HABITABILITY, ORGANIC TAPHONOMY, AND THE SEDIMENTARY RECORD OF MARS.

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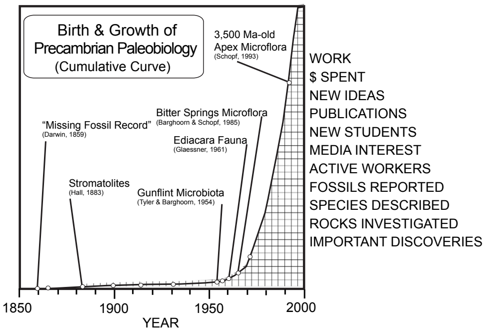
Habitability: Loosely defined, a habitable environment is one that has water, a source of carbon (to enable organism metabolism), and a source of energy (to fuel organism metabolism) – in other words, the essential ingredients for life as we know it on Earth. A space mission such as Mars Science Laboratory (MSL) ideally needs to be able to detect C,H,N,O,P and S, minerals that show mixed valence states, provide constraints on water activity (salinity), and also that a past aqueous environment had longevity sufficient support a microbial biosphere. The MSL *Curiosity* rover did accomplish all of these goals [1] in the context of an ancient fluvial-lacustrine-groundwater system. It is important to extend this to other settings that may involve fundamentally different geology, such as that discovered by the *Opportunity* rover in an ancient hydrothermal setting [2], as well as other low-temperature sedimentary settings.

Each of these settings requires a conceptual model to guide exploration in order to enhance mission efficiency. Such an approach worked well in guiding exploration with *Curiosity*. Mission data indicate that an ancient habitable environment existed at Yellowknife Bay, Gale Crater, where stream waters flowed from the crater rim, and pooled in a curvilinear depression at the base of Gale's central mountain to form a lake/stream/groundwater system that might have existed for millions of years [1]. *Curiosity's* X-ray diffraction data provide evidence for moderate to neutral pH, as shown by the presence of Fe-smectite clay minerals and absence of acid-environment sulfate minerals, and show that the environment had variable redox due to the presence of mixed valence Fe (magnetite) and S (sulfide, sulfate) minerals formed within the sediment and cementing rock [3]. Elemental data show that lake salinities were low due to the very low concentration of salt in the lake deposits; these data indicate that clays were formed in the lake environment and that minimal weathering of the crater rim occurred, suggesting to that a colder and/or drier climate was prevalent [4].

Evolved gas analysis data, via pyroloysis, indicate the presence of nitrogen and carbon-bearing materials. CO_2 may have been generated by either carbonate or organic materials [5]. Concurrent evolution of O_2 and chlorinated hydrocarbons indicates the presence of oxychlorine species. Higher abundances of chlorinated hydrocarbons in the lake mudstones, as compared to modern windblown materials, suggest that indigenous Martian or meteoritic organic C sources are preserved in the mudstone; however, the possibility of terrestrial background sources brought by the rover itself cannot be excluded.

For sedimentary settings, Earth provides many useful analogs that can be modified for application to Mars, and the martian geologic record increasingly shows substantial diversity of sedimentary rocks. Application of geologic models in the search for ancient organic materals is particularly important, as only a subset of ancient habitable environments will also preserve organic compounds.

Organic Taphonomy: MSL results demonstrate that early Mars was habitable, but that does not mean that Mars was inhabited. Even for Earth it was a formidable challenge to prove microbial life existed billions of years ago - a discovery that occurred almost 100 years after Darwin predicted it [6], through the recognition of microfossils preserved in silica (see figure). The trick was finding a material that could preserve cellular structures. A future mission could do the same for Mars had life existed there. *Curiosity* can help now by trying to understand how organic compounds are preserved in rocks which, in turn, could provide guidance to narrow down where and how to find materials that could preserve fossils as well. However, it is not obvious that much organic matter, of either abiologic or biologic origin, might survive degradational rock-forming and environmental processes. Our expectations are conditioned by of our understanding of Earth's earliest record of life, which is very sparse.



The rate of discovery of Precambrian fossils increases dramatically after the discovery of chert as a "magic mineral in 1954. Adapted from Schopf, 2000.

Paleontology embraces this challenge of record failure through the subdiscipline of "taphonomy", which seeks to understand the process of preservation of materials of potential biologic interest. On Mars, a first step would involve detection of complex organic molecules, of either abiotic or biotic origin; the point is that organic molecules are reduced and the planet is generally regarded as oxidizing, and so their preservation requires special conditions. For success, several processes must be optimized. Primary enrichment of organics must first occur, and their destruction should be minimized during the conversion of sediment to rock, and by limiting exposure of sampled rocks to ionizing radiation. Of these, the third is the least Earth-like (Earth's thick atmosphere and magnetic field greatly reduce incoming radiation). *Curiosity* can directly measure both the modern dose of ionizing cosmic radiation [7], as well as the accumulated dose for the interval of time that ancient rocks have been exposed at the surface of Mars [8].

The radiation environment on Mars impacts how any organic molecules that might be present in ancient rocks may degrade in the shallow surface (top few meters) [7]. This shallow zone is penetrated by radiation, creating a cascade of atomic and subatomic particles that ionize molecules and atoms in their path. Their measurements over the first year of *Curiosity's* operations provide an instantaneous sample of radiation dose rates affecting rocks, as well as future astronauts. Extrapolating these rates over geologically significant periods of times, and merging with modeled radiolysis data, predicts 1000 fold decrease in 100 amu organic molecules in ~650 million years.

Sediments that were buried and lithified beneath the radiation penetration depth, possibly with organic molecules, would eventually be exhumed by erosion and exposed at the surface. During exhumation organics would become subject to radiation damage as they entered the upper few meters below the rock/atmosphere interface. The timescale of erosion and exhumation, and thus the duration that any parcel of rock is subjected to ionizing radiation, can be determined by measuring cosmogenically produced noble gas isotopes that accumulate in the rock. ^{36}Ar is produced by the capture of cosmogenic neutrons by Cl, whereas ^{3}He and ^{21}Ne are produced by spallation reactions on the major rock-forming elements. MSL results show that the sampled rocks were exposed on the order of ~80 million years ago, suggesting that preservation of any organics that accumulated in the primary environment was possible although the signal might have been substantially reduced [8].

Wind-induced saltation abrasion of the rocks in Yellowknife Bay appears to have been the mechanism responsible for erosion and exhumation of the ancient lakebed sampled by *Curiosity* [8]. The geomorphic expression of this process is a series of rocky scarps that retreated in the downwind direction. Understanding this process leads to the prediction that rocks closest to the scarps were most recently exhumed and thus most likely to preserve organics, all other factors being equal. This approach can be applied to future missions. In this manner, the MSL mission has evolved from initially seeking to understand the habitability of ancient Mars, to developing predictive models for the taphonomy of Martian organic matter.

References: [1] Grotzinger, J.P., *et al*., *Science* 10.1126/science.1242777 (2014). [2] Arvidson, R.A. et al., *Science*,10.1126/science.1248097 (2014) [3] Vaniman, D.T., et al., *Science* 343, 1243480 (2014). [4] McLennan, S.M., et al., *Science* 343, 1244734 (2014). [5] Ming, D., et al., Science 343, 1245267 (2014). [6] Schopf, J. W., PNAS, v. 97, (2000). [7] Hassler, D.M., et al., *Science*, 1244797 (2014). Farley, K.A., et al., *Science*, 1247155, (2014).

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