GLASSY SUBAQUEOUS LAVAS AS A HABITAT FOR LIFE ON EARTH, MARS, AND ELSEWHERE?

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Introduction: Numerous studies over the past decade have demonstrated that microbial life rapidly colonizes terrestrial subaqueous volcanic glass [1-5]. Evidence for microbial alteration of terrestrial subaqueous volcanic rocks has been reported from modern ocean crust, ophiolites, and Archean greenstone belts [1-5]. Microbial alteration structures with characteristic granular and tubular morphologies are produced by microbial etching of glassy lavas. These structures are preserved in the geological record via mineralization by a variety of phases including titanite ($CaTiSiO_5$). It is hypothesized that microbes alter the local pH to enhance glass dissolution, and may extract chemical energy and nutrients such as Fe, Mg, Mn, Co and Zn. It is proposed that metabolically unimportant elements including Ti are passively accumulated in this process; Ti thus accumulated may then form titanite. Comparison of bioalteration textures throughout the terrestrial rock record to microbial alteration textures in modern seafloor glasses shows striking similarities, see Fig. 1. Exploration of these terrestrial biosignatures may elucidate the possibilities for the detection of traces of ancient Martian life in similar environments, and may inform the choice of future robotic/human sample return missions.

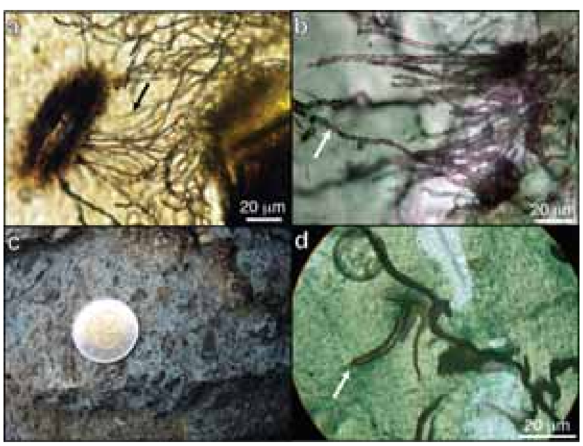

Figure 1: Tubular microbial alteration structures in a) modern oceanic crust, and b) mineralized by titanite in an Archean greenstone belt. c) Field photograph of hyaloclastite in an Archean greenstone belt. d) Tubular bioalteration structures mineralized by titanite from hyaloclastite shown in c.

Biogenicity: The biogenic nature of these structures is supported by diverse and independent lines of evidence.

Morphology and Population Distributions: Two textural types of microbial alteration are commonly observed in basaltic glass preserved as pillow rims or within volcaniclastic rocks: tubular and granular. Tubules tend to be larger than granules, but both display log-normal size distributions, a common property of biological systems [6]. Tubular textures are characterized by micron-scale, tubular to vermicular features and branching bodies. These tubes are commonly highly convoluted, ramose, and/or twisted. Granular textures appear as solid bands, semicircles or irregular patches of individual and/or coalesced spherical bodies with irregular protrusions into fresh glass. Both textures are observed to extend away from fractures and glass shard boundaries, along which liquid water was once present, into unaltered glass. Detailed SEM imaging reveals the presence of delicate filament-like structures and material resembling desiccated biofilm. The filaments are commonly attached to tube walls and display complex morphologies including hollow, filled, and segmented varieties. The filaments are primarily composed of clay minerals similar in composition to palagonite formed during abiotic alteration of basaltic glass. However, these morphologies do not resemble diagenetic clay minerals or inorganic dissolution features but are suggestive of a biogenic origin.

Element Distribution: X-ray element maps collected by electron microprobe show elevated levels of C, N, P, S and K associated with microbial alteration features in modern oceanic crust samples. Similar enrichments in C and to a lesser extent N and P have been detected in Archean samples. In all cases, the enrichments are highly restricted to the immediate area of the microbial alteration features. Further, the C-enriched areas are not correspondingly enriched with elements such as Ca, Mg, Fe or Mn, which commonly form carbonates; therefore this C-enrichment is interpreted to represent residual organic matter [2,4]. Modern samples have been characterized at the nanometer scale with Scanning Transmission X-ray Microscopy to map carbon speciation and iron redox state within the microbial alteration channels in modern samples [5]. Partially oxidized Fe^{2+} and pervasive carbonate groups are intimately associated with organic carbon in the channel-filling smectite, which is separated from the fresh basalt glass by very regular 30 nm-wide silica-rich rims.

Stable Isotope Geochemistry: Disseminated carbonate in pillow-rim basaltic glasses from *in situ* oceanic crust show differences in C isotope ratio from those of the adjacent crystalline cores that likely relate to microbial activity during alteration. Bulk-rock carbon isotope ratios of carbonates in samples of microbially altered volcanic glass are commonly variably depleted by as much as –20‰, consistent with microbial oxidation of organic matter [7]. Conversely, crystalline basalt commonly has $\delta^{13}C_{VPDB}$ values bracketed between normal marine carbonate (0‰) and mantle values (–5‰ to –7‰).

Nitrogen isotope data on modern samples suggest that microbial N-isotope biosignatures may also be preserved. Basaltic whole-rocks and separates of variably palagonitized volcanic glass, from the modern seafloor, are enriched in N (whole-rocks and glasses up to 18.2 ppm; [8,9], unpublished data) and have elevated $\delta^{15}N_{air}$ (up to +8.3‰) relative to that of fresh MORB (the latter near -5‰). The N signatures identified in this preliminary work are consistent with the addition of sedimentary/organic N via interaction with pore fluids, with or without direct mediation by biological activity.

Preservation by titanite mineralization: Titanite is an important mineral for the preservation of these bioalteration textures, as it is stable under a wide range of metamorphic conditions and can be dated using the U-Pb system [10]. Petrographic observations, overlapping metamorphic and magmatic ages from the pillow lavas, as well as direct dating of the titanite by *in situ* laser ablation multi-collector-ICP-MS demonstrates that the titanite ($CaTiSiO_5$) in ancient samples is of Archean age and implies that the microbial alteration process occurred soon after eruption. Titanite has been detected in association with the rims of glass shards in samples of modern oceanic crust using micro X-ray diffraction (μXRD) [11]. This suggests that titanite formation is penecontemporaneous with glass emplacement; therefore, titanite mineralization is a plausible mechanism for the preservation of these textures through geologic time. Further, the closure age of the titanite as determined by U-Pb geochronology may be considered a reasonable lower limit for the age of the bioalteration structures.

Astrobiology: A compelling body of evidence from a diverse range of remote sensing data and *in situ* robotically-obtained data sets points to a substantially warmer, wetter and more geologically active environment on early Mars. Recent spectroscopic data from the MRO CRISM instrument suggests that water-basalt interaction products are common in the Martian crust. In terrestrial settings, such water-basalt interaction provides an environment suitable for microbial colonization and the preservation of biosignatures over geological timescales. Therefore, areas displaying spectral and geomorphological evidence of water-basalt interaction are of great potential value as targets for astrobiological exploration.

The association between ancient microbial life and subaqueous volcanic rocks suggests a possible connection with the origin of life itself. Such environments may have provided shelter for early life against impact bombardment and solar radiation; as well as a source of thermal and chemical energy.

Basaltic rocks are ubiquitous in the solar system. While Mars is the most accessible extraterrestrial environment where water-basalt interaction may have created microbial habitats, subaqueous volcanism may occur on numerous other solar system bodies. The habitability of basaltic rock therefore has implications for the distribution of life throughout the solar system and beyond. Solar system bodies such as Europa and Enceladus; which show evidence of long-term geological activity and abundant water, could potentially host environments where the interaction of water and subaqueous volcanism create conditions suitable for microbial colonization.

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