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Acid saline lake systems give clues about past environments and the search for life on Mars

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Abstract

Acid saline lake systems in Western Australia may be the best known modern terrestrial analog for the Burns formation on Mars and, thus, provide information about past environments and life on Mars.

Keywords: Mars, surface; Geological processes; Mineralogy; Exobiology; Earth

1. Introduction

Ephemeral acid saline lakes and adjacent environments in southern Western Australia may provide the best known Earth analog for past environments on Mars. Mineralogy, sedimentary characteristics, and alteration features in these lake systems are strikingly similar to those of the Burns formation at Meridiani Planum. We propose that acid saline systems such as these once existed on Mars. These unusual environments and their deposits are very different than other terrestrial lake deposits and their sedimentological processes and products are only starting to be understood. Microbial life exists in these modern terrestrial acid saline lake systems and microbial remains are found entrapped in halite and gypsum from these modern environments, as well as in halite from their Permian counterparts. If past life existed within the depositional environment of the Burns formation on Mars, it may be best preserved as microbial remains in saline minerals.

Several ancient and modern Earth environments have been proposed as analogs based on either sedimentary characteristics (Chan et al., 2004) or mineralogy (Fernandez-Remolar et al., 2003, 2005). However, acid saline lakes in Western Australia share more sedimentary and mineralogic characteristics with the recently discovered Burns formation on Mars (Grotzinger et al., 2005) than any other known Earth environment. The shallow, acid saline lakes and their adjacent groundwaters have pHs that range from 1.5 to 4 and precipitate gypsum, halite, iron oxides, and jarosite. These environments are strongly influenced by flooding, evaporation, desiccation (Lowenstein and Hardie, 1985), and winds, as well as surface and groundwater chemistry. Similar acid saline lake systems are believed to have been present in the mid-US during the Permian (∼270 million years ago; Benison et al., 1998).

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2. Observations

Burns (1987) and Clark (1979, 1994) used mineralogic interpretations and theoretical calculations, respectively, to predict that sulfuric acid-rich solutions were the most likely liquids to have ever existed on the martian surface. Minerals in modern and ancient terrestrial acid saline lake systems compared favorably to those interpreted from Mars based on data collected prior to the Mars Exploration Rovers (MER) mission (Benison and LaClair, 2003). Now, the MER data confirm and expand mineralogic information, as well as provide images of sedimentary structures and diagenetic (alteration) features (Squyres et al., 2004a), all of which give important clues about past environments that existed on Mars (Squyres et al., 2004b; Kargel, 2004). The assemblage of martian minerals, sedimentary structures, and diagenetic features are strikingly similar to those at acid saline lake systems in southern Western Australia.

The Yilgarn Craton is a large area of southern Western Australia (∼1.78 million km^2) composed of highly weathered and diverse Archean (∼4–2.5 billion years old) igneous and metamorphic rocks, including granite, gneiss, anorthosite, quartzite, and ironstone. Inset valleys carved by rivers in the Eocene and partially filled by Eocene and younger sediments provide shallow depressions in which modern lakes exist (deBroekert and Sandiford, 2005). Some lakes are hosted by these young sediments, but others are in direct contact with the underlying Archean bedrock. The lakes are small (1–200,000 acres^2), shallow (<0.5 m deep), saline (∼60–280% of total dissolved solids), and Na–Mg–Cl–SO_4-rich, with relatively high Al, Fe, and Br and variable amounts of Ca and K. Hundreds of individual lakes of different pHs exist in this region and include extremely acid (pHs $<$ 4), moderately acid (pH 4–6), neutral (pH 6–8), and moderately alkaline (pH $>$ 8) lake water and groundwaters. Even where lake waters are neutral or moderately alkaline, groundwaters tend to be extremely acid. Weather, climate, and seasonal variations affect the size, shape, depth, and water geochemistry of these lake systems.

Martian outcrop characteristics: A) Mineralogy B) Sedimentary Textures/Structures

Proposed Earth analogs		Ca and/or Mg sulfate	jarosite	hematite	chloride	siliciclastic component	fine-med. sand grains	planar laminations	cross-bedding	hematite concretions	displacive crystals	ripple marks	mudcracks
Ancient	1) Jurassic Navajo Sandstone, Utah			X		X	X	X	X	X		X	?
	2) Permain Basin, Texas					X	X	X	X			X	X
	3) Permian acid salt lake deposits	X		X	X	X	X	X	X	X	X	X	X
Modern	4) Rio Tinto, Spain		X	X		X	?	?	?			X	X
	5) Hydrothermally-altered volcanics		X	?				?	?				
	6) White Sands, New Mexico	X					X	X	X		?	X	?
	7) Western Australia acid salt lakes	X	X	X	X	X	X	X	X	X	X	X	X

Fig. 1. Comparisons of Earth analog environments and characteristics of the Burns formation outcrop on Mars. X represents documented occurrence. ? represents possible, but not clearly documented occurrence. References for Earth analogs include: (1) Chan et al. (2004), (2) Kargel (2004), (3) Benison and LaClair (2003), Benison (2006), (4) Fernandez-Remolar et al. (2003, 2005), (5) Bishop et al. (2004), and (6) Grotzinger et al. (2005), Langford (2003), Schenk and Fryberger (1988).

Saline lakes in southern Western Australia are strongly influenced by flooding, evapoconcentration, desiccation, and winds. Flooding occurs when infrequent rain causes runoff into the lake basins. Flooding events carry siliciclastic sands and silts into the lakes and create sandflats around them. Lake waters are fed by both acid saline groundwater and rainfall runoff and evaporate in the arid climate and precipitate halite, gypsum, and iron oxide. Desiccation occurs to some lakes during drier times and leaves behind mudflats, sandflats, and/or saltflats where the lakes once existed. Winds rework these sediments to produce aeolian sand and silt grains composed of evaporite and siliciclastic minerals. Subsequent flooding partially or totally dissolves evaporite crystals.

These varied processes result in a specific set of sedimentary features. Although these lake systems are dominated by bedded fine-to-medium grained quartz and gypsum sand, variations in the sedimentology allow for interpretations of deposition in the lakes or the surrounding mudflats, sandflats, and dunes. Laminations and thin beds are deposited in the lakes and are composed of siliciclastic grains, evaporite crystals, and/or decayed plant material. Small ripples in the lakes form from water motion, both driven by wind and flooding. Mudflats and sandflats, areas adjacent to lakes, vary greatly over time, depending upon flooding, evapoconcentration, desiccation, and wind activity. During flooding events, these areas are covered with sandy aprons and coarse-grained flood lags and associated complex ripples and meandering channels. During drier times, sediment is finer and mudcracks are formed by both shrinkage of mud and expansion of evaporites. "Bathtub rings," some composed of efflorescent halite crusts and others of halite rafts that have been pushed shoreward by winds, outline former lake shores. In addition, winds play a greater role in drier times, eroding lake-precipitated, but then exposed, evaporites and redepositing them on wind-rippled sandflats and cross-bedded dunes. This group of sedimentary features are specific to continental ephemeral shallow saline environments.

A unique suite of minerals form as chemical precipitates in the extremely acid lake systems. Halite, gypsum, and hematite precipitate from lake waters during evapoconcentration and desiccation. Lake-precipitated halite and gypsum accumulate as beds on lake bottoms. Hematite precipitates directly from lake waters and is deposited as thin layers of pure hematite mud or is trapped as solids within the evaporite crystals. Groundwaters also precipitate this halite–gypsum–hematite mineral suite, as well as goethite, jarosite, and alunite. All of these minerals precipitate in pores between the siliciclastic and reworked evaporite host grains. Hematite and goethite coat grains and fill pores. They also form spheroidal concretions in shallow loose sands under some of the lakes. Some silicate clays, such as kaolinite, occur in the shallow subsurface and also seem to be an early diagenetic feature. Hematite, goethite, jarosite, alunite, and silicate clays form irregular blebs and stringers that may consolidate to form a single bed. Some halite and gypsum crystals grow displacively from shallow groundwater by pushing aside host grains under the sandflats, mudflats, and lakes. These acid saline lake systems in Western Australia are the only places on Earth known to form this mineral assemblage in these distinct forms.

3. Comparison of terrestrial and martian acid saline systems

The sedimentary and mineral characteristics of these ephemeral acid saline lakes are strikingly similar to those observed in the lithified strata of the Burns formation on Mars (Figs. 1 and 2). MER scientists recognize the importance of winds (Grotzinger et al., 2005), as well as acid saline waters (Squyres et al., 2004b) in the formation of these rocks. Based upon our comparisons with the Western Australia environments, we deduce that the martian rocks appear to have formed in ephemeral acid saline lake systems. Sedimentary features in the Burns formation include fine-medium sand-sized and mud-sized grains, planar bedding, cross-bedding, ripple marks, mudcracks, displacive crystal molds, and concretions. Chemical analyses suggest some siliciclastic component, Ca-sulfate minerals, Mg-sulfate minerals, hematite, jarosite, and chloride (Klingelhofer et al., 2004; Clark et al., 2005). Collectively, these mineralogical, sedimentary, and diagenetic characteristics indicate deposition in ephemeral, shallow, saline, acid lake and groundwater systems affected by wind. The best terrestrial analogs to the martian Burns formation are the acid saline lake systems in southern Western Australia.

4. Implications for extraterrestrial life

Understanding life in terrestrial acid saline lake systems may provide clues to any possible past life on Mars. Life within these acid lake systems is likely dominated by bacteria, fungi, algae, and/or Archaea. Field observations reveal several features suggestive of microbial life, including gas production from the subsurface, filamentous structures along shores, hydrogen sulfide odors in some sediments, and juxtaposed sediment colors suggesting reducing and oxidizing conditions in close contact (Figs. 3A–3C). However, preservation of these features is dubious. The best preservation for life within these systems is as organic remains within the evaporite crystals. Rapid growth of chemical precipitates, as is common in saline lake halite and gypsum, can trap microbes as solid inclusions and within fluid inclusions (Mormile et al., 2003; Vreeland et al., 2000). "Hairy blobs," clumps of sulfate crystals and microbes, are closely associated with extremely acid fluid inclusions in the Permian Opeche Shale halite and modern halite and gypsum from Western Australia (Benison and Goldstein, 2002; Figs. 3D–3I). Laser Raman spectroscopy indicates that these "hairy blobs" have a carbon signature. Scanning electron microscopy shows features characteristic of microbes, such as hollow and bent rods, meniscus structures, and bumpy surface textures on crystals. Ultraviolet fluorescence microscopy of Permian "hairy blobs" suggests that they contain fungi.

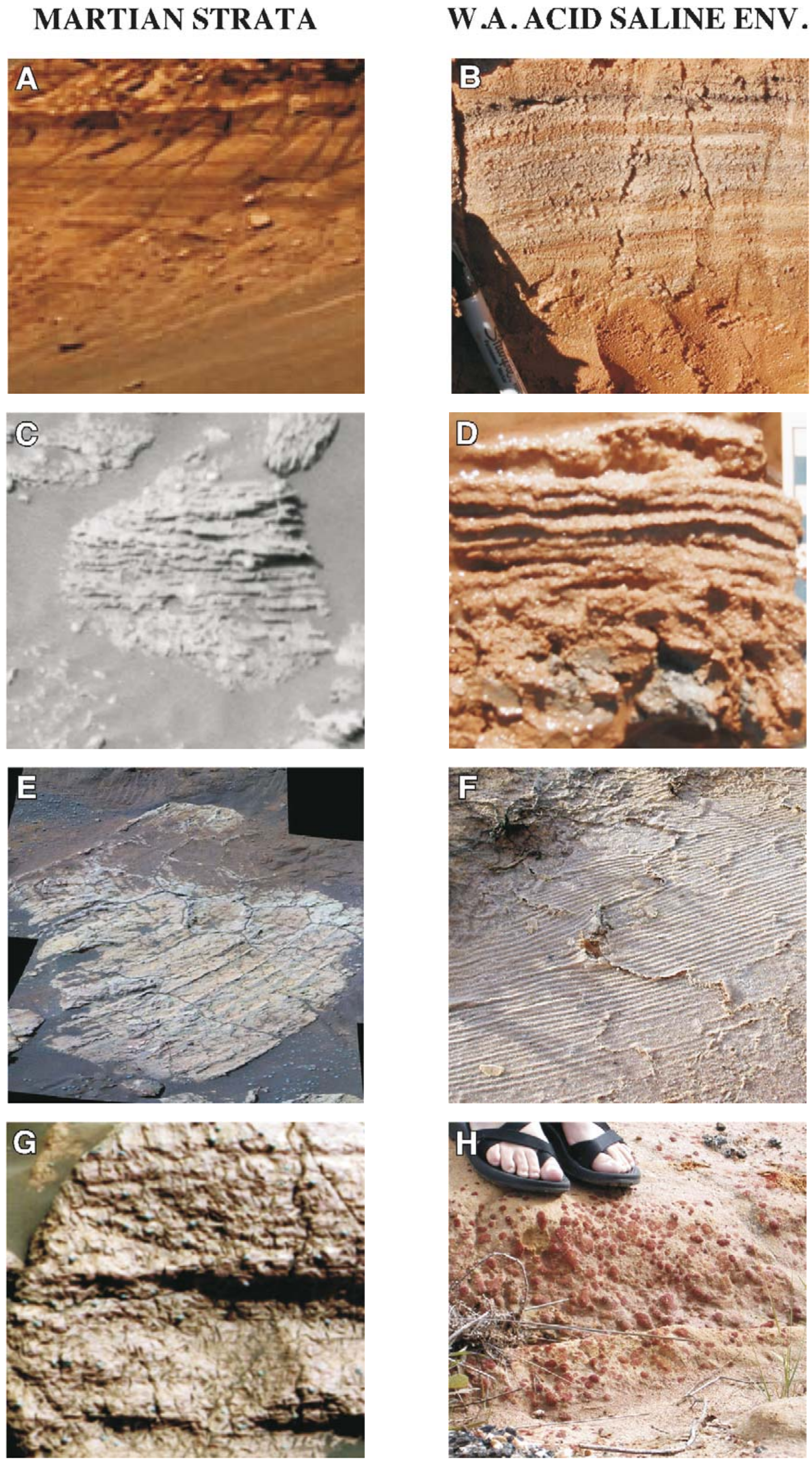

Fig. 2. Photographs of sedimentary structures and early diagenetic features in martian strata compared to those in the Western Australian acid saline environments. (A) and (B): cross-sectional views of bedding. (A) Burns' Cliff. Image courtesy of NASA/JPL/Cornell. Vertical field of view is ~3.5 m. (B) Sandflat at Lake Aerodrome, Lake Cowan basin. Note pen for scale. (C) and (D): cross-sectional views of low-angle, planar cross-strata. (C) Outcrop at Meridiani Planum. Image courtesy of NASA/JPL/Cornell. Rock in center is ~12 cm across. (D) Gypsum/anhydrite- and hematite-rich sand from sandflat at Lake Aerodrome, Lake Cowan basin. Vertical field of view is ~11 cm. (E) and (F): bedding plane views of ripple marks and mudcracks. (E) "Escher" rock at Endurance Crater. Image courtesy of NASA/JPL/Cornell. Rock is ~60 cm across. (F) Wind ripples composed of gypsum clasts and quartz grains cross-cut by expansion cracks at Cumulate Raceway, Lake Cowan basin. Field of view is ~1 m across. (G) and (H): hematite concretions. (G) Concretions in and on "El Capitan" rock at Meridiani Planum. Image courtesy of NASA/JPL/U.S. Geological Survey. Field of view is ~43 cm across. (H) Hematite concretions in recent sandstone near Bandee Lakes. Note feet for scale. (I) and (J): cross-sectional views of displacive crystals and molds. (I) Probable sulfate displacive crystal molds in "El Capitan" rock at Meridiani Planum. Image courtesy of NASA/JPL/U.S. Geological Survey. Field of view is ~9 cm across. (J) Displacive gypsum crystals hosted by quartz- and hematite-rich sand under Twin Lake West. Note finger for scale.

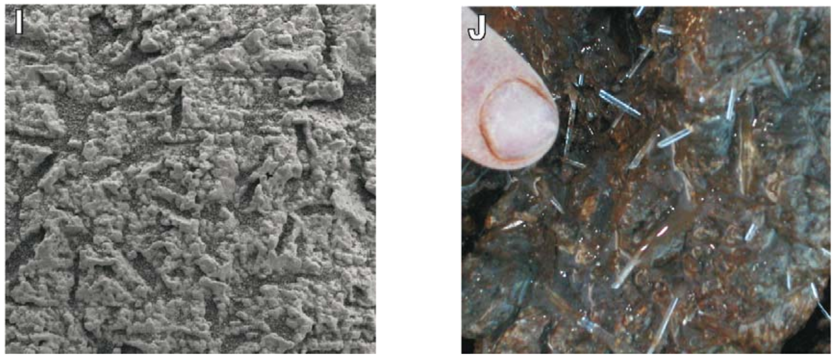

Fig. 2. (*continued*)

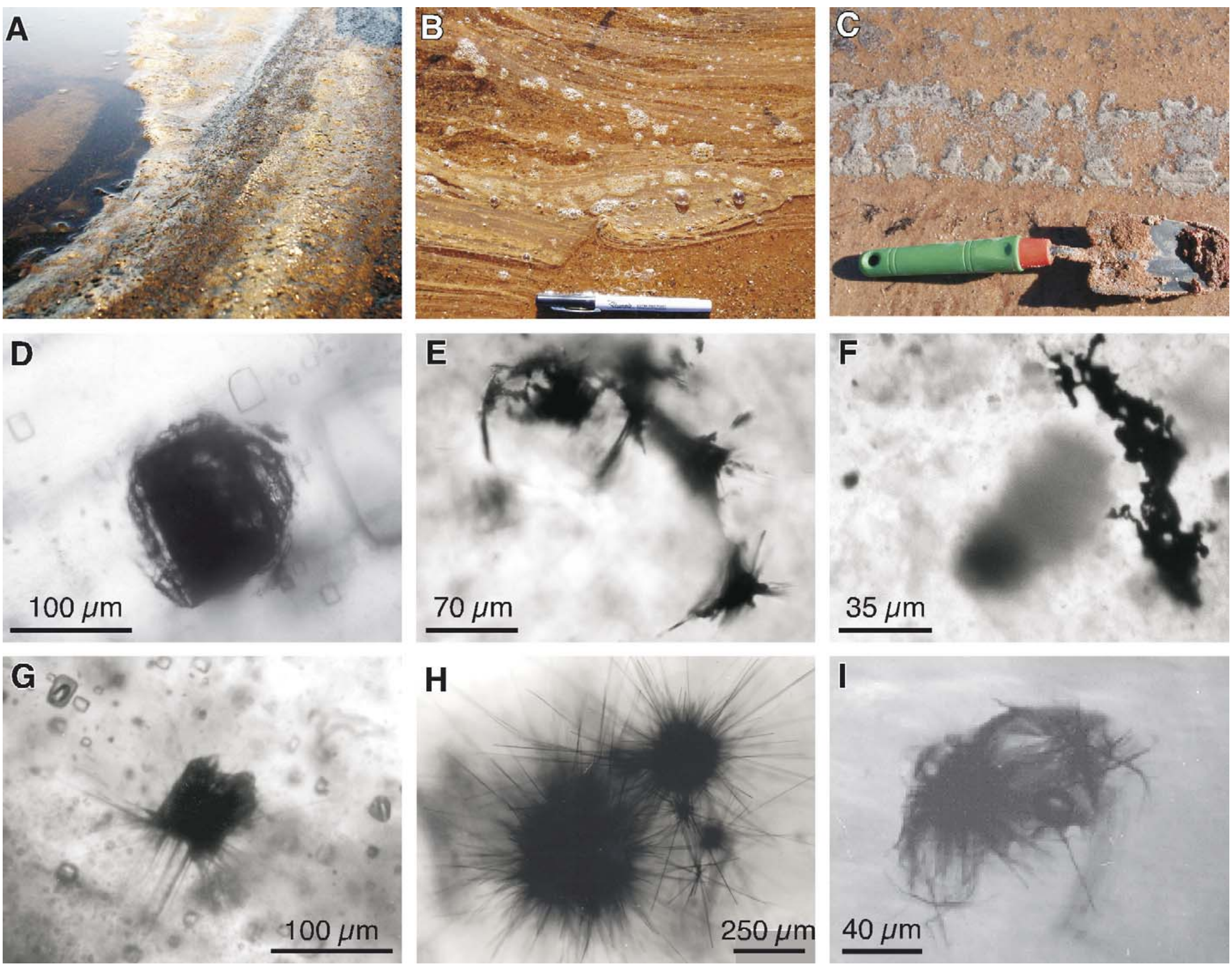

Fig. 3. Photographs of microbial suspects at terrestrial acid saline lake environments and within evaporite crystals. (A–C) In field in Western Australia. (A) Foam at leeward end of Lake Brown. Field of view ~1 m across. (B) Filamentous structures along shoreline at Lake Aerodrome, Lake Cowan basin. Note pen for scale. (C) Gray algal mat contrasted against reddish brown sediment along shoreline of Lake Brown. Note trowel for scale. (D–F) In evaporite crystals from modern acid lakes from Western Australia. (D) Organic body in primary fluid inclusion in halite. (E) Organic bodies in halite. (F) Organic bodies in gypsum crystal. (G–I) In halite from Permian Opeche Shale, Gulf-Romanysyn 2-33-4B core, Billings County, North Dakota. (G) Organic body in primary fluid inclusion. (H) Clump of organic bodies. (I) Clumps of organic bodies closely associated with fluid inclusion and sulfate crystals.

The search for life on Mars should focus on microbes preserved in chemical precipitates. We make this claim because: (1) terrestrial acid saline lake systems in Western Australia are a good analog for past martian environments; and (2) the best fossil preservation over time in these systems are microbial remains entrapped within halite and gypsum crystals. The evaporites most likely to survive dissolution in these environments are reworked lake-precipitates that are coated with iron oxides and redeposited as eolian sands. Future missions to Mars, as well as other planets and moons should include microscopic-resolution optical and chemical capabilities for evaluating any of these minerals for microbial remains.

5. Conclusions

The ephemeral acid saline lake systems in Western Australia are strikingly similar in mineralogy, sedimentary structures, and diagenetic features to the Burns formation on Mars. This analogy strongly suggests that Mars once had shallow acid saline surface and groundwaters. Evaporite minerals should be considered a possible repository for any remains of past martian organisms. Only by studying extreme environments that serve as terrestrial analogs for extraterrestrial systems, will we be able to better understand and predict the physical, chemical, and biological evolution of our Earth as well as the Solar System.

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