LIFE ON MARS AND EARLY EARTH: LESSONS FROM THE SUBGLACIAL LAKES OF ICELAND.

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Introduction: Life as a self-organizing, replicating system requires free energy, and the hardiest forms of life on Earth harvest ambient energy from sunlight or chemicals in their environment [1]. Before the invention of phototrophy (photorespiration or photosynthesis) sometime before 2.4 Ga life depended on chemical disequilibrium in the environment, i.e. chemolithotrophy. This situation persists in deep habitats on the modern Earth that are isolated from the products of photosynthesis, i.e. molecular oxygen and organic carbon [2]. Chemolithotrophic-based life may be the only viable scenario for Mars life if the surface of the planet is sterile [3]. Investigations of chemolithotrophic ecosystems thus inform us of the possible scenarios on Mars and their potential biosignatures.

Subglacial lakes in Iceland: Iceland hosts active volcanoes, including several covered by the Vatnajokull ice cap. Volcanic heat melts overlying ice, which collects at minima in the glaciostatic potential, forming subglacial lakes [4]. These lakes drain episodically in floods (jokulhaluaps) through conduits under the ice. Three lakes are currently known under Vatnajokull: one under an ice shelf in the Grimsvotn caldera and two under depressions in the ice surface called the west and east Skaftarkatlar lakes (Figure 1) Each is covered by about 300 m of ice and is up to 115 m deep.

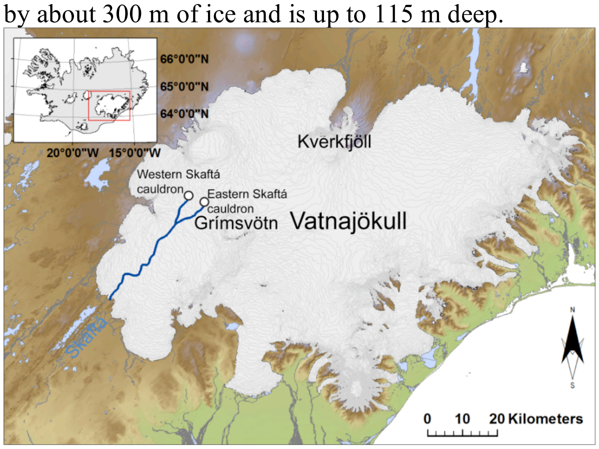

Figure 1. Locations of three subglacial lakes under the Vatnajokull ice cap, Iceland, showing the drainage conduits of the Skaftarkatlar lakes to the Skafta river.

Life in the subglacial lakes: We have carried out a biological reconnaisance of all three lakes: Because the Grimsvotn lake drained immediately before we obtained samples, our findings for this are ambiguous [5], and we focus on the two Skaftarkatlar lakes.

Geochemistry. The Skaftarkatlar lakes are cold (4-5°C), highly sulfidic, charged with CO_2, and contain low dissolved solids. The lakes appear to be a mix of glacial melt, hydrothermal fluid, and solutes from the low-temperature weathering of basaltic glass and minerals (Figure 2) [6]. Oxygen in the single sample was < 2 micromolar in the single sample it was measured. In two profiles of the east lake water column sulfate exhibits a gradient; other dissolved solids are uniform to a few percent.

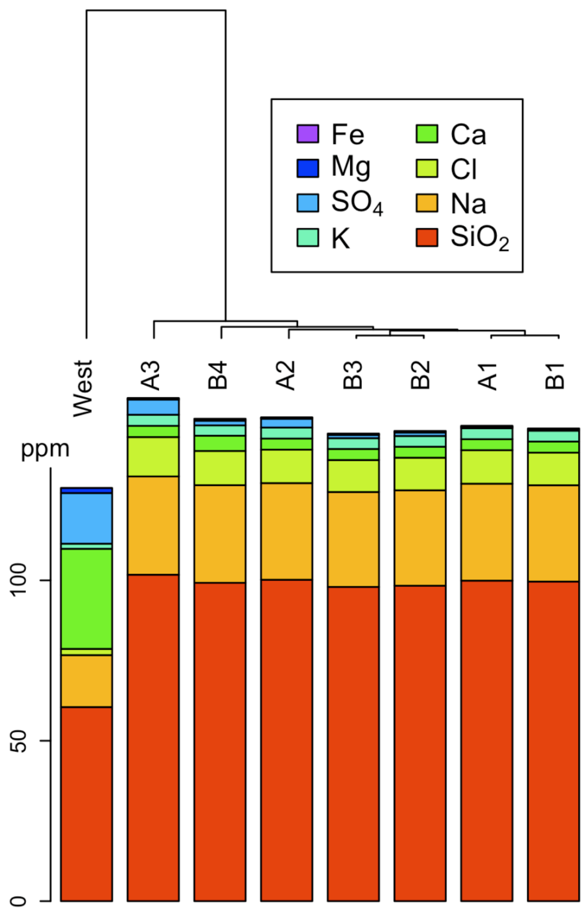

Figure 2. Concentrations of dissolved solids in samples from a sample from the west and east Skaftarkatlar lakes [7,8]. There are 7 samples from the latter from 2 boreholes (A and B). Total CO_2 and H_2S, which are volatile and can be lost during depressurization of retrieved samples, are highly variable and not shown.

Microbial ecology. Both Skaftarkatlar lakes contain a microbial community dominated by a few bacterial taxa ("species"), and lacking detectable archaea [7,8] (Figure 3). More than 97% of ~340,000 sequences in our pyrosequencing libraries are affiliated with 6 taxa in the genera *Acetobacterium*, *Geobacter*, *Sulfuricurvum*, *Sulfurospirillum*, and *Desulfosporosinus*. An aspect of this community that is especially striking is that each of these taxa are closely related to a cultivated organisms with established metabolism can be assigned to a particular niche of this chemolithotrophic ecosystem (Figure 4).

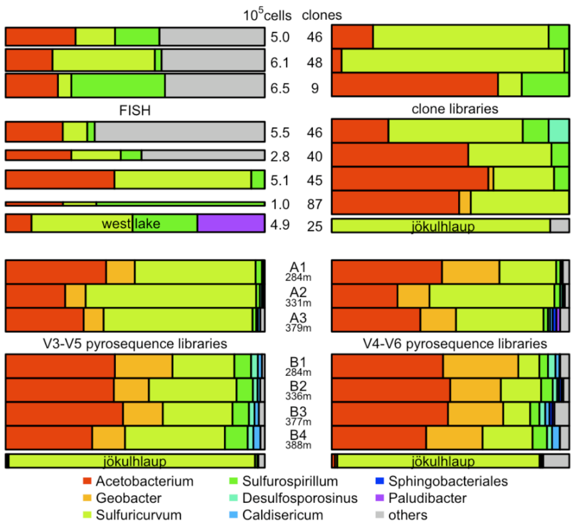

Figure 3. Distribution of bacterial taxa ("species") in the Skaftarkatlar lakes as well as a jokulhlaup in the Skafta river, as assayed by different molecular techniques. Lake samples are arranged by borehole and depth of retrieval [8].

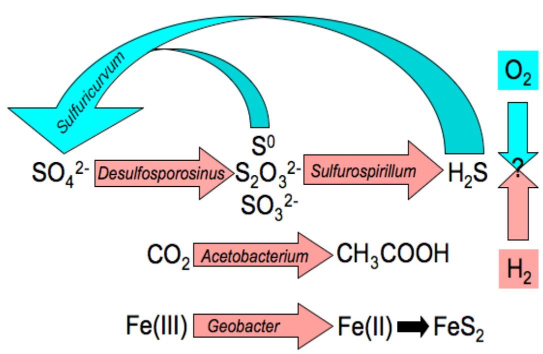

Figure 4. Hypothetical chemolithotrophic ecosystem in the Skaftarkatlar lakes. Blue arrows represent pathways that consume O_2; red pathways consume H_2. Pathways are labeled by cultivated species related to the major taxa in the lake which have those metabolisms. No lake taxon has been identified for the knallgas (H_2/O_2) reaction.

Discussion: Three aspects of this ecosystem are germane for the search for life on Mars and studies of life on early Earth:

A hydrogen economy. Alteration of mafic volcanic rock produces H_2, an important energy source for any deep chemolithotrophic ecoystem [2], and uptake of H_2 in the crust of Mars is a possible biosignature [9]. We have detected, but not quantified H_2 in the west Skaftarketill lake but we expect accumulation of H_2 in these lakes because of weathering of glassy hyaloclastite basalt, low or no O_2 and the overlying ice seal. The close relatives of several of the lake taxa use H_2 as an electron donor.

Acetogenesis vs. methanogenesis. In many anoxic environments, homoacetogens compete with methanogens for H_2; experiments have shown that some of the former can out-compete some of the latter at low temperature and high pH_2 [10], conditions which may exist in these lakes (although we have not yet been able to quantify H_2). However, all known methanogens are archaea and the apparent absence of archaea in general raises the possiblity that some other factor, such as nutrient limitation. Methane is a invoked as a useful biomarker in the search for life elsewhere [11]; here we have identified a potential "false negative" system.

Nanonaerobic sulfur oxidation? Oxygen may be introduced to these lakes via glacial meltwater, but is unlikely to persist at micromolar concentrations in the prsesence of high (~1 millmolar) sulfide. Nevertheless, the lakes are populated by active relatives of microaerobic sulfur oxidizers. Recent advances in electrovoltammetry reveal that *E. coli* (not considered an extremophile) can consume O_2 to a few nanomolar concentration [12]. Low levels of O_2 are produced in Mars' atmosphere by CO_2 dissociation; low O_2 might also have been present on the Archaean Earth.

References: Use the brief numbered style common in many abstracts, e.g., [1], [2], etc. References should then appear in numerical order in the reference list, and should use the following abbreviated style:

[1] Gaidos, E. et al. (1999) *Science* 284, 1631. [2] Nealson, K. H. et al. (2005) *Trends Microbiol*. 13, 405. [3] Jakosky, B. M., Shock, E. L. (1998) *J. Geophys.* Res. 103, 19359. [4] Bjornsson, H. (2003) *Global Planet. Change* 35, 255. [5] Gaidos, E. et al. (2004) *Astrobiology* 4, 327. [6] Johanesson, T. et al. (2007) *Geophys. Res. Lett.* 34, 19502. [7] Gaidos, E. et al. (2009) *ISME J.* 3, 486. [8] Marteinsson, V. et al. submitted to *ISME J.* [9] Weiss, B. P. et al. (2000) *PNAS* 97, 1395. [10] Kotsyurbenko, R. et al. (2001) *FEMS Microbiol. Ecol.* 38, 153. [11] Mumma, M. (2009) *Science* 323, 1041. [12] Stolper, D. et al. (2010) *PNAS* 107, 18755.