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Introduction to special section on Microcosms in Ice: The Biogeochemistry of Cryoconite Holes

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[1] ''Cryoconite'' holes are small, water-filled, cylindrical holes found in the surface of glacier ice, first reported during an expedition to Greenland in 1870 [*Leslie*, 1879]. Cryoconite, ''cold dust,'' refers to the thin layer of sediment at the hole bottom. The holes form from surficial sediment patches that absorbs more solar radiation than the surrounding ice and which preferentially melt into the glacier forming a cylindrical water-filled hole. These holes form on the ice-covered, as opposed to snow covered, parts of glaciers world-wide, wherever there is sufficient energy for melting. Two broad types of water-containing holes have been identified to date. The most common holes form as pools of surface water open to the atmosphere that aid in routing water off the glacier surface (Figure 1, right). The more unusual kind is found in the McMurdo Dry Valleys of Antarctica (and probably elsewhere at high latitudes) where energy-balance conditions favor frozen surfaces and internal melting. The pool of meltwater is enclosed in ice, isolating it from direct contact with the atmosphere. These sealed holes may be connected to a subsurface runoff system or may be entirely isolated from air and water exchange.

[2] Biogeochemically, cryoconite holes are interesting because the sediment is inncoculated with biologic material, a fraction of which thrives in the cryoconite environment of near-freezing waters and limited nutrient supply. The holes are thus oases for microbial life and biologically mediated chemical reactions on otherwise relatively inert glacier surfaces. Cryoconite holes can be thought of as natural terraria set into or entombed by the ice, many of which survive from year to year, thereby oscillating from being entirely frozen throughout the winter to fully melted in the summer, albeit with an ice cover in Antarctica. Fundamental questions include the interactions of competing biogeochemical processes that maintain and maximize microbial activity in these little habitats, how the chemistry of the water and sediment evolve in the light of biological activity, how do freezing and melting processes produce phase changes and speciation of nutrients, and how the biology of the glaciers affect nonglacial habitats downstream. Answers to these questions are relevant to the fundamentals of nutrient exchange and ecosystem structure in glaciers, as well as the possibility of ''cold life'' in environments on ''Snowball earth'' and Mars and icy planets elsewhere.

[3] The six articles presented in this volume cover both open and closed cryoconite holes. Three papers examine the open cryoconite holes on Svalbard glaciers [*Anesio et al.*, 2007; *Hodson et al.*, 2007; *Stibal and Tranter*, 2007], while the other three examine the ice-lidded cryoconite holes on glaciers in Taylor Valley, one of the McMurdo Dry Valleys [*Bagshaw et al.*, 2007; *Foreman et al.*, 2007; *Fountain et al.*, 2008]. We believe that these articles together provide a comprehensive overview of our current understanding of biogeochemical processes in cryoconite holes. Fountain et al. examine how holes develop over the ablation season, providing insight into the variability of physical and chemical parameters within the holes and noting hole to hole variability. Hodson et al. estimate the mass of debris within cryoconite holes on a Svalbard glacier, and determine the relative rates of bacterial carbon fixation and respiration in the debris. Respiration is two orders of magnitude higher that fixation. They scale their measurements to determine the total amount of respiration occurring on the glacier surface for the first time. Stibal and Tranter examine the impact of pH on the rate of inorganic carbon fixation in slurries from cryoconite holes under laboratory conditions similar to those in the field. The cyanobacteria which dominate the microbes in the slurry are able to fix carbon across a wide range of pH. Foreman et al. summarize the phylogenetic diversity across different glaciers and between the cryoconite sediment and overlying ice within individual holes. They measure bacterial production rates of 1.5 ngC l^{-1} hr^{-1}. This compares to the laboratory rates of carbon fixation of 6–15 ngC l^{-1} hr^{-1} found by Stibal and Tranter, and 40 ngC l^{-1} hr^{-1} for bacterial production measured by Hodson et al. Anesio et al. focus on the importance of viruses to bacterial mortality and the recycling of carbon and nutrients on glaciers. They showed that viruses from cryoconite holes are able to infect bacteria in proglacial lakes, so indicating the potential for cryoconite holes to impact on downstream aquatic ecosystems. Foreman et al. also echo this theme from a biogeochemical perspective. Finally, Bagshaw et al. examine the chemical evolution of waters in cryoconite holes, showing how biogeochemical processes in cryoconite holes lead to increasing concentrations of dissolved organic carbon over time, which in turn

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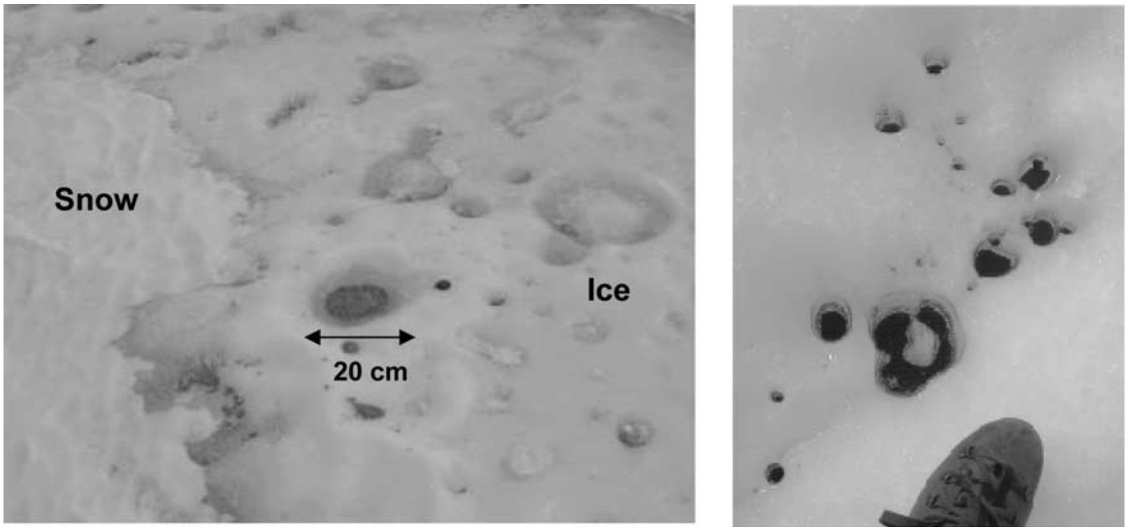

Figure 1. Cryoconite holes. (left) Photo is taken from a glacier in the McMurdo Dry Valleys, Antarctica, showing a sedment patch melting into the ice (above the scale arrow) and frozen-over holes with meltwater ~20 cm below (above the ''Ice'' label). Other holes in various stages of development can be seen in the photo. (right) Photo shows open holes on Storglaciaren, Sweden,with a boot for scale. They are part of a flow network that drains meltwater from the glacier surface.

may enhance adsorption of solar radiation by the water, aiding the development of deeper holes. If this is true, it suggests that there are a number of complex interactions between the biology, chemistry and biology of cryoconite holes, which act in concert to maintain life on glacier surfaces. We hope that such a thought inspires a new generation of studies, perhaps with astrobiological leanings, and eagerly await their observations and conclusions.

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