The geology of Australian Mars analogue sites

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ABSTRACT

Australia has numerous landforms and features, some unique, that provide a useful reference for interpreting the results of spacecraft orbiting Mars and exploring the martian surface. Examples of desert landforms, impact structures, relief inversion, long-term landscape evolution and hydrothermal systems that are relevant to Mars are outlined and the relevant literature reviewed. The Mars analogue value of Australia's acid lakes, hypersaline embayments and mound spring complexes is highlighted along with the Pilbara region, where the oldest convincing evidence of life guides exploration for early life on Mars. The distinctive characteristics of the Arkaroola Mars Analogue Region are also assessed and opportunities for future work in Australia are outlined.

1. Introduction

Australia has much to offer researchers interested in Earth analogues of both ancient and modern environments on Mars. The ancient terrains and arid regions of central Australia have preserved many landforms that are unique to Australia. Low-relief deserts with extensive duricrust plains, stony deserts and continental-scale dune fields abound along with numerous well-preserved impact structures. Examples of drainage aligned playas, clay pans, acid lakes, hypersaline embayments and mound spring complexes can also be found and are analogous to features suspected of existing on Mars in the past. Australia also possesses some of the best studied and largest hydrothermal systems on Earth and the earliest convincing evidence of life is recorded in the Pilbara region of Western Australia.

In addition to the array of interesting geological sites, Australia has a stable political situation, excellent local infrastructure and modern services, researchers with extensive experience operating in the arid interior and a scientific community well versed in planetary geology. The climate is bearable and the areas of interest are remote enough that land use does not create problems with interpreting deposits; a common problem elsewhere (Cooke and Reeves, 1976). Furthermore, the country is well imaged by various orbiting instruments and results from sophisticated airborne remote sensing instruments are available locally.

In this work, the geology of various landforms are reviewed in

Mars landers. Many features common to Australia's desert regions have also been identified in images taken from Mars orbit. To date, however, there has been little exploration of the potential of Australian examples of quintessential desert landforms, dunes and dry fluvial deposits as Mars analogues. For example, the large areas of duricrust materials in central Australia, particularly silcrete, may have formed when silica-rich ground water met saline waters contained in paleolakes. Given the evidence for paleolakes on Mars and for earlier wetter conditions, the formation of silcrete in a fashion similar to that found in Australia's gibber plains might be possible. Thomas et al. (2005) have discussed the gibber plains of the Sturt Stony Desert (Fig. 1) as an analogue of deflation surfaces imaged at Chryse Planitia by the Viking 1 lander. In the Sturt Stony Desert silcrete gibbers armour a surface dominated by fine silt with scattered floating silcrete clasts.

2.2. Dune fields and sands

Australia's desert dune fields represent more the 38% of the world's aeolian landscape (Wasson et al., 1988) yet few studies have investigated their potential as Mars analogues. Contained in seven interconnected deserts, most dunes are longitudinal and are up to 300 km long, 10–35 m high and spaced 16–200 m apart. Linear dunes such as these are rare on Mars. HoweverT(ran-50e)-2 Howa8-437(38%)-439(of)- moreee6riil-i0N(0(cN2d4(sculaic)10)-291(rar)3)]T(b(

that more impact sites may yet be discovered in the even more remote desert regions. This was recently demonstrated, for example, by the discovery of the 260 m diameter Hickman Crater in Western Australia, which was originally detected using satellite imagery in Google Earth (Glikson et al., 2008). Australia's impact sites include some of the best-preserved small impact craters, a secondary craters ranging in size from 10 to 200 m in diameter that are concentrated in radial streaks that extend up to 1600 km from the primary crater. The Acraman impact structure in South Australia and the associated distal ejecta are a good terrestrial example of the large scale distribution of ejecta material observed at Zunil crater. At 160 km in diameter, Acraman is Australia's largest impact structure and led to the formation of a subcircular playa lake with islands (Lake Acraman). Distal ejecta deposits have been confidently linked to the impact and can be traced out to distances as far as 540 km from the impact site, although no secondary craters have been observed. A 40 cm thick layer of clasts ∼30 cm in diameter is well exposed in the Bunyeroo Formation in the Flinders Ranges, about 300 km to the east of Acraman (Gostin et al., 1986; Williams and Gostin, 2005).

Aside from the smallest craters of the Henbury crater field, Dalgaranga in Western Australia is Australia's smallest confirmed impact crater with a diameter of only 24 m and a depth of 3 m (Bevan, 1996). It is also the only known impact caused by a mesosiderite stony-iron projectile (Nininger and Huss, 1960). On Mars, impacts as small as 10 cm in diameter have been imaged by the Mars Exploration Rover Opportunity on the plains of Meridiani (Schröder et al., 2008) and the Mars Pathfinder mission produced evidence of craters less than 1 m in diameter (Hörz et al., 1999). Such small craters are possible because of Mars' low atmospheric pressure, which admits projectiles without them burning up in the atmosphere before impacting the surface.

Lindsay and Brasier (2006) have recently suggested that the 18 km diameter Lawn Hill Structure in northern Australia may also prove a useful martian analogue. This structure contains a these regions has demonstrated techniques that can be adapted to hyperspectral datasets currently being acquired at Mars by the OMEGA and CRISM

The cementing agents on Mars are not known but based on observations by orbiters and landers, there are several possibilities. These include sulfates (jarosite, gypsum, keiserite), iron oxides (haematite) and allophane (amorphous clay-like phases) (Clark et al., 2005). Halide salts and amorphous silica (opal), are also likely (Osterloo et al., 2008; Milliken et al., 2008).

6. Hypersaline embayments

One of the best examples of modern analogues of early microbial life on Earth is the existence of living stromatolites. These are organo-sedimentary structures formed by the interactions of benthic microbial communities with their environment. By extension, they are often considered as the sort of structures that should be targeted in any search for former life on Mars because although built by microbes, they can be as large as the largest reefs on Earth. Among the most extensive modern stromatolites are those forming in Hamelin Pool, a hypersaline marine environment that is part of Shark Bay on the western coast of Australia (Logan, 1961; Logan et al., 1974; Playford and Cockbain, 1990; Burns et al., 2009).

The living marine stromatolites of Hamelin Pool are the most diverse, abundant, and widespread examples known (Fig. 6). The salinity is up to twice that of normal seawater ().iviserknl2tri36(ber)14(ise9362(t2)-394(t).iv)v9(e)alurin-11356(of(9)40(Shar)121(xt)h6264.66-1.

Other salt lakes and groundwater systems in Western Australia may also be potential Mars analogues. Very recently a range of $MgCl_2$ and $MgSO_4$ minerals have been discovered in natural and anthropogenically perturbed systems near Lake Deborah (Shand and Degens, 2008). Given the predominance of Mg and sulfate rich sediments in the Burns formation at Meridiani Planum on Mars, the discovery at Lake Deborah of precipitation sequences from near neutral to acid, consisting of magnesite ($MgCO_3$), halite (NaCl), gypsum ($CaSO_4{:}2H_2O$), starkeyite ($MgSO_4:4H_2O$) and carnallite ($KMgCl_3:6H_2O$), is of particular interest. Further work is required to assess the Mars analogue potential of these sites and the relevance of these acid lakes and groundwater systems to the precipitation sequences found on Mars.

7.3. Other acid systems

Lake Tyrrell in Victoria (Fig. 7) is a near neutral salt lake that is fed by local springs with moderate to low pH (3–6.1) (Macumber, 1992). Lake Tyrrell is a groundwater discharge complex, or boinka, and is the first and best-studied naturally occurring acidic lake and groundwater system in Australia (Long et al., 1992a, b). The system was proposed as a possible Mars analogue by Benison et al. (2007a, b) although the waters are not as concentrated and at higher pHs than those observed in Western Australia (Bowen and Benison, 2009). While it is unreasonable to expect martian surface environments to be strongly acidic everywhere, as shown by the recent results from the Phoenix lander where the soil pH is 8.3 ± 0.5 (Kounaves et al., 2009), such moderate to slightly acidic saline environments such as Lake Tyrrell may still be applicable as analogues to many ancient martian environments. The weakly acidic lakes and boinka complexes of the Eyre Peninsula (Kimber et al., 2002) may also have Mars analogue potential, but further work is required to assess their value.

Bloethe (2008) has recently investigated iron bacteria in the southern acidic end of Lake Tyrrell. Here the nearly constant pH of $\sim$4 is conducive to both Fe(II) oxidation and Fe(III) reduction. Analysis of the lake sediments revealed low but detectable populations of two different aerobic halophilic Fe(II)-oxidising organisms. The results suggest that a coupling of microbial Fe oxidation and reduction may take place in these acidic and Fe-rich sediments. This process may provide a model for how microbially catalysed Fe-redox cycling under hypersaline conditions could occur in subsurface martian environments where fluids and solids contact oxidant-bearing water or water vapour. This phenomenon has also been investigated at other Mars analogue locations, such as Rio Tinto in Spain (Davila et al., 2008; Amils et al., 2007).

7.4. Acid systems in the context of landscape evolution

Much of the work on acid minerals on Mars has assumed that the acidity indicated by the presence of jarosite and similar minerals was a primary condition of the depositional environments (Klingelhofer et al., 2004; Grotzinger et al., 2005; Benison and Bowen, 2006). However, as Burns (1993) recognised, the presence of minerals indicative of acid conditions may be superimposed on materials formed under very different conditions. Indeed, as shown by Clarke (1998), aridity (and acidity) is a very recent phenomenon in the landscape and sedimentary evolution in the Western Australian salt lakes. The lakes themselves occur in landscapes dominated by calcareous weathering (Mann, 1983; McArthur et al., 1991), indicating that

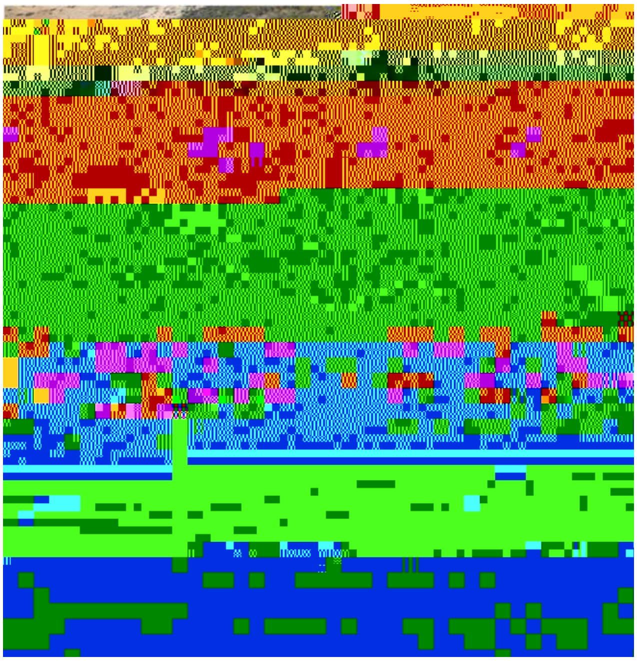

Fig. 8. The Dalhousie springs complex. (A) Aerial view of a spring pool. Note the sinuous, vegetation-rimmed discharge channel. (B) A small mesa formed by the erosion of a former pool leaving behind a carbonate cap.

mounds. When spring flow decreases, the mounds are eroded to form carbonate-capped mesas (Fig. 8B). Outflow channels also precipitate carbonate and, when abandoned and eroded, can form elongate ridges through relief inversion.

As a result of ascending non-supersaturated water, the DSC is a carbonate-limited precipitation system and, to date, has been poorly described. Fourteen specific microfacies belonging to seven facies have been identified (Clarke et al., 2004). These were deposited in environments ranging from cool to hot springs. Pool, marsh, and outflow channel environments can be recognised from detailed textures. Diagenesis has occurred in several stages. From oldest to youngest these are: phreatic diagenesis during initiation and main discharge of the spring; vadose zone diagenesis during the waning of spring discharge; and a range of pedogenic overprints by clays, sulphates, and iron oxides-hydroxides in remnant cavities. The overprinting of primary pool facies with, for example, fluvial, pedogenic and groundwater facies suggests that detailed textures of spring deposits can yield information on the diverse range of processes involved in the formation of the spring mounds. These textures may be readily apparent at the resolution provided by microscopic imagers on current Mars lander and rover missions (Clarke and Bourke, 2009).

8.2. Implications for Mars analogue research

The martian surface exhibits many small dome, mound and pitted cone features. These may represent volatile release from the subsurface by processes such as mud volcanism or mound spring formation (Crumpler, 2003; Farrand et al., 2005; Skinner and Tanaka, 2007). Terrestrial spring deposits have a wide range of morphologies, yet there are few published accounts of their characteristics and formation. This inevitably limits our ability to accurately detect these features on Mars from either satellite or lander perspectives. Detailed characterisation of sites such as the DSC will potentially assist in recognition of such features on Mars.

The DSC was evaluated for its Mars analogue potential during the Jarntimarra expedition in 2001 (Mann et al., 2004) and the results from the reconnaissance were presented by Clarke and Stoker (2003). Bourke et al. (2007) published a preliminary geomorphic analysis of the DSC and compared the results to a number of small martian features not previously linked to possible spring formation. The morphometric data presented improved the ability to identify potential spring deposits on Mars from satellite platforms. It has been shown that the preserved form can be as domes, pitted cones, or mesas, which suggests that the range of morphologies assigned to potential spring deposits on Mars can be extended beyond cone-shapes. The data suggest that mound spring sediments have high preservation potential. Furthermore, spring complexes and their outflows form a characteristic suite of sedimentary fabrics readily identifiable at the small and microscopic scale. These findings are being used to build and improve models of mound spring formation and spring discharge on Earth and on Mars. Modeling of the hydraulic properties of DSC mounds by Nelson et al. (2007) has been used to predict past and present hydrological parameters based on the mound spring morphologies. If mound springs can be correctly identified on Mars, models such as this could be used to infer the hydrogeological history of the region on Mars.

Petrographic studies of the DSC carbonate sediments (summarised in Clarke et al., 2007) recognised a set of distinctive megascopic and microscopic textures that can be used to recognise spring deposits in the field. Although martian features are unlikely to be carbonate deposits like most of the spring mounds on Earth, they may represent other water-deposited minerals such as sulphates, sulphides, silica, and iron oxides or oxy-hydroxides. The generic processes described for mound spring formation and evolution above would still apply for these different types of deposits.

Recently Rossi et al. (2008) have suggested that large-scale spring deposits, such as Dalhousie, may have formed the various enigmatic light-toned deposits on Mars. Images from the HiRISE camera have shown spring-like features in Vernal Crater, Arabia Terra that have a striking similarity to those at Dalhousie (Oehler and Allen, 2008, Allen and Oehler, 2008a, b). Squyres et al. (2008) also report silica-rich deposits from a former hydrothermal spring in Gusev crater, identified by the Mars Exploration Rover Spirit. Given the level of information that hydrothermal spring deposits contain about hydrology and climate, and their habitat potential and micro-organism preservation potential, such sites have been proposed as potential targets for future Mars sample return missions (Walter and Des Marais, 1993; Allen and Oehler, 2008a, b; Oehler and Allen, 2008).

9. Deep weathering analogues

Deep weathering, that is, the creation of a thick weathered layer through strong and/or sustained chemical weathering, is not normally considered significant on Mars. This is based on the current low temperature and arid surface environment that has persisted through much of the Amazonian and perhaps earlier (Bibring et al., 2006). The widespread occurrence of olivine (Mustard et al., 2005) and low temperatures recorded in some martian meteorites (Shuster and Weiss, 2005) at the surface suggest limited alteration of primary basaltic mineralogy. However, onion skin weathering patterns (Thomas et al., 2005) indicate that locally intense weathering is present and the recent report by Ehlmann et al. (2008) of kilometer-scale outcrops of magnesium carbonate associated with nontronite (iron-rich smectite clays) strongly suggests the action of low temperature aqueous alteration of ultramafic rocks in weathering, lacustrine

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