ANTARCTIC MIRABILITE MOUNDS AS MARS ANALOGS: THE LEWIS CLIFFS ICE TONGUE REVISITED.

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Introduction: It has been proposed, based on geomorphic and geochemical arguments, that subsurface water has played an important role in the history of water on the planet Mars [1]. Subsurface water, if present, could provide a protected and long lived environment for potential life. Discovery of gullies [2] and recurring slopes [3] on Mars suggest the potential for subsurface liquid water or brines. Recent attention has also focused on small (<~1km dia.) mound-like geomorphic features discovered within the mid to high latitudes on the surface of Mars which may be caused by eruptions of subsurface fluids [4, 5]. We have identified massive but highly localized Na-sulfate deposits (mirabilite mounds, $Na_2SO_4 \cdot 10H_2O$) that may be derived from subsurface fluids and may provide insight into the processes associated with subsurface fluids on Mars. The mounds are found on the end moraine of the Lewis Cliffs Ice Tongue (LCIT) [6] in the Transantarctic Mountains, Antarctica, and are potential terrestrial analogs for mounds observed on the martian surface. The following characteristics distinguish LCIT evaporite mounds from other evaporite mounds found in Antarctic coastal environments and/or the McMurdo Dry Valleys: (1) much greater distance from the open ocean (~500 km); (2) higher elevation (~2200 meters); and (3) colder average annual temperature (average annual temperature = -30ºC for LCIT [7] vs. –20ºC at sea level in the McMurdo region [8]. Furthermore, the recent detection of subsurface water ice (inferred as debris-covered glacial ice) by the Mars Reconnaissance Orbiter [9] supports the use of an Antarctic glacial environment, particularly with respect to the mirabilite deposits described in this work, as an ideal terrestrial analog for understanding the geochemistry associated with near-surface martian processes.

S and O isotopic compositions ($\delta^{34}S$, $\delta^{18}O$ and $\Delta^{17}O$) of sulfate have been successfully used to decipher the source and processes that have occurred during sulfate formation in other terrestrial environments. Those parameters were systematically measured in this study. Sulfate formation requires water, thus the ambient water bodies: ice, snow and moraine lakes, were also examined in order to elucidate their relationship with mirabilite mounds, i.e., to the in-situ sulfate formation scenario.

Results and Discussion: The mirabilite has high $\delta^{34}S$ values (average = +49.1‰ (V-CDT)), low $\delta^{18}O$ values (lowest for Earth sulfate to date, average = -16.9‰ (V-SMOW)), and small negative $\Delta^{17}O_{(sulfate)}$ values (average -0.37 ‰ (V-SMOW)) compared with previously reported stable isotope measurements of sulfate deposits from the Antarctic region. The highly enriched ^{34}S values imply the involvement of bacterial sulfate reduction, and the ^{18}O and $\Delta^{17}O$ values suggest the incorporation of isotopically light glacial water. These data point to initial sulfate formation within an anoxic water body, either as a stratified deep lake on the surface, a sub-glacial water reservoir, or possibly in an as-yet unidentified sub-glacial lake. Mirabilite precipitation is likely the result of evaporation or freezing of sulfate-rich brines of unknown origin. Only small lakes are present within this region on the surface and our data suggest that moraine lake water was derived from the glacial ice, with some local mixing of a snow component, and underwent moderate evaporation. The $\delta^{18}O$ and δD (V-SMOW) values of snow, glacial ice, secondary glacial ice (ice lenses) and moraine lake water range from -64.2 to -29.7‰, and -456.0 to -231.7‰, respectively. Also, ion chromatography data show that lake water is fresh to brackish in origin, with TDS less than 1000 ppm, and sulfate concentration less than 300 ppm, both of which suggest that these lakes were not the source of the mirabilite mounds. Additionally, dissolved sulfate from lake water ($\Delta^{17}O$ = +1.82‰) indicates that the sulfate inputs of this region are mainly from an atmospheric origin (reduced sulfur oxidation by ozone and/or H_2O_2) and are not consistent with the $\Delta^{17}O$ values measured in the mirabilite.

$\delta^{18}O$ and $\Delta^{17}O$ values from sulfates, lake waters, and ice are plotted in figure 1. Mirabilite samples plot in a narrow range from -16.6 to -17.1‰, and from -0.34 to -0.41‰, respectively. We interpret these negative values as indicative of sulfate oxygen derived entirely from Antarctic glacial water. The highly negative $\delta^{18}O$ values of the mirabilite likely represent a continental oxidative weathering origin in an Antarctic setting, similar to background sulfate ($\delta^{18}O$~-20‰) suggested by Bao and Marchant [10]. The slight negative $\Delta^{17}O$ values of both water and mirabilites are intriguing. Interpretation of these data is ongoing.

$\delta^{34}S$ values of mirabilite also vary within a narrow range (fig. 2) and are very enriched in $\delta^{34}S$ (+48.8 to +49.3‰) likely due to bacterial-mediated sulfate reduction similar to what was observed in glacial sulfur springs found in the Canadian High Arctic [11]. Under this scenario, the parent sulfate (originally marine anhydrite or gypsum), derived from sedimentary depos-

its, is buried sub-glacially and is reduced to sulfide by bacteria under anaerobic conditions removing ^{32}S and enriching the remaining sulfate reservoir in ^{34}S.
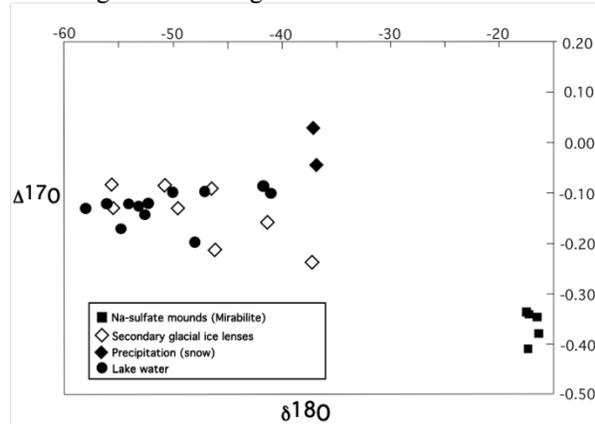

Figure 1. δ^{18}O vs. Δ^{17}O of solid mirabilite, glacial ice lenses, precipitation, and lake water.

The lack of surface expressions of sulfur springs and no apparent sulfide minerals or H_2S within the moraine lakes at LCIT suggest that all bacterial activity occurs well beneath the evaporite mounds sub-glacially.

Mirabilite mound formation model and implications for martian mounds: We propose a simple model to explain mirabilite mound formation at the LCIT. Sulfur redox processes occur predominantly sub-glacially as a result of liquid-water-based glacial conditions (Alpine style glacier), most likely formed by pressure melting of overlying ice [12]. Alternatively, an unidentified sub-glacial lake may exist beneath the ice (glacier) and above the bedrock. We suggest that the aqueous base of the LCIT contains dissolved SO_4^{2-} ions and is anoxic where sulfate reduction to H_2S or HS^- takes place. Sulfide is removed by either precipitation as sulfide minerals or by escape of H_2S (which has not been observed). The remaining sulfate is then carried up and becomes a component of the ice lenses or lakes where it later precipitates as mirabilite in mounds either by freezing or evaporation. Pressure from the overlying ice contributing to a pressure-melting scenario that creates the sub-glacial aqueous environment or sub-glacial lake also contributes to the mechanism of upward transport of the sulfate-rich fluids rising to the surface. Further evidence to support this upward transport model comes from the nature of ice motion at the LCIT. Cassidy et al [13] pointed out that it is the vertical ice motion in this area that creates the meteorite-stranding surface that could also account for upward transport of sulfate-rich fluids. We believe this LCIT mirabilite mound formation model fits well as a terrestrial analog for martian mound formation. Upward transport of sulfate rich fluids through ice-covered regolith is followed by precipitation of

evaporites in mound-like geomorphic features by freezing and/or evaporating the fluid. Inasmuch as mirabilite mound formation at the LCIT involves the action of sulfate-reducing bacteria, the martian mounds may also preserve biosignatures and therefore be excellent locations to study subsurface activity without drilling.
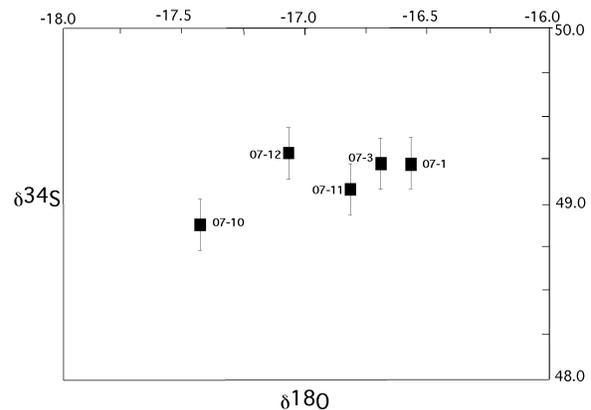

Figure 2. δ^{18}O vs. δ^{34}S of solid mirabilite.

Summary: Sulfate-rich evaporite mounds at LCIT have anomalously high δ^{34}S values, low δ^{18}O values, and small negative Δ^{17}O $_{(sulfate)}$ values. O and D isotope compositions of surface lake waters confirm that they are derived from a mixture of glacial ice and snow that underwent slight evaporation. Our data point to mirabilite mound formation processes involving bacterial sulfate reduction, followed by precipitation due to evaporation or freezing of the sulfate brines. These mounds may be an analog to mounds found on the martian surface and may be an excellent means for investigating the role of subsurface water without expensive drilling.

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