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Characterization of the acidic cold seep emplaced jarositic Golden Deposit, NWT, Canada, as an analogue for jarosite deposition on Mars

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ABSTRACT

Surficial deposits of the OH-bearing iron sulfate mineral jarosite have been observed in several places on Mars, such as Meridiani Planum and Mawrth Vallis. The specific depositional conditions and mechanisms are not known, but by comparing martian sites to analogous locations on Earth, the conditions of formation and, thus, the martian depositional paleoenvironments may be postulated. Located in a cold semi-arid desert ~100 km east of Norman Wells, Northwest Territories, Canada, the Golden Deposit (GD) is visible from the air as a brilliant golden-yellow patch of unvegetated soil, approximately 140 m × 50 m. The GD is underlain by permafrost and consists of yellow sediment, which is precipitating from seeps of acidic, iron-bearing groundwater. On the surface, the GD appears as a patchwork of raised polygons, with acidic waters flowing from seeps in troughs between polygonal islands. Although UV–Vis–NIR spectral analysis detects only jarosite, mineralogy, as determined by X-ray diffraction and inductively coupled plasma emission spectrometry, is predominantly natrojarosite and jarosite, with hydronium jarosite, goethite, quartz, clays, and small amounts of hematite. Water pH varies significantly over short distances depending on proximity to acid seeps, from 2.3 directly above seeps, to 5.7 several m downstream from seeps within the deposit, and up to 6.5 in ponds proximal to the deposit. Visual observations of microbial filament communities and phospholipid fatty acid analyses confirm that the GD is capable of supporting life for at least part of the year. Jarosite-bearing sediments extend beneath vegetation up to 70 m out from the deposit and are mixed with plant debris and minerals presumably weathered from bedrock and glacial till. This site is of particular interest because mineralogy (natrojarosite, jarosite, hematite, and goethite) and environmental conditions (permafrost and arid conditions) at the time of deposition are conceivably analogous to jarosite deposits on Mars. Most terrestrial analogues for Mars jarosites have been identified in temperate environments, where evaporation rates are very high and jarosites form along with other sulfates due to rapid evaporation (e.g. Rio Tinto, Spain; Western Australian acidic saline lake deposits). The GD is a rare example of an analogue site where jarosite precipitates under dominant freezing processes similar to those which could have prevailed on early Mars. Thus, the GD offers a new perspective on jarosite deposition by the upwelling of acidic waters through permafrost at Meridiani Planum and Mawrth Vallis, Mars. The GD also demonstrates that martian deposits may show considerably more chemical and mineral variability than indicated by the current remote sensing data sets.

1. Introduction

Mars today is a cold, dry planet, and most of the surface consists of permafrost (Carr and Schaber, 1977), which is defined as ground that remains at or below 0 °C for at least 2 years (Harris et al., 1988). Liquid H_2O (water) is unstable on the surface for long periods of time under current atmospheric conditions, but substantial deposits of ground ice are hypothesized to occur within a depth of 1 m in circumpolar latitudes (Mitrofanov et al., 2003). A variety of observations support the existence of ice in the martian subsurface, including the detection of near-surface ground ice in martian

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northern latitudes by the Phoenix lander (Smith et al., 2009), and the Mars SHAllow RADar (SHARAD) sounder onboard Mars Reconnaissance Orbiter (MRO; Phillips et al., 2008).

Despite the lack of water on Mars' surface today, past and present missions have observed minerals consistent with long-term crustal interaction with liquid H_2O, including phyllosilicates, hydrous sulfates, and halides (e.g., Bibring et al., 2006; Squyres et al., 2004b). Many scenarios for conditions on early Mars have been proposed, ranging from a cold, dry, but locally wet Mars (e.g., Carr and Head, 2003; Christensen, 2008; Ehlmann et al., 2011; Johnson et al., 2008) to a cold Mars with a cold (Parker et al., 1993) or glacially bound ocean (Fairén et al., 2011), to a warmer Mars, with warm oceans (Chevrier et al., 2007; Pollack et al., 1987). There is no consensus on what Mars' climate was like during the time these minerals were deposited, but recent studies suggest temperatures may have hovered around the freezing point of water (Fairén, 2010; Johnson et al., 2008). Even if we take a conservative approach and assume that conditions were indeed relatively cold and dry with local transient surface water, phyllosilicates, hydrous sulfates, and halides could have precipitated (Christensen, 2008; Ehlmann et al., 2011).

Of particular interest are the discoveries of layered deposits containing the OH-bearing Fe-sulfate mineral, jarosite, throughout Meridiani Planum (Christensen et al., 2004; Klingelhofer et al., 2004; Squyres et al., 2004b), and in several patches at Mawrth Vallis (Farrand et al., 2009; Michalski and Niles, 2011). Jarosite is thermodynamically stable under a majority of temperature and pressure conditions on present-day Mars (Navrotsky et al., 2005; Cloutis et al., 2008). As such, provided it has not recrystallized or decomposed, jarosite may contain chemical or textural indicators of Mars' history, perhaps including evidence of biological activity via ^{34}S isotopic composition (Navrotsky et al., 2005). Global mapping has revealed that similar sulfate-bearing mineralogical assemblages are widespread over the martian surface (Bibring et al., 2006). The layered deposits in Meridiani Planum have been interpreted as evidence for past upwelling and evaporation of acidic groundwater or surface water (Squyres et al., 2004b, 2006), likely during the late Noachian (Andrews-Hanna et al., 2010; Hurowitz et al., 2010). Based on the wide distribution of sulfate deposits, acid sulfate aqueous systems could have directed the geochemistry of surface waters for extended periods of time during the late Noachian, either globally (Bibring et al., 2007; Fairén et al., 2004), or in isolated locations (Christensen, 2008). This places constraints on the type of mineral deposits that could have precipitated and also on the habitability of surface waters during that period of time.

A major question related to the martian acidic deposits is their mode of formation. Jarosite deposition requires acidic waters and oxidizing conditions. Natural acidic surface water systems most commonly occur on Earth in two types of settings. The first type is volcanic, where gases including H_2S and SO_2 are dissolved and oxidized in caldera lakes or hot springs (Varekamp et al., 2000; Zolotov and Shock, 2005). However, neither Meridiani Planum nor Mawrth Vallis are situated near enough to volcanoes, so this type of setting was not likely responsible for jarosite deposition. The second type is in areas where iron sulfide minerals are oxidized. Several terrestrial jarosite-rich sites of this formation nature have been described as analogues for Mars. For example, Rio Tinto, Spain (Amils et al., 2007; Buckby et al., 2003; Fairén et al., 2004; Fernández-Remolar et al., 2005), the Goldfield Au–Ag mining district, Nevada (Papike et al., 2006), Western Australian acidic saline lake deposits (Benison and LaClair, 2003; Baldridge et al., 2009), and Eagle Plains, Yukon, Canada (Lacelle and Léveillé, 2010). Many of these sites and most models developed to explain their martian counterparts invoke heating, or at the very least warm climates, for jarosite precipitation (e.g., Zolotov and Shock, 2005). More recently, however, analogue sites and mechanisms have been reported in cooler climates, with average annual temperatures below freezing (e.g., Lacelle and Léveillé, 2010; Michalski and Niles, 2011). This suggests the possibility of jarosite production under colder conditions, closer to those currently prevailing on Mars. Although surface temperatures during jarosite deposition at Meridiani Planum and Mawrth Vallis are not known with certainty, it is important to consider analogue sites in colder settings, with environmental properties representative of a colder Mars. These properties include prevailing freezing temperatures, frozen soils forming a thick layer of permafrost, and semi-arid to arid climate regimes (Fairén, 2010; Fairén et al., 2009).

In addition, if the deposits formed in an environment where evaporation dominated, the resulting geochemical conditions and the mineral phases that precipitate would have been different from an environment dominated by freezing and sublimation (Lacelle and Léveillé, 2010). Distinguishing one from the other would help constrain climate models of Early Mars and also habitability models of surface aqueous environments. Lacelle and Léveillé (2010) determined through modeling and ground truthing that mineral assemblages at Eagle Plains were produced by freezing, rather than evaporation. The same techniques could be applied to other cold-climate acidic aqueous systems. The polar regions of Earth present some of the most relevant analogue science opportunities for ground truthing models and evaluating hypotheses concerning physicochemical processes on Mars (e.g., High Lake gossan deposit in Nunavut, Canada (West et al., 2009); Eagle Plains, Yukon, Canada (Lacelle and Léveillé, 2010)). The Golden Deposit (GD), Northwest Territories, Canada (Michel and van Everdingen, 1987), features jarosite and other sulfates precipitating from cold acidic groundwater seeps and is of particular interest as analogous martian features may have been produced through similar processes. Here, we report on the first detailed field, mineralogical, and geochemical characterization of the GD. Table 1 compares temperature and precipitation, along with additional properties of the GD, to Meridiani Planum and Mawrth Vallis, Mars, and other terrestrial analogue sites.

1.1. The Golden Deposit

The Golden Deposit (GD) is located in the Canadian Arctic ~100 km east of Norman Wells, Northwest Territories (65°11′58″N, 124°38′15″W; Fig. 1). It is visible from the air as a golden-yellow patch of unvegetated soil approximately 140 m long × 50 m wide, within the muskeg-rich boreal forest typical of the subarctic taiga. It was discovered in 1975 and referenced as the "Golden Deposit" by Michel (1977). The surface of the GD features an interconnected network of 1–3 m diameter raised polygons (Fig. 2a and b). Water flows in small channels within the troughs between polygons.

The GD consists of an accumulation of yellow ochre, precipitating from numerous closely spaced seeps in troughs. Seeps deliver cold, acidic, iron-bearing waters from the sub-surface, and can be identified by slow streams of small bubbles. In most cases flow rates are very low, at approximately 2–3 L/min (Michel and van Everdingen, 1987). The seeps range in diameter from roughly several mm to 20 cm across, can be 10 or more cm deep, and vary in appearance from discreet holes in sediment (Fig. 2i) to obvious deep holes within channels (Fig. 2i), to "craters", up to 1 m in diameter. The GD is bounded on the west by a shale outcrop in the form of a small hill, and on the southwest and southeast by Ponds 1 and 2 (Fig. 1). In other directions the GD is surrounded by older deposits produced by the same system, which are now buried beneath muskeg. Water flows in a predominant northwest to southeast direction across the GD, and exits into a pond at the southeast end (Pond 2, Fig. 1). Small ponds along the perimeter on the north and west sides may receive some active layer seepage