PI: Jacob Buffo
Program: 2019 Lewis and Clark Fund for Exploration and Field Research in Astrobiology
Project: Biosignature Dynamics in British Columbia's Frozen Hypersaline Lakes: Implications for the Habitability and Bioburden of Ice-Brine Environments

Project Report

(Figures and References can be found in the Supplementary Material at the end of this document – Page 4)

Summary

From February 20th-27th, 2020 Dr. Jacob Buffo and undergraduate researcher Emma Brown carried out field work in central British Columbia's interior plateau. We made thermophysical observations of and extracted ice and brine samples from five hypersaline lake systems. These lakes are novel analogs to planetary ice-brine environments (e.g. the subsurface oceans of Europa and Enceladus, past and present brine systems on Mars). Understanding the thermodynamics and biogeochemistry of the lake ice and brine can provide insight into the evolution, habitability, and detectability of high priority astrobiology targets and will help identify organismal coping strategies which facilitate microbial success in low-temperature high-salinity environments.

Field Site Overview

The Interior Plateau of central British Columbia houses a diverse array of endorheic (closed basin) hypersaline lakes. Seasonal snowmelt and groundwater flow leaches salts from the local rocks before collecting in the low-lying playas. The hot and arid summer climate of the region leads to substantial evaporation of the lakes. With minimal rainfall to refresh the lakes their salinities dramatically increase, reaching concentrations of 30-40% salt by weight. In some cases, the lakes reach their saturation point and pure hydrated salts begin to precipitate in the lake waters [*Renaut and Long*, 1989]. While these extremely high salinity environments are toxic to many organisms, there exists a rich and unique halophilic ecosystem within each of the lakes [*Pontefract et al.*, 2019; *Pontefract et al.*, 2017].

As autumn ends the resident organisms are subjected to an additional environmental stressor – extreme cold. With mean January temperatures ranging from -9 to -12°C and nighttime lows that can exceed -45°C the lakes form a substantial ice cover [*Renaut and Long*, 1989]. The ice that forms from the hypersaline brines of these lakes is highly porous and contains both salts and organisms entrained during the ice's formation. This process further concentrates the underlying brine, depressing its freezing point by as much as 6°C, depending on the composition of the lake [*Buffo et al.*, 2019]. The interstitial brine of the ice layer and the underlying brine reservoir constitute novel and extreme environments that support a unique community of halophilic psychrophiles [*Buffo et al.*, 2019; *Pontefract et al.*, 2019; *Pontefract et al.*, 2017].

Five lakes were visited during the field campaign: Basque Lake 1 [N 50.60012 W 121.35967], Basque Lake 2 [N 50.59336, W 121.34974], Basque Lake 4 [N 50.58867 W 121.34317], Last Chance Lake [N 51.32775 W 121.63576], and Salt Lake [N 51.07298 W 121.58441]. A map of the region can be found in Figure 1. Basque Lakes 1, 2, and 4 as well as Salt Lake are magnesium sulfate ($MgSO_4$) dominated systems, while Last Chance Lake is a sodium sulfate (Na_2SO_4) and carbonate (CO_3) dominated system. Images of Basque Lake 2, in both summer and winter, can be seen in Figure 2. The characteristic brine pools (e.g. Figure 2A and 2D) are a feature unique to the lakes within this region and are likely the byproduct of freeze-thaw processes in the shallow subsurface, akin to frost heave driven patterned ground formation [*Peterson and Krantz*, 2008]. They are stable structures whose perimeters do not vary seasonally, however the brine composition and microbial ecology from pool to pool can vary drastically, even within the same parent lake [*Pontefract et al.*, 2017; *Renaut and Long*, 1989].

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Scientific Motivation

The most promising locales within the solar system that may harbor environments suitable for life all lie beyond the sun's habitable zone (e.g. Europa, Enceladus, Mars) [*Fox-Powell et al.*, 2016; *Marion et al.*, 2003; *Parkinson et al.*, 2008; *Priscu and Hand*, 2012; *Tosca et al.*, 2008]. This means that liquid water is not stable at the surface of these bodies. As such any near surface water will be in the form of ice. In the case of Europa and Enceladus this manifests itself as global ice shells overlying regional or global subsurface oceans [*Čadek et al.*, 2016; *Sotin and Tobie*, 2004]. For Mars it has been suggested that both historical and contemporary shallow subsurface brine systems and episodic surface expression of brine are responsible for many of the planets fluvial geomorphology and observed ground ice [*Carr*, 1987; *Rapin et al.*, 2019; *Toner et al.*, 2014; *Vaniman et al.*, 2004; *Wray et al.*, 2011; *Zorzano et al.*, 2009]. With the unique link between water and life as we know it, these ice-brine systems are understandably high priority astrobiology targets.

The remaining hurdle is accessing and observing the underlying ocean/brine reservoir, as it frequently lies beneath meters or kilometers of ice [*Schubert et al.*, 2004; *Schubert et al.*, 2010]. In the absence of *in situ* measurements, we must rely on remote sensing techniques (e.g. spectrographs, ice penetrating radar) to observe ice characteristics and relate these measurements to properties of the underlying liquid [*Di Paolo et al.*, 2016; *Fanale et al.*, 1999; *Kalousová et al.*, 2017; *Ojha et al.*, 2015; *Orosei et al.*, 2018]. Fortunately, when ice forms it entrains biogeochemical signatures of its parent water reservoir [*Buffo et al.*, 2018; *Buffo et al., in review; Buffo et al.*, 2019; *Kargel et al.*, 2000]. On Earth, this has been observed in the salinity and bioburden profiles of sea [*Cottier et al.*, 1999; *Cox and Weeks*, 1974; *Eicken*, 1992; *Loose et al.*, 2011; *Nakawo and Sinha*, 1981; *Thomas and Dieckmann*, 2003] and lake ice [*Santibáñez et al.*, 2019], which can be used to reconstruct the formation history of the ice. While the thermodynamics and biogeochemistry of ice formed from our sodium chloride (NaCl) rich ocean has been studied at length for nearly a century (e.g. [*Malmgren*, 1927]), the analogous processes in ices formed from more exotic ocean/brine compositions remains largely unconstrained. This is important as evidence suggests the oceans and brines of other solar system bodies may be quite different than Earth's ocean [*Kargel et al.*, 2000; *Pontefract et al.*, 2017; *Toner et al.*, 2014; *Zolotov*, 2007; *Zolotov and Shock*, 2001]. Fortuitously, the hypersaline lakes of British Columbia provide a natural laboratory in which to observe the biogeochemical evolution of ices formed from compositionally diverse brines. Furthermore, the $MgSO_4$ and Na_2SO_4 chemistries of some lakes may mirror the predicted ocean/brine compositions of both icy satellites and Mars. Placing empirical constraints on the relationships between ice biogeochemical properties, system thermodynamics, and brine biogeochemistry will provide a novel data set of an understudied extremophilic environment on Earth and act as a benchmark to validate models designed to simulate these and analogous planetary environments [*Brown et al.*, 2020; *Buffo et al.*, 2019].

Methods

At each of the five lakes 1-3 sample sites were selected. Sites were chosen so as to sample diverse locations within the lake (either discrete brine pools, or edge to center transects when pools could not be identified due to high lake levels leading to subaqueous pools). At each site the thickness of the ice and underlying brine layer was measured. If there existed any precipitated salt at the base of the brine layer this was also measured. Ice cores were extracted from descending sections of the ice column (Figure 2C) and stored in sterile amber Nalgene bottles. A temperature profile was taken using a probe thermometer as the cores were extracted and brine was extracted from the underlying pool/lake (Figure 2C). Additionally, we recovered long-term temperature loggers which were deployed in September 2019 to observe seasonal variations in brine and air temperature. Lastly, sackhole experiments were conducted. Here, boreholes were drilled to different depths within the ice cover and allowed to fill with brine via percolation through the porous ice. By measuring the rate at which the brine infills the hole, the permeability of the ice beneath the hole can be estimated.

To prepare the samples for biogeochemical analysis the ice and brine samples were melted and warmed in a hot water bath, before being split into two subsamples. One split involved aliquoting 45ml of the unfiltered sample to a 50ml falcon tube and adding 4.5ml of 2.5% glutaraldehyde solution to fix the cells for bioburden analysis. Cell counts will be acquired using two techniques; 1) staining the cells with 4′,6-diamidino-2-phenylindole (DAPI) and imaging them using a fluorescence microscope and 2) flow cytometry. The result will be bioburden profiles of the ice and underlying brine. For the second split we filtered the remaining sample through a 0.2-micron polyethersulfone membrane Sterivex filter. These splits will be analyzed for major ion concentrations (Cl, SO_4, CO_3, Mg, and Na), total dissolved solids, and pH to produce ion specific profiles of the ice and underlying brine. Cumulatively, these measurements will provide physical, thermal, chemical, and biological profiles of these unique ice-brine systems as well as a temporal record of the air temperatures that produced the ice.

Implications

The novel dataset produced by this field expedition is relevant to both the astrobiology and planetary science community. It will extend our understanding of the biogeochemistry of terrestrial analog ice-brine systems. Specifically, we will investigate the microbial distribution and limits of life in low-temperature high-salinity environments and constrain the relationship between observable ice properties, the underlying brine composition, and the thermal evolution of the system. The collected profiles will be used to validate reactive transport models of planetary ice formation and evolution (e.g. [*Brown et al.*, 2020]), which seek to simulate the thermal and physicochemical properties of diverse ice-brine systems. Physicochemical heterogeneities likely play an important role in ice shell geophysical processes [*Barr and McKinnon*, 2007; *Johnson et al.*, 2017; *Pappalardo and Barr*, 2004; *Schmidt et al.*, 2011] and proliferous biological communities are sustained by physical and thermochemical gradients at terrestrial ice-ocean/brine interfaces [*Daly et al.*, 2013; *Loose et al.*, 2011]. As such, devising methods and models which quantify the thermophysical and biogeochemical properties of planetary ices has implications for constraining the geophysics of icy worlds and assessing the habitability of ice-brine systems.

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