Salty Environments: The importance of evaporites and brine environments as habitats and preservers of biosignatures

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1. Executive Summary

The habitability of ancient Mars is directly related to the presence of late Noachian surface waters and their stability over geologic time. Evaporite minerals can capture and entomb organic matter, biological compounds, and intact cells within their intercrystalline and intracrystalline structure because they precipitate relatively quickly (Schopf et al. 2012). Additionally, evaporites can form macroscopic sedimentary structures understood to form in association with biological processes (e.g. stromatolites and other microbialites; Babel 2004, Braissant et al., 2008; Allwood et al. 2013). Thus, evaporite minerals constitute a target for biosignature investigation on Mars where evaporitic deposits have been observed by orbital CRISM spectroscopy (Viviano-Beck et al. 2014). Such environments may be found in ice interfaces on Europa as well, where NaCl and Mg-rich sulfate salt minerals are thought to exist (Trumbo et al. 2019), and other ocean worlds. The purpose of this National Academy of Sciences white paper for the 2023-2032 Planetary Science and Astrobiology Decadal Survey is to highlight the strategic importance of evaporite minerals and brine settings on Mars and Europa as astrobiological targets of interest that would be able to contribute to future mission objectives. These are:

- A) Evaporite minerals can preserve intact fluids over geologic time, thereby recording ancient aqueous environments within the mineral matrices.
- B) Extant life can utilize preserved mineral fluids within micron-scale inclusion environments.
- C) Biosignatures from extinct life can also be preserved within fluid inclusions of evaporite minerals.
- D) Brine environments can support extant cellular life via depression of the freezing point of liquid water and by lowering eutectic temperatures.
- E) Both evaporites and brines offer radiation protection and long-term desiccation prevention allowing for extant life to potentially be maintained in modern Mars and Europa environments.
- F) Evaporite minerals are widespread globally across Mars and can benefit future Mars Sample Return mission objectives.

2. Introduction and Motivation

Hydrated minerals and evaporites have been observed within the shallow subsurface of Mars in proximity to ancient aqueous settings either via groundwater or evaporated lake beds, and thus these minerals are relevant to Mars investigations (Barbieri & Stivaletta, 2011; Ehlmann et al. 2014). Moreover, recent *in situ* observations of sulfate-bearing bedded deposits, sulfate nodules, and secondary mineral veins (e.g. Rapin et al. 2019) on Mars show that these evaporite, hydrated, and fluid-altered features from ancient surface and groundwaters are of significant size, being able to survive physically over geologic time (Fig. 1). These meter-scale regions can provide ample sample sizes for future Mars Sample Return analyses from already selected mission sites containing hydrated minerals and evidence of direct exposure to ancient fluids and fluid-rock interactions. Upcoming missions include the *Perseverance* Mars rover, which will arrive at Jezero crater in 2021 and perform the first stage of a sample collection for eventual returned analyses. To

enhance the probability of detecting biosignatures on the Martian surface, it is imperative that samples from sites that had direct access to late Noachian waters be included both for *in situ* analyses and for returned samples.

Fig 1. Examples of Ca-sulfate mineral veins. (Top) Adopted from Rapin et al. (2019) showing Ca-sulfate veins as mapped in the Murray formation from MastCam images mcam09306 and mcam08521. (Bottom) MAHLI image adopted from Yawar et al. (2019) showing multiple sets of variable oriented striations from Sol 2044. Both mineral vein assemblages imply significant volumes of hypersaline water for a prolonged amount of time allowing for precipitation.

At Europa, cracks open and close due to tidal forces, enabling the possibility for ocean water to permeate the ice crust in the form of dikes and sills in the subsurface (e.g. Manga and Michaut 2017; Craft et. al 2016) as well as material that may extrude onto the surface (e.g. Fagents et al., 2000; Quick et al., 2017; Walker et al. 2020). As these features cool and solidify, the material,

“cryomagma/-lava” may concentrate down to highly saline layers in the subsurface or within the surface feature, and may act as excellent locations for harboring life or preserving biosignatures.

3. Targets of Opportunity: Evaporites provide direct access to ancient fluvial processes

The widespread hydrous precipitation and alteration phases and closed basin nature of many of the regions on Mars observed by digital elevation models from HiRISE and CRISM onboard the Mars Reconnaissance Orbiter (MRO) (Viviano-Beck et al. 2014; Ehlmann and Edwards, 2014; Weitz & Bishop, 2018; Jolliff et al. 2019; Ye and Glotch, 2018) shows how craters and other closed-basin hydrogeological settings are host to these hydrated minerals. Regions where depressions (from craters or other similar landmass) and hydrated minerals are found together show the frequency of potentially hundreds of ancient salt lake sites on the Martian surface. On Earth, previous studies (Perl and Baxter, 2020) have utilized Great Salt Lake as an analogue site to monitor transfer of halophilic microbial life and biological/cellular material from the lake brine to the evaporitic minerals. This process uses the hypersaline waters as the source for both the mineral precipitation and the transfer mechanism. On Mars, these minerals from late Noachian waters would have remained behind as the atmosphere dissipated over millions of years (Mancinelli et al., 2004). In addition, the halite and gypsum deposits on Mars are favorable to radiation protection while allowing exposure to visible light that supports photobiology (Cockell and Raven, 2004). If life (either similar or dissimilar to Earth life) ever existed on Mars during a time when water was stable on the surface and evaporating, resulting in hypersaline waters, that life would likely be halophilic. These halophiles would have evolved to tolerate ever increasing osmotic stress as those hypersaline waters dried up over many thousands to perhaps millions of years. Moreover, evaporitic minerals would have recorded the last presence of stable surface waters from the early Hesperian with potential alteration processes of later groundwater movement possibly dissolving these soluble minerals. **Therefore, these hydrated minerals, already detected by CRISM all across Mars, are the last mineral assemblages to have been precipitated by ancient Martian waters or later altered by fluvial processes.** These two factors make evaporite minerals a prime target for both ancient records of water and evidence of ancient or extant life. With these factors in mind, we suggest the following strategies for astrobiological investigation of salty environments:

- Orbital investigations of hydrated minerals should constantly be updated for future landing site candidates and spectral diversity of mineral detections (see White Paper by Rivera-Valentin et al. (2020) for further VNIR details). This will require replacing CRISM at the end of its lifetime to be able to continue the investigation with increasing level of detail.
- Future in-situ observations by *Curiosity*, *Perseverance*, and new future landed missions should treat exposed bedded sulfates and hydrated mineral veins (Fig. 1) as potential organic hotspots. Sample analyses should include both dust-covered and cleared mm-scale areas. While the minerals themselves help preservation (Cockell and Raven, 2004; Perl and Baxter, 2020; Carrier et al. 2020), further UV-C protection may occur from the dust itself depending on thickness and seasonal winds.
- Should evaporite features be chosen for Mars Sample Return, samples should be collected from as “deep” as possible within the evaporitic structure. Moreover, if the rover’s mobility permits,

those samples should be obtained from a section that has had the least amount of UV-C exposure, such as under an overhang within a sediment layer or outcrop.

- Seismic investigations of Europa should be prioritized to detect brine layers as well as surface features indicative of cryovolcanism (Walker et al. 2020 *White Paper*) that would enable a landed mission to target a location where ocean water has reached near or to the surface. Subsurface cryobot technology development should be supported in the next decade to enable access to deeper ice layers and later the ocean itself (Schmidt et al. 2020 *White Paper*)

4. Extant Life: Preservation of Biology and Biological Processes

On Earth, ocean salinity is ~3.5%, whereas in closed-basin lake systems salinities can range up to ten-fold higher. Due to similar salt mineral assemblages on Mars and their widespread diversity of chlorides, phyllosilicate clays, sulfate salts, and other hydrated minerals it is likely that many of the ancient lake systems had salt concentrations that would have allowed organisms to be preserved rather quickly as those lakes dried out. On Mars, the CRISM instrument has shown the direct relationship between exposed km- and meter-scale hydrated minerals and the locations of ancient aqueous environments where late Noachian / early Hesperian waters were located, likely in the form of lakes, river deltas, and other standing bodies of water. Groundwater events possibly aided in secondary alteration processes with global desiccation allowing for evaporite minerals to remain undisturbed by mineral dissolution, providing a zone between the surface and shallow subsurface where pristine minerals could be preserved. If life ever existed on Mars (independently from Earth), it may have evolved in response to changing UV conditions via photoprotection mechanisms (see Fig. 2a). Some of the underlying adaptations may be measured remotely as well as in laboratory settings; for example, membrane-embedded pigments could be measured by a rover's payload using Raman spectroscopy or by a myriad of instruments with returned samples. Terrestrial evaporites that preserve carotenoid-containing cells may feature distinct pigmentation correlated with depth, based on environmental exposure to visible or damaging ultraviolet light (UV). Entombed fluids (Fig. 2b,c) are usually a product of the original fluid inputs to the evaporite mineral during precipitation, making the internal entombed fluids potentially as old as the age of the mineral. However, if fracturing occurs, fluids can be lost or replaced with later fluidic events (e.g., secondary / late-stage alteration).

Mineral Pigments

On Earth, examples of pigmented brine and evaporite minerals can be found at the salt-saturated Great Salt Lake north arm where studies have revealed carotenoid-containing microorganisms in abundance (Perl et al. 2019; Perl and Baxter, 2020). Although there are bacterial and algal species that have these pigments, the consortia here are largely dominated by halophilic archaea (Almeida-Dalmat et al., 2015). These pigments underlie important strategies for overcoming the challenges of an extreme environment as they allow halophilic archaea to survive high doses of UV light (Jones and Baxter, 2017). This capability, in addition to desiccation resistance, metabolic flexibility, and osmophily, suggest that these are poly-extremophiles, and thus archaea may be excellent life forms to study when considering a search for potential extinct or extant life in a Martian evaporite formation. Considering that the timescale of geologic change is magnitudes longer than the demonstrated preservation timescale of living microorganisms on Earth,

biosignatures in ever-changing hypersaline settings could be either physical or chemical. In the case of hypersaline environments, it is possible to see physical biosignatures (e.g., pigments, organic layering, and biofabrics) with the naked eye or visual color images. Chemical biosignatures (e.g., highly variable and concentrated amino acids, hopanes, fatty acids, and other long-chained macromolecules) require more in-depth analyses and some of them may be produced abiotically and thus not diagnostic of life, but are significant alongside physical biosignatures (Perl et al. *in-review*).

Fig. 2 (Adopted from Perl and Baxter, 2020)
Evaporite minerals at the north arm of Great Salt Lake. (a) Halite terrace forming as the north arm waters of Great Salt Lake recede in summer desiccating conditions. Evaporation may lead to entrapped pigmented halophilic microorganisms as the lakeshore is desiccated, which results in pink halite. Note the layered pigmented sections below non-pigmented material (Perl 2019). The scale bar represents ~12 cm. (b) A typical halite hopper crystal collected from the north arm of the lake. Fluid inclusions are evident in the crystalline structure. The scale bar represents 0.10 cm. (c) Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) crystal retrieved from the sediment of evaporated brine from the north arm shore, showing entombed Fe-rich clays within the transparent mineral matrix. The scale bar represents ~1 cm. During precipitation, these minerals tend to align vertically and perpendicular to saturated sediments and fluids needed for crystal growth

We suggest the following astrobiological strategies for extant life detection:

- Future instrumentation such as high resolution, i.e., micron-scale, optics combined with enhanced Raman analyses to distinguish between preserved organics and mineral substrates.
- A combination of “standoff distance” (e.g., MSL laser-induced breakdown spectroscopy) and on-board measurements of the vibrational spectra of water and ice using Raman and VNIR spectroscopy for *in situ* sample analyses would be needed for confirmation of evaporite minerals still preserving liquid water. These could also be utilized for Recurring Slope Lineae brine analyses, should special region measurements be allowed in the future.
- Pigments within hydrated minerals should be a top priority for *in situ* future analyses and returned sample collection (Neveu et al. 2018; Perl and Baxter, 2020). Moreover, spectral separation of pigmented features vs. minerals and regolith needs to be understood for preservation metrics.

5. Ancient Life and Biosignature Preservation

The current search for biosignatures from ancient life relies directly on the preservation medium and the original volume of potential biological matter being preserved. Whether that is in the form

of cellular material, pigments, total organic species, hopanes, or other complex compounds (Cockell et al. 2020), the preservation potential is highest when fluids are involved (Summons et al. 2011) and are potentially the same source fluids as those that precipitated the original minerals. The global distribution of hydrated minerals, including Gyr-old sulfate veins, large gypsum deposits, and mm-scale evidence of soluble salts on Mars that are in close proximity to ancient aqueous settings from the late Noachian/early Hesperian could have been host to *in situ* microbial processes/organic matter should it have ever existed within the water column of a Martian lake or evaporative setting.

Morphological Biosignatures

Previous studies have shown that morphological fossil biosignatures may be captured and preserved in evaporative environments on Earth. These biosignatures occur over a range of spatial scales including cm to meter-scale gypsum-hosted stromatolites (Allwood et al., 2013) and other microbialites (Babel 2004), and as micro-scale organic microfossil remains (Schopf et al., 2012). Although further technology development would be required to directly image micron-scale microfossil structures during *in situ* robotic exploration activity, these fossil structures can retain organic carbon signatures in the form of kerogen. Aggregates of carbonaceous microfossil remains may be measured by higher optical resolution Raman spectroscopy instruments. Therefore, one ideal target for *in situ* investigation would be macro-scale biomediated sedimentary structures (e.g. stromatolites) that might retain organic carbon signatures of a relict microbial population. Further detailed analysis of such samples in Earth-based labs would be required using multiple lines of evidence (e.g. microfossil complexity, the presence of biomolecules, isotope distributions, etc.) in order to establish biogenicity.

Fluid Inclusions

On Mars the limited availability of groundwater *after* evaporite precipitation near present-day dried lakebeds could allow for stability of highly soluble evaporites to remain physically intact over geologic timescales. Secondary mineral precipitation can also play a role if post-evaporation fluids are at low enough volumes as not to dissolve the primary mineralogy likely in close proximity to evaporating lakebeds. The volume of water, water chemistry, and salinity are the major controls on the type and size of evaporite minerals precipitated. Evaporite minerals are uniquely suited for both informing past (ancient surface waters) and modern aqueous (closed basin lake systems) activity of a region and for entombing sediment, clays, and organisms (Fig. 2) in its crystal substrates via fluid inclusions, providing life with enough energy to maintain homeostasis and nutrient cycling. Of course, this is not to say that all evaporite minerals contain microorganisms, but having preserved records of ancient water activity in rover-accessible settings would be vital for future sample return mission decisions and *in situ* analysis. This also intuitively shows the direct relationship between the medium of preservation and the ability to “protect” its entombed organic contents for an extended period. Summons et al. (2011) assessed several early environments in the context of ancient Mars to determine which settings had the likelihood of supporting organic matter formation both abiotically and biotically, the concentration/preservation of those organics, and the probability of *in situ* discovery within geomorphic, mineralogical, and stratigraphic contexts. This assessment ranks lacustrine settings “high” for relative preservation ability, pointing to the significance of brine and evaporite sites. We suggest the following astrobiological strategies for ancient biosignature preservation and detection:

- *In situ* exploration activities should seek macroscopic sedimentary features suggestive of biological activity (e.g. stromatolitic structures and other “microbialite” structures and potential biofabrics)
- Aggregates of microfossil remains may retain a measurable organic carbon signature. We therefore should look for such signatures within the sedimentary structures mentioned above, and among other distinct evaporite textures that may retain ancient organic material.
- On Earth, fluid inclusions can be maintained and preserved at least to the Permian and are measurable via Raman analyses. Thus, these micron-scale environments should be top priority for *in situ* and return sample analyses.

6. Strategies for Life Detection and Validation of Biology

As we proceed into the future of life detection missions, the context of prospective life and its potential habitats should be considered, especially with regards to available nutrient reservoirs and metabolic potential. The goal of life detection should involve more than a single aspect of evidence; thus, the burden of proof should be undeniably large, requiring data from several independent fields (e.g., Cady, 2001). For extant life, these lines of evidence should include biochemical analyses to explain critical survival strategies (McKay, 2004; Pross, 2011) in varied energetic and extreme environments where nutrients may be photochemical and/or geochemical. For extinct/ancient life, biosignatures related to adaptation of Earth’s extreme life should be sought and correlated to the analyses of the geologic environment over time.

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