A Martian analog in Kansas: Comparing Martian strata with Permian acid saline lake deposits

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ABSTRACT

An important result of the Mars Exploration Rover's (MER) mission has been the images of sedimentary structures and diagenetic features in the Burns Formation at Meridiani Planum. Bedding, cross-bedding, ripple marks, mud cracks, displacive evaporite crystal molds, and hematite concretions are contained in these Martian strata. Together, these features are evidence of past saline groundwater and ephemeral shallow surface waters on Mars. Geochemical analyses of these Martian outcrops have established the presence of sulfates, iron oxides, and jarosite, which strongly suggests that these waters were also acidic. The same assemblage of sedimentary structures and diagenetic features is found in the salt-bearing terrestrial red sandstones and shales of the middle Permian (ca. 270 Ma) Nippewalla Group of Kansas, which were deposited in and around acid saline ephemeral lakes. These striking sedimentological and mineralogical similarities make these Permian red beds and evaporites the best-known terrestrial analog for the Martian sedimentary rocks at Meridiani Planum.

Keywords: Mars, red beds, evaporites, acidity.

INTRODUCTION

The middle Permian Nippewalla Group is exposed at the surface in south-central Kansas. In southwestern Kansas, these rocks are found in subsurface cores composed of bedded halite, bedded gypsum/anhydrite, and red shales and sandstones (many with displacive halite and gypsum crystals and/or halite cement; Benison and Goldstein, 2001). However, the halite is dissolved near the surface, leaving outcrops composed of only bedded gypsum/anhydrite, red shales, and red sandstones (Benison, 1997; Fig. 1). The siliciclastic grains are primarily quartz grains coated with hematite, which have been transported by winds and then carried into lakes by both winds and sheet floods. Some gypsum/anhydrite beds are composed of altered, but in situ, lake-bottom-growth gypsum crystals. However, many gypsum/anhydrite beds contain rounded, fine- to medium-sized sand grains, which likely originated as lake-grown gypsum crystals and were later reworked locally during desiccation, wind, and flooding events.

Laser Raman microprobe analyses of unaltered primary fluid inclusions in halite in two Nippewalla Group cores suggest that this halite precipitated from acid lake waters (Benison et al., 1998). All 51 primary fluid inclusions analyzed contained high amounts of sulfate (between 3500 and 19,250 ppm; Benison, 1997), but 8 inclusions (15% of sample) were also strongly acidic, with pH between 0 and 1 (pH higher than 1 cannot be detected with this method; Benison et al., 1998). Detailed study of the Nippewalla Group cores and outcrops shows that shallow, ephemeral saline acid lakes, surrounded by mud flats, sand flats, and sand dunes, existed in Kansas ca. 270 Ma (Benison and Goldstein, 2001).

Two other terrestrial acid saline lake deposits besides the Nippewalla Group are the Permian Opeche Shale and modern lakes in Western Australia. The Opeche Shale, found primarily in the subsurface of North Dakota, is the age and lithologic equivalent of the Nippewalla Group (Benison and Goldstein, 2000). Laser Raman spectroscopy of fluid inclusions indicates that both bedded and displacive halite in the Opeche Shale was precipitated by strongly acidic lake and groundwaters, respectively. All inclusions analyzed had pH values less than 1; inclusions from one halite bed had pH less than 0 (Benison et al., 1998). Modern acid saline lake systems in southern Western Australia serve as a modern counterpart. These Australian lakes are shallow, often ephemeral, and acidic (pH ~1.5–4.0) and precipitate abundant gypsum, halite, and hematite. Acid saline groundwater associated with the lakes also precipitates these minerals, as well as jarosite and alunite (Alpers et al., 1992; Benison et al., 2001; Gray, 1997; McArthur et al., 1991). Although the Opeche rocks and modern Australian environments also are similar to the Martian strata in terms of sedimentology and mineralogy (Benison and LaClair, 2003), the excellent field exposures of the Nippewalla Group allow it to be compared with greater ease to the lithified Martian outcrops.

MARTIAN OUTCROPS

The Mars Exploration Rover (MER) mission has supplied a wealth of new data about past environments on Mars. The Opportunity Rover provided the first detailed documentation of the chemistry of past surface waters on Mars (Bell et al., 2004; Christensen et al., 2004; Herkenhoff et al., 2004; Klingelhofer et al., 2004; Rieder et al., 2004; Squyres et al., 2004a, 2004b). Geochemical data improve upon and confirm previous interpretations about the mineralogy of Mars rocks (i.e., Bell, 1996; Burns, 1987). The Meridiani Planum outcrops contain fine-grained siliciclastics, sulfate minerals, hematite, and some jarosite (Clark et al., 2005; Squyres et al., 2004a, 2004b). The same mineral assemblage found at Meridiani Planum is a criterion for the recognition of acid deposition in terrestrial rocks (Benison and Goldstein, 2002). Images of the Martian outcrops at Meridiani Planum show sedimentary structures and diagenetic features, which include ripple marks, cross-bedding, mud cracks, randomly oriented, crystal-shaped vugs, and hematite concretions (Grotzinger et al., 2005; Herkenhoff et al., 2004; Kargel, 2004; Squyres et al., 2004b). This combination of geochemical and photogeologic data is considered reasonable evidence of past saline, highly acidic, shallow surface and ground waters (Benison and LaClair, 2003; Caitling, 2004; Kargel, 2004).

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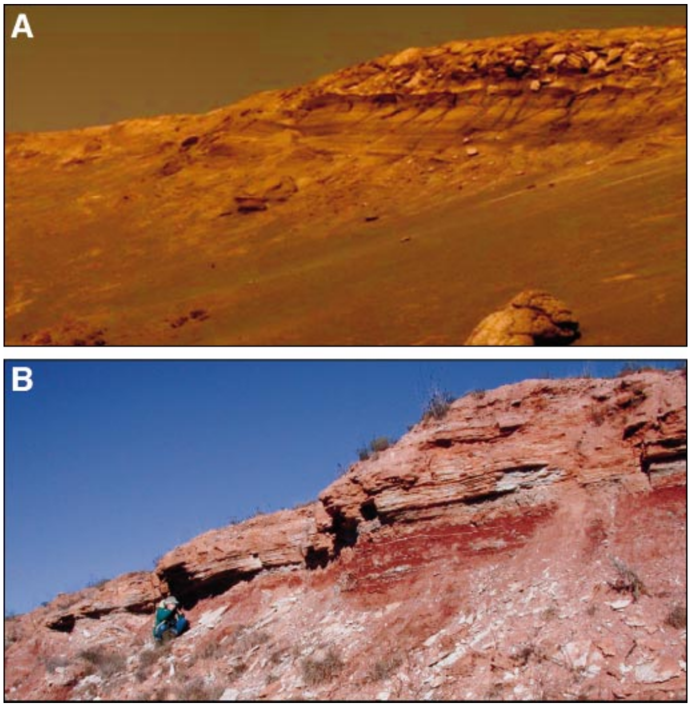

Figure 1. Photographs of outcrops on Mars and in Kansas. A: Burns Cliff within Endurance Crater (image courtesy of National Aeronautics and Space Administration [NASA]/Jet Propulsion Laboratory/ Cornell). Outcrop is approximately 7 m high. B: Representative outcrop of Nippewalla Group in Barber County, Kansas. Pale blue cap rock is composed of gypsum/anhydrite with some hematite. Underlying dark red rocks are siltstones and sandstones composed of quartz, hematite, and gypsum/anhydrite poorly cemented by easily dissolved halite. Note person in green coat for scale.

A TERRESTRIAL ANALOG

In recent literature on the MER data, several terrestrial analogs for the Martian strata at Meridiani Planum have been proposed. Rio Tinto, a river system in southern Spain influenced by sulfuric acid mine drainage, has been proposed due to its precipitation of hematite and jarosite (Fernandez-Remolar et al., 2005; Squyres et al., 2004b). The marine sedimentary rocks of the Permian Basin in Texas and New Mexico have been suggested as a terrestrial analog, because they contain both gypsum/anhydrite beds and three types of similar sedimentary structures (Kargel, 2004). In addition, hematite concretions in the Jurassic Navajo Sandstone of Utah have been compared favorably to the ‘‘blueberry’’ concretions on Mars (Chan et al., 2004). The middle Permian Nippewalla Group is a stronger terrestrial analog, because it has striking similarities to the Martian outcrops in mineralogy, sedimentary structures, and diagenetic features.

SEDIMENTOLOGICAL COMPARISON

Outcrops of the Nippewalla Group and the Martian rocks show an overall similarity in that they are both capped by relatively thick strata overlying thinner, slope-forming beds (Fig. 1). The mineralogy is also similar, with fine-grained siliciclastic and/or sulfate mineral grains coated by pervasive hematite. In south-central Kansas, gypsum/ anhydrite is the rock type most resistant to weathering, so it forms the cap rocks of the buttes. The siliciclastics are very friable due to the dissolution of the halite cement near the surface.

The dominant sedimentary structure in both the Nippewalla and Martian strata is bedding (Fig. 1). Mud cracks overlying current ripple marks indicate shallow surface waters that dried up (Fig. 2A–B). Features suggestive of desiccation cracks in Martian strata include both: (1) regularly spaced, vertical cracks seen in cross-sectional views of some strata, and (2) polygon shapes defined by cracks on bedding planes (Fig. 2A). A variety of centimeter-scale cross-bedding structures suggests paleocurrents, some of which were produced in shallow moving water, but some others which may be eolian (Fig. 2C–F). This assemblage of sedimentary structures in both the Nippewalla and Martian rocks suggests past sediment deposition in water that usually was shallow and occasionally underwent desiccation, with winds as a secondary depositional agent.

Diagenetic features in common in both the Nippewalla Group and Martian strata are pervasive hematite coatings and cement, hematite concretions, and evidence of displacive sulfate crystals. In the Nippewalla Group, hematite coats all siliciclastic grains and some evaporite grains, and it is also trapped as solid inclusions in some evaporite crystals. These hematite coatings form intergranular cements and hematite concretions. Nippewalla hematite is more abundant in the lake and near-lake mudflat lithofacies than in eolian sand-dune and sandflat lithofacies. Hematite in the Nippewalla Group likely precipitated early from acid saline waters, as indicated by: (1) the lithofacies distribution, (2) its paragenetic timing before early halite cement and displacive halite and gypsum/anhydrite, and (3) observations of hematite precipitation from modern lake and groundwaters in Australia.

Hematite concretions are present in both the Nippewalla and Martian rocks (Fig. 2G–H). Nippewalla concretions are up to 5 cm long, are subangular to well-rounded and have moderate to low sphericity, a homogeneous hematite composition, and are constrained to rare red sandstone beds. In the field, these concretions easily weather out of the host sandstones. The Martian hematite concretions are smaller and have a much different shape (Squyres et al., 2004b), but both Martian and Nippewalla concretions are the likely result of diagenetic growth from iron-rich fluids.

Randomly oriented crystal shapes in both the Nippewalla and Martian rocks (Fig. 2I–J) provide important clues about the chemistry of past groundwater. Water underlying saline lakes or associated mud flats or sand flats, if saline enough, will precipitate evaporite mineral crystals within the unconsolidated sediment, either pushing away the surrounding host sediment or incorporating it into the crystal. In the Nippewalla Group, displacive halite and gypsum crystals are abundant in quartz- and hematite-rich mud-flat deposits. The presence of crystal-shaped vugs (i.e., fairly soluble minerals) and their random orientation in some Mars outcrops suggest that saline groundwaters once existed on Mars (Squyres et al., 2004b).

SUPPORTING EVIDENCE: THE MINERALOGICAL AND GEOCHEMICAL COMPARISON

The Meridiani Planum outcrops are composed of siliciclastic grains, hematite, and sulfate minerals, and only a few deposits on Earth match this description (Benison and Goldstein, 2002). The Nippewalla Group is one such rock formation. The sulfate minerals in the Nippewalla Group are primarily gypsum and anhydrite, but there are also small amounts of glauberite ($Na_2Ca[SO_4]_2$) and polyhalite ($K_2MgCa_2[SO_4]_2 \cdot H_2O$; Benison and Goldstein, 2001). The primary sulfate minerals in Martian strata are thought to be magnesium sulfate and calcium sulfate (Christensen et al., 2004; Clark et al., 2005). Other similarities between the Nippewalla and Martian outcrops include: (1) the presence of Cl^- (Clark et al., 2005), and (2) the lack of carbonate minerals. No halite remains in the outcrops of the Nippewalla Group, although halite crystal casts are not uncommon, and halite is found throughout subsurface core samples. Small amounts of jarosite, a sulfate mineral that forms only in oxidized sulfuric acid solutions, has also been documented at Meridiani Planum (Clark et al., 2005; Herkenhoff et al., 2004; Klingelhofer et al., 2004). Although no jarosite has been documented in the Nippewalla Group or Opeche Shale, it has been found in their modern counterpart in Western Australia, precipitating from shallow acid saline groundwater (Benison and LaClair, 2002, 2003). Jarosite does not seem to be stable on Earth for long time periods and may be altered through chemical weathering to gypsum or anhydrite. If jarosite had precipitated in the Nippewalla Group during the middle Permian, it would likely have been altered to gypsum/anhydrite.

A possible difference in the mineralogy of the Nippewalla Group and the Martian outcrops is the composition of the siliciclastic sediments. The majority of siliciclastic grains (~85%) in the Nippewalla Group siliciclastic sandstones and mudstones is quartz. However, the Meridiani Planum outcrops may have grains that are basaltic in character (Reider et al., 2004), although Squyres et al. (2004b, p. 1711) claimed that ‘‘small amounts of olivine, pyroxene, and feldspar in outcrop exposures are best explained as surface contamination by the abundant wind-blown basaltic sand.’’ More detailed mineralogical characterization shows that the strata at Meridiani Planum are composed predominantly of silica and sulfates with lesser amounts of chlorides and hematite. Mafic minerals make up a minor component of the rock (Clark et al., 2005). Regardless, clastic grains composed of mafic igneous minerals could still be host sediments for acid waters, as is true for some modern acid saline lakes in Western Australia.

CONCLUSIONS

There are mineralogical and sedimentological similarities between the Martian outcrops and the Nippewalla Group rocks. The middle Permian Nippewalla Group of Kansas, along with other acid saline lake systems, such as the middle Permian Opeche Shale and the modern acid saline lakes of Western Australia, should be considered excellent terrestrial analogs for the Martian outcrops at Meridiani Planum.

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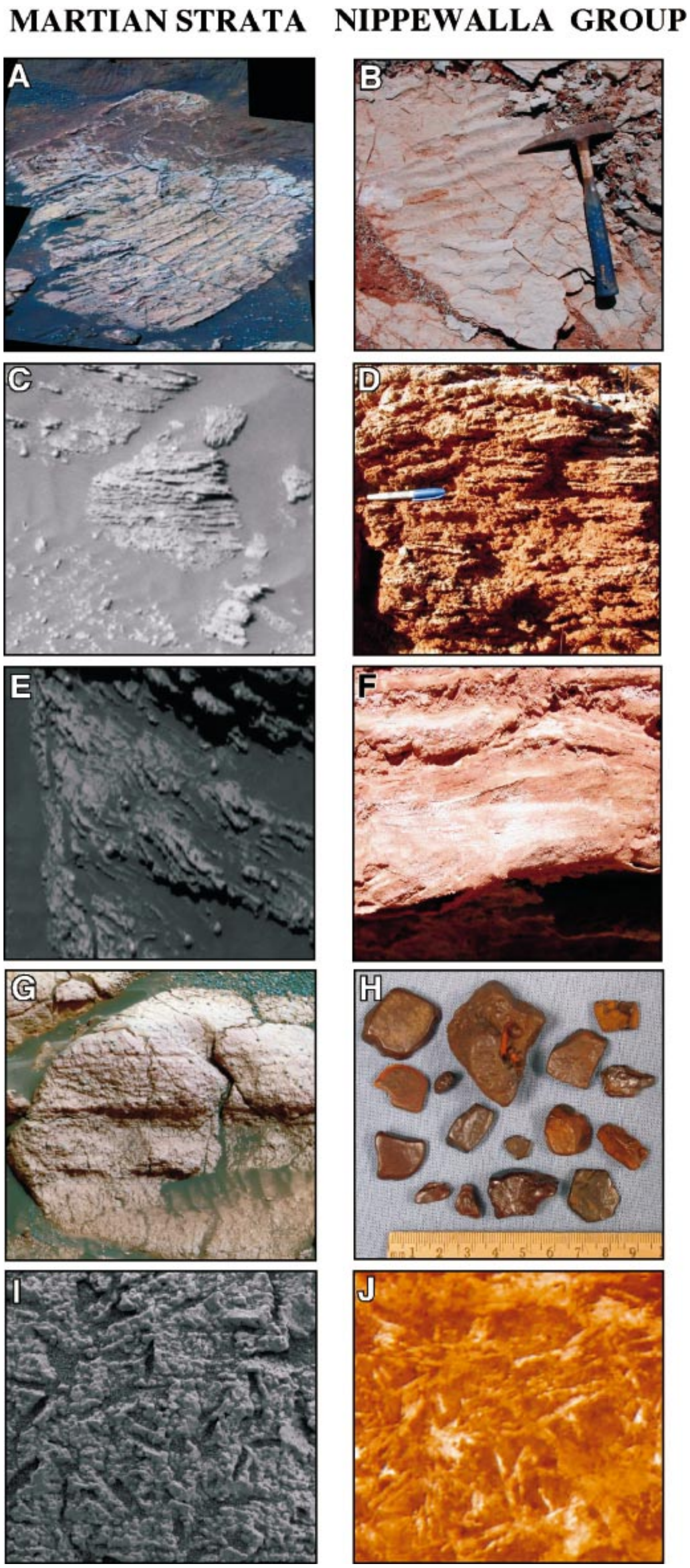

Figure 2. Photographs of sedimentary structures and early diagenetic features in Martian strata compared to those in the Permian Nippewalla Group. A–B: Bedding-plane views of ripple marks and mud cracks. A: “Escher” rock at Endurance Crater (image courtesy of National Aeronautics and Space Administration [NASA]/Jet Propulsion Laboratory/Cornell). Rock is ~60 cm across. B: Gypsum/anhydrite-rich siltstone partially covered with hematite-rich silt and sand weathered from outcrop in the Nippewalla Group, Barber County, Kansas. Note hammer for scale. C–D: Cross-sectional views of low-angle, planar cross strata. C: Outcrop at Meridiani Planum (image courtesy of NASA/Jet Propulsion Laboratory/Cornell). Rock in center is ~12 cm across. D: Gypsum/anhydrite- and hematite-rich sandstone in Nippewalla Group, Barber County, Kansas. Note pen for scale. E–F: Cross-sectional views of high-angle, tangential cross strata. E: “Last Chance” rock at Meridiani Planum (image courtesy of NASA/Jet Propulsion Laboratory/Cornell). Field of view is ~12 cm across. F: Quartz- and hematite-rich fine-grained sandstone in Nippewalla Group, Barber County, Kansas. Field of view is 16 cm across. G–H: Hematite concretions. G: Concretions in and on “El Capitan” rock at Meridiani Planum (image courtesy of NASA/Jet Propulsion Laboratory/U.S. Geological Survey). Field of view is ~43 cm across. H: Hematite concretions weathered from sandstone in Nippewalla Group, Barber County, Kansas. Ruler numbers mark centimeters. I–J: Cross-sectional views of displacive crystals and molds. I: Probable evaporite displacive crystal molds in “El Capitan” rock at Meridiani Planum (image courtesy of NASA/Jet Propulsion Laboratory/U.S. Geological Survey). Field of view is ~9 cm across. J: Displacive anhydrite crystals hosted by quartz- and hematite-rich mudstone in Nippewalla Group, Anadarko-Davis No. 1 core, 1371 ft depth, Seward County, Kansas. Field of view is 5 mm across.

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