

**LIFE BENEATH THE ICE – EARTH (!) MARS (?) EUROPA (?)**Carlton C. Allen<sup>1</sup>, Stephen. E. Grasby<sup>2</sup>, Teresa G. Longazo<sup>3</sup>, John T. Lisle<sup>1</sup> and Benoit Beauchamp<sup>2</sup><sup>1</sup>NASA Johnson Space Center, Houston, TX 77058 carlton.c.allen1@jsc.nasa.gov <sup>2</sup>Geological Survey of Canada, Calgary, Alberta, Canada T2L 2A7 <sup>3</sup>Hernandez Engineering, Houston, TX 77062.

**Introduction:** The existence of life beneath thick layers of ice, and the expression of that life at the surface, are important topics in both terrestrial and planetary Astrobiology. Earth history apparently includes several periods of essentially total glaciation [1]. Ice in the near subsurface of Mars may have discharged liquid water in the recent past [2]. Cracks in the ice crust of Europa have apparently allowed the release of water to the surface [3]. Chemolithotrophic bacteria, analogous to those at deep sea vents, could have survived beneath the ice of “Snowball Earth”, and life forms with similar characteristics might exist beneath the ice of Mars or Europa. Periodic discharges of water to the surface could provide accessible evidence for the existence of life beneath the ice.

We are investigating a contemporary terrestrial analog – a set of springs that deposit sulfur and carbonate minerals on the surface of a glacier in the Canadian arctic [4,5]. The deposits contain microorganisms, as well as clear evidence that biological processes mediate both mineral formation and isotopic fractionation beneath the ice.

**Field Setting:** The springs are located at 81°01'N, 81°35'W, on northern Ellesmere Island. Bedrock is dominated by Carboniferous to Triassic marine carbonates, evaporites and clastics. Structures include high amplitude folds and thrust faults, and later stage normal faulting. A prominent reverse fault has associated massive pyrite mineralisation with veins up to 2 m thick. The sulphur springs occur immediately north of the projected intersection of this fault and the axis of a N-S trending anticline running through the valley.

Extensive ice sheets occur in the high mountain ranges and flow down and coalesce within the valley. Temperature logging of an exploration well drilled 43 km SW of the springs site indicates 540 m of permafrost and a 22 °C/km geothermal gradient. The mean annual air temperature is -19.7 °C.

Ten springs and seeps discharge from the surface of an approximately 200 m thick ice sheet. Most sites are easily located due to bright yellow precipitates of native sulphur. Intermittent odors of H<sub>2</sub>S are common in the area. Native sulphur is typically thinly dispersed over several square meters of the ice surface around the discharge sites. At some localities central mounds, comprised of varying amounts of native sulphur, gypsum, calcite and ice stand up to 30 cm high. Active discharges of approximately 1 l/min from the centers of the mounds was observed at some locations, whereas

diffuse seeps were more common at others. The springs were visited only during the summer (1999 to 2001), and hence it is uncertain if the flows are perennial.

**Samples and Analyses:** Water samples were collected from five actively flowing spring sites as well as nearby glacial melt water streams. Temperature, pH and dissolved HS<sup>-</sup> were measured on site. Solids were collected at the spring discharges, from nearby rock outcrops and filtered from spring water. Stable isotope ratios were measured for the water (oxygen, deuterium) and solids (sulfur). Precipitates and solid samples were examined by analytical and environmental SEM, as well as by XRD. Total bacteria counts were performed using DAPI stain and fluorescence microscopy.

**Water.** Spring water temperatures are low (1 to 2 °C), but higher than surface melt water (~ 0.2 °C). The spring waters have pH values of 9.0 to 9.5, distinctly different from glacial melt waters that have pH values of 4 to 6. Conductivity values range from 115 to 230 μS, as compared to < 2 μS for melt water elsewhere on the ice. HS<sup>-</sup> concentrations of up to 0.2 mg/l were measured in spring water. The springs have a greater deuterium excess than the local precipitation, but the spring water value is consistent with the range measured for glacial melts in the area.

**Solids.** Estimated mineral abundances vary among samples: sulphur (4 to 99%); calcite (12 to 75%); gypsum (1 to 99%). The δ<sup>34</sup>S of native sulphur from the springs ranges from 7.7 to 11.4 ‰. Gypsum δ<sup>34</sup>S ranges from 18.2 to 27.8 ‰. The average δ<sup>34</sup>S value for anhydrites from the underlying Otto Fiord Formation is 14.6 ‰, and massive sulphides along the nearby reverse fault have average δ<sup>34</sup>S values of 9.1 ‰.

**Microbiology.** Total bacteria counts for spring water samples ranged from 2 to 3 x 10<sup>4</sup> cells/ml. Sulfur particles are partially enmeshed in a carbon-rich webbing, fractions of a micrometer thick. This material matches the morphology and composition of the extracellular polymeric substance produced by many microorganisms. SEM images show coccoidal objects, characteristically 1 to 5 μm in diameter, as well as rods characteristically 5 μm long and 1 to 2 μm in diameter. These objects contain elevated amounts of carbon, strongly suggesting that they are individual cells.

**Discussion:** *Origin of the Springs.* Stable isotope values for spring waters are indistinguishable from those of glacial melt waters, suggesting that the spring waters originate from melt water rather than from pre-

precipitation or deep sources. The recharge zones for the spring system are likely to be in the nearby glaciated mountains.

Sulphurous springs are often associated with an active volcanic source, but no evidence of recent volcanism has been reported in the region. An alternative source of sulphur is weathering of sulphur-rich geologic horizons. Pyrite veins associated with the nearby fault are chemically stable and are unlikely to form significant quantities of  $\text{HS}^-$ . The only other abundant sulphur-rich horizon in the area is the extensive anhydrite beds of the Early Pennsylvanian Otto Fiord Formation. There is no surface exposure of this rock in the area, but we estimate that the Otto Fiord lies  $\sim 1.5$  km below the valley floor.

These observations imply a deep circulation, topography driven flow system along bedding and/or fracture planes. The correspondence of these springs with the intersection of a N-S trending anticline and a newly recognized reverse fault, suggests that cross cutting structures control the discharge site.

**Formation of Native Sulphur Deposits.** Spring waters at the glacier surface exsolve  $\text{H}_2\text{S}$  and deposit gypsum and native sulphur. The simultaneous presence of sulphur in three oxidation states suggests a combination or series of redox reactions, either abiological or mediated by chemolithotrophic microorganisms. Native sulphur does not form by direct reduction of sulphate, but rather by oxidation of reduced sulphur species such as  $\text{H}_2\text{S}$ . Dissolution of anhydrite and subsequent sulphate reduction must be an intermediate step in forming the native sulfur deposits. Temperatures of  $\sim 140$  °C are needed for abiological thermochemical sulphate reduction (TSR). Based on the local geothermal gradient of 22 °C/km, TSR would require surface water to circulate more than 6 km deep. In contrast, sulphate reducing bacteria thrive between 0 and 45 °C, consistent with the estimated 1.5 km depth of the Otto Fiord anhydrite.

When  $\text{H}_2\text{S}$  accumulates at near-surface redox interfaces with oxygen present, native sulphur can be formed either abiologically or by sulphide oxidizing bacteria. Little or no elemental sulphur precipitates abiologically at  $\text{pH} > 8.5$  and high  $\text{pO}_2$ . The high pH of the glacial spring waters ( $> 9$ ), as well as the fact that native sulphur is forming in the open atmosphere (i.e. high  $\text{pO}_2$ ), argues for biologically mediated oxidation of  $\text{H}_2\text{S}$  to native sulphur.

Biologically mediated sulphate reduction (BSR) to  $\text{H}_2\text{S}$ , and subsequent oxidation to native sulphur in this spring system, is analogous to the formation of biogenic sulphur deposits associated with evaporites. Here, dissimilatory BSR often occurs with a Rayleigh-type fractionation process, creating deposits with large

$\Delta\delta^{34}\text{S}$  values. The  $\delta^{34}\text{S}$  value for the Otto Fiord anhydrites (14.6 ‰) plots between values for precipitates of native sulphur (7.7 to 11.4 ‰) and gypsum (18.2 to 27.8 ‰) at the spring sites, consistent with fractionation by chemolithotrophic bacteria. We therefore argue for bacterially mediated, subsurface reduction of sulphate in anhydrite to  $\text{H}_2\text{S}$ , and subsequent bacterially mediated oxidation of  $\text{H}_2\text{S}$  to native sulphur.

**Microorganisms.** Analysis of the spring waters demonstrates the ubiquitous presence of bacteria. The total bacteria counts for five springs, ranging from 2 to  $3 \times 10^4$  cells/ml, are similar to total bacteria counts for melt water in other glaciers [6]. We are currently working to identify these bacteria.

The proposed model for microbial sulphate reduction, followed by microbial oxidation of sulphides to native sulphur, requires chemolithotrophic bacteria to metabolize in a subglacial environment. Temperatures range from an estimated maximum of 33 °C at a depth of 1.5 km to approximately 0 °C within the glacier. Anaerobic sulfate reducing bacteria occur in the basal ice layer of an Ellesmere glacier and metabolize at near-freezing temperatures [7]. Sulphide oxidizing bacteria isolated from the basal ice layer of a Swiss glacier metabolize at temperatures of 4 °C [6].

**Implications:** A variety of evidence supports the interpretation that native sulphur and associated deposits in these springs are related to bacterially mediated reduction and oxidation of sulphur below the glacier. This work provides evidence that a non-volcanic, topography driven geothermal system, that harbors microbiological communities, can operate in extreme cold environments and discharge through solid ice.

This conclusion supports the idea that life can exist in isolated geothermal refuges despite subfreezing surface conditions such as those on Snowball Earth, and perhaps on Mars or Europa. Discharges of water from such refuges may bring to the surface living microbes, as well as mineralogical and isotopic indications of subsurface life.

**References.** [1] Hoffman, P.F. et al (1998) *Science* 281, 1342-1346. [2] Malin, M.C. and Edgett, K.S. (2000) *Science* 288, 2330-2335. [3] Greeley, R. et al (2000) *Journal of Geophysical Research* 105, 22,559-22,578. [4] Allen, C.C. et al (2000) *LPSC XXXII* abstract # 1019. [5] Grasby, S.E. et al (2002) submitted to *Astrobiology*. [6] Sharp, M. et al (1999) *Geology* 27, 107-110. [7] Skidmore, M.L. et al (2000) *Applied and Environmental Microbiology* 66, 3214-3220.