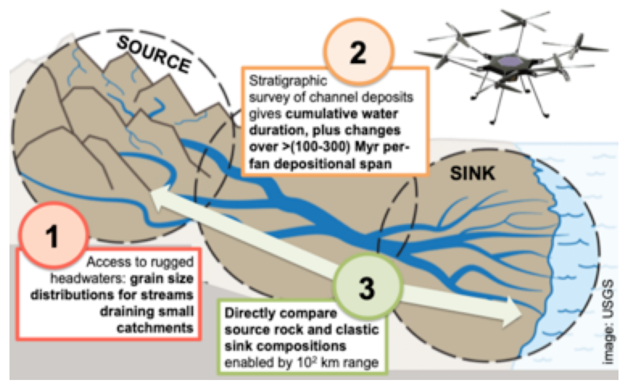

Fig. 3. Helicopter mission can close knowledge gaps. *Advantages of a helicopter are range (10^2 km), ability to hop over hazards, ability to view deposits from above and from the side, and ability to capture images and spectra even in rough, inaccessible terrain where landing is not possible.*

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