HABITABILITY OF THE SHALLOW SUBSURFACE ON MARS: CLUES FROM THE METEORITES

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Introduction The properties that define habitability are commonly understood to include the following:

- ⇒ Presence of water
- ⇒ Temperature range allowing some or all of the water to be liquid
- ⇒ A suitable physical volume or space permitting metabolism and growth
- ⇒ Presence of organic compounds or the building blocks to make them
- ⇒ Presence of an energy source suitable for utilization by living organisms

Interpretations of Mars Viking, Surveyor, and Odyssey orbital images have built a strong case that Mars had surface water during its past geological history. Neutron spectrometer data from Mars Odyssey show that poleward of about 60 degrees North and 60 degrees south, significant hydrogen, likely as ice or permafrost, is present in at least the upper meter or so of the martian regolith and crust and that similar high hydrogen areas exist, even near the equator [1]. Here we present a summary of independent data from the Mars meteorites showing that liquid water was present for at least some of the time in the upper few meters or tens of meters as early as 3.9 billion years (Ga), and was present at intervals and at various locations throughout most of Mars history.

Results and Discussion Currently, about 28 martian meteorites are available in collections on Earth. These meteorites have formation ages ranging from 4.5Ga to 165 million years (Ma). Estimates of formation depths have been done for some of these meteorites based on silicate zoning profiles and results give relatively shallow crystallization depths of <1m to ~5m [2]. Model depths before ejection from Mars range from the upper meter to a maximum of ~100 meters [3]. Consequently, many Mars meteorites probably spent most of their lifetime on Mars in the very shallow subsurface.

All of the meteorites recovered so far are igneous rocks and would not be expected to contain information on sedimentary or low temperature processes. Yet, many of these meteorites contain cracks and pores formed on Mars that display clear evidence of secondary alteration, weathering, and mineral and precipitation from a water phase. Textural evidence shows that much of this alteration and precipitation is secondary and occurred on Mars but after the original igneous rocks cooled and became fractured [4-7]. Within these meteorites the evidence for aqueous alteration includes:

a) abundant weathering and corrosion textures,
b) the production of secondary water-precipitated minerals including smectite, carbonate, magnetite, hematite, Fe-sulfides, and Ca-sulfate
c) very thin clay-rich layers deposited in cracks and pores [8-10]. Amorphous SiO2, probably originally a gel, is also present in some meteorites; more than one generation is sometimes apparent (Fig. 1).

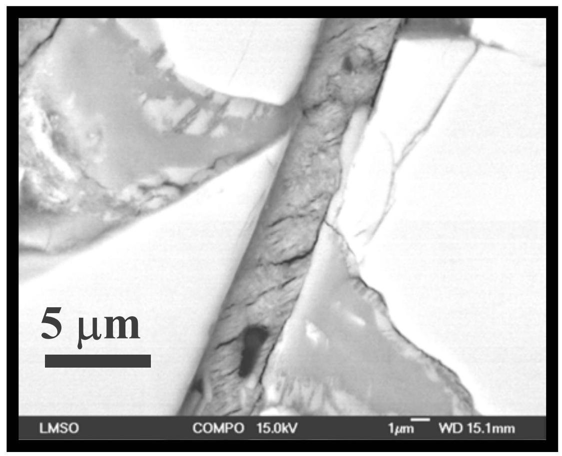

Fig. 1. Clay minerals (darker gray) and carbonates (lighter gray) filling cracks in olivine (white), cut by a later generation of Ca-sulfate filling. (Nakhla)

Many of these secondary minerals likely formed at relatively low temperatures; all apparently formed from liquid water. Examples of meteorites showing extensive secondary alteration by water include ALH84001, Nakhla, and Lafayette [e.g., 7,8,11] (Fig. 2). The evidence that these secondary minerals were formed on Mars is both textural and chemical. Secondary minerals in cracks show truncation and heating by the terrestrial fusion crust. Some of the secondary minerals have deuterium isotopic ratios much higher than any terrestrial values showing that the bound water was Martian. A terrestrial analogy might be the altered zone in sub-oceanic basalts in which basaltic glass is altered into clays, carbonates, and other secondary minerals at low temperatures along fractures and within vesicles [12].

While these secondary phases are common, they are not pervasive in any of the rocks. Most of the original minerals remain including both olivine and pyroxene.

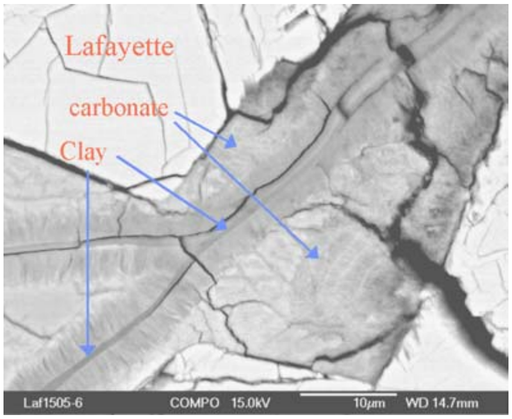

Fig. 2. Complex martian secondary assemblege in cracks in olivine in Lafayette.

Long-term exposure (hundreds of millions of years) to water would likely completely alter these minerals, even at low temperatures. It is therefore unlikely that these rocks were immersed in liquid water over a significant proportion of their residence time in the upper martian crust or regolith. Rather, they were likely subjected to occasional exposure to water, perhaps episodically. However, even short intermittent exposure to water could provide a favorable habitat for microbial life which may have survived in a dormant stage between these wet episodic events. Survival of microbes in permafrost for extended periods of time is well-documented [e.g., 13].

Indigenous organic carbon is also present in many Mars meteorites. Nakhla, for example, has at least 300ppm organic carbon, 80% of which lacks terrestrial ^{14}C signature and is therefore from Mars [14].

Conclusions If microbes inhabited the secondary cracks and pores observed in Martian rocks, they required a source of energy and nutrients. Energy can come from disequilibria in redox states. For example, iron can occur as both both Fe^{2+} and Fe^{3+}, where the $Fe^{3+}/\Sigma Fe$ ratio can be used as an indicator of redox conditions. Critical nutrients for many microbes include Fe, P and S. These elements are present in Mars meteorites in the form of abundant readily water-extractable phosphate including apatite and whitlockite. Iron is present in both ferrous (Fe^{+2})and ferric (Fe^{+3}) oxidation states in the following minerals: hematite (Fe^{+3}), magnetite (Fe^{+2}, Fe^{+3}), siderite (Fe^{+2}), pyroxene (Fe^{+2}), olivine (Fe^{+2}), and smectite (Fe^{+3}) (Note: for simplicity the most typical oxidation states are given here). Important sulfur-bearing phases in Martian meteorites include sulfates (S^{+6}) and sulfides (pyrite (S^{-1}) and pyrrhotite (S^{-2})). These minerals could readily provide energy for iron or sulfur oxidizing and reducing microbes.

Summary All of the requirements for a habitable environment on Mars are present as revealed by the meteorites: the presence of liquid water, significant organic carbon, microenvironments in cracks and crevices suitable for sheltering microbes, energy sources provided by reduced and oxidized iron and sulfur mineral, chemical disequilibria between the water and the enclosing rocks, and the presence of abundant labile minor and trace elements important to life such as phosphorous. It is clear that at least some of the shallow martian subsurface, as sampled by these martian meteorites, has been a hospitable place for life at least episodically throughout most of all of Mars history.

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