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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 the context of their Mars analogue value and comparisons are made with features observed or inferred on Mars. This work aims to augment similar reviews of Mars analogue science activities at locations in the Canadian Arctic, United States, South America, Europe and North Africa (Lee and Osinski, 2005; Osinski et al., 2006; Pollard et al., 2009; Pacifici, 2009; Léveillé, 2010). The testing of technologies and strategies for Mars exploration in Australia's analogue sites are discussed in a companion work (West et al., 2009) and the education and public outreach opportunities of Mars analogue research activities in the Australian context are discussed elsewhere (Laing et al., 2004, 2006; West et al., 2009).

2. Desert landforms

2.1. Gibber plains

The gibber plains of the Strzelecki and Sturt Stony Deserts bear a striking resemblance to the panoramas produced by several

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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. However, a localised occurrence of mobile crescentic dunes (barchans) at Gurra Gurra Waterhole on the edge of the Strzelecki Desert were studied by Bishop (2001, 1999) and compared to dunes on Mars. In particular, Bishop (2001) noted the importance of the formation of cementing crusts in stabilising dunes. This was borne out by Bourke et al. (2008) who attributed the immobility of some dunes and the mobility of others to the presence or absence of cementing crusts. The Gurra Gurra dunes were also cited as possible analogues of the barchans imaged on the floor of Proctor Crater by the Mars Orbital Camera (Fenton et al., 2003; Taniguchi and Endo, 2007).

The dune sands of Australian ergs range in colour from white to dark red. Debate continues as to whether this is a function of age or sediment source. Kuhlman et al. (2001) investigated red dune sand from a desert region near Kata Tjuta/Mt Olga, Northern Territory as a potential martian regolith analogue. Microanalytical techniques, including pseudoconfocal microscopy and transmission electron microscopy, revealed the ubiquity and non-uniformity of the red-orange coating on every grain of sand. Nanocrystals were identified with a distinctly hexagonal shape that is strongly indicative of hematite, which has recently been detected by the Mars Exploration Rover *Opportunity* at Meridiani Planum (Calvin et al., 2008). A very small amount of hematite nanocrystals could be responsible for the intense red colour of the dune sand at Kata Tjuta/Mt Olga, Northern Territory.

Fig. 1. The gibber plains of the Sturt Stony Desert in South Australia which Thomas et al. (2005) has proposed as an analogue of deflation surfaces imaged at Chryse Planitia by the *Viking 1* lander.

Greeley and Williams (1994) have also proposed 'parna' as an analogue of dust deposits on Mars. 'Parna' is an Aboriginal word meaning 'sandy and dusty ground' and describes a hybrid aeolian deposit consisting of a mixture of sand, silt and clay. Parna deposits, also know as desert loess, occur in many parts of Australia (Haberlah, 2007; Haberlah et al., 2007) and several possible sites on Mars that may be similar to the Australian deposits have been identified by Greeley and Williams (1994). Understanding sediment sources, transport distances and mechanisms and the ages of dune fields in Australia also has implications for understanding similar features on Mars.

Mars also contains many examples of streamlined erosional wind forms, known as yardangs, that are similar in form to inverted boat hulls (Ward, 1979; Fergason and Christensen, 2008). In terrestrial deserts yardangs can range in length from meters to kilometers but despite Australia's extensive deserts and eolian features, few good examples are known (Goudie, 2007). The consensus in the literature is that Australia's deserts are not characterised by extremely low rainfall (less than 50 mm per annum) and there is not sufficient transport of materials (Goudie, 2007). Some very small examples are known at Lake Mungo in New South Wales and the examples at the Gurra Gurra dunes discussed by Bishop (1997) as a Mars analogue are very ephemeral and could not be found by an expedition investigating Mars analogues in the region in 2004 (Clarke et al., 2006).

2.3. *Desert flood outs*

Flood outs are very low-relief, unconfined, and fine-grained depositional features that form at the distal end of arid rivers where they discharge into dune fields or playas. They form the termini of major rivers such as the Finke and the Todd in inland Australia. Unlike the better defined coarse-grained alluvial fans deposited proximal to high-relief features (Waclawik and Gostin, 2006) (and also found on Mars, see Howard, 2007), flood outs are often poorly defined and can extend considerable distances (many hundreds of kilometers) from the range fronts in which the ephemeral streams have their source. Flood outs in central Australia were postulated by Bourke and Zimbelman (1999, 2000, 2001) and Bourke (2003) as potential analogues for some of the major channels on Mars that flow out onto and apparently merge with the sedimentary cover of the northern plains of Mars without obvious terminal fans. Although not specifically referring to these studies, the observation by Howard (2007) that the apparent scarcity of well developed fans on Mars may be due to extremely fined-grained distal sediments suggests the utility of analogues based on central Australian flood out deposits.

3. Impact craters

Australia's arid climate, generally low-relief and long-term tectonic stability has resulted in one of the best-preserved records of terrestrial impact cratering that has been reviewed by (Glikson, 1996) and more recently by Haines (2005). The great age of the basement rocks in the Australian craton means that the Proterozic impact record is without peer and the density of impact sites is similar to that of North America and parts of northern Europe (Haines, 2005). Most known impact sites are located in Australia's arid interior and in easily accessible pastoral districts, suggesting 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 crater field that includes a rayed crater, one of the most thoroughly studied partially eroded complex impact structures and possibly the world's oldest preserved simple crater. Such diversity provides plenty of scope for analogue studies of the different impact cratering processes that occur on Mars as well as at other locations in the Solar System such as on the Moon, Phobos' Stickney Crater or impacts on asteroids.

One of the best known impact structures, and the best studied of Australia's large impact structures, is Gosses Bluff in the Northern Territory. A remarkable rock formation standing alone in a nearly flat plain like a lone, circular mesa, Gosses Bluff is in fact the central part of a highly eroded impact structure estimated to be ~24 km in diameter. The ring of hills ~5 km in diameter is the skeletal remains of the central uplift of the impact crater which has been extensively eroded (Hodge, 1994). Gosses Bluff was studied extensively in the 1960s by US Geological Survey workers (Milton et al., 1972; Milton and Michel, 1977; Milton, 1977) in order to establish the geological and geophysical techniques required to confirm the origin of lunar craters investigated during the Apollo program. For example, the discovery of abundant shatter cones in the vicinity highlighted their importance as a feature diagnostic of impact cratering (Milton et al., 1972). Our understanding of structures such as Gosses Bluff can be applied to and serve as exceptional analogues of processes that degrade the original morphology of impact craters on Mars.

The Henbury Meteorite Craters in the Northern Territory is an excellent example of a small crater field as shown in Fig. 2. Caused by the atmospheric break up of an iron meteorite, the crater field consists of at least 13 or 14 craters (the exact number is still disputed) ranging in diameter from 6 to 180 m. The largest is an elongated double crater caused by the explosion of two closely related projectiles (Milton, 1977). One of the larger craters displays well-developed down-range ejecta rays making it the only terrestrial example of a rayed crater (Milton and Michel, 1977). The rays consist of ejected fragments of sandstone that are similar to those identified on the Moon, Mercury and Mars (Hodge, 1994). A rayed crater on a similar scale to that found at Henbury has been imaged recently by the *HiRISE* camera aboard the Mars Reconnaissance Orbiter (Fig. 3). Located in the northern hemisphere Tharsis region, this crater is approximately 160 m in diameter and displays rays of ejecta composed of fine material that is markedly darker than the surrounding regolith. The ejecta blanket also consists of large boulders and contains smaller secondary craters.

Geomorphic studies of Henbury Meteorite Crater and Gosses Bluff have been used to understand the complexities of fluvial dissection in the heavily cratered terrains of Mars (Baker, 1984). At Henbury, the impact craters have been modified by the semiarid drainage system. The breaching of crater rims by gullies was facilitated by the northward movement of sheetwash along an extensive pediment surface extending from the Bacon Range. South-facing crater rims have been preferentially breached because gullies on those sides were able to tap the largest amounts of runoff. At Crater 6, a probable rim-gully system has captured the headward reaches of a pre-impact stream channel. The interactive history of impacts and drainage development is critical to understanding the relationships in the heavily cratered uplands of Mars. Whereas the Henbury craters are younger than 4700 yrs B.P., the Gosses Bluff structure formed about 130 million years ago. The bluff is essentially an etched central peak composed of resistant sandstone units. Fluvial erosion of this structure is also discussed by Baker (1981).

Zunil crater in the Cerberus Plains of Mars is one of the largest, at 10 km in diameter, and best-studied rayed craters on Mars (McEwen et al., 2005). The impact created several million

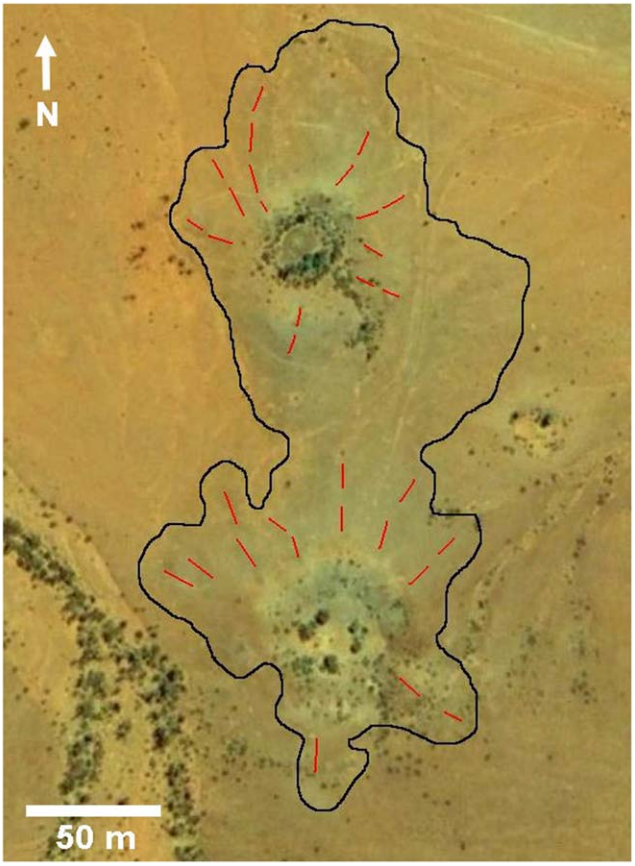

Fig. 2. Craters 3 and 4 of the Henbury Meteorite Craters in the Northern Territory, Australia. The rays (red lines; grey in print) and the outline of the ejecta blanket (solid blue line; black in print), as described by Milton (1977), are shown. (Image from Google Earth, Image copyright 2009 Digital Globe.)

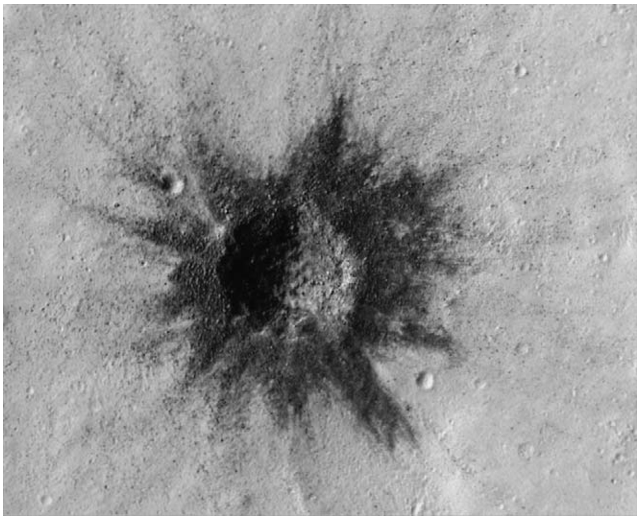

Fig. 3. A small rayed impact crater, about 160 m in diameter, in the Tharsis region of the northern hemisphere of Mars similar to that found at Henbury Meteorite Crater in the Northern Territory, Australia. *HiRISE* Image: PSP_008011_1975 courtesy of NASA/JPL/University of Arizona.

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 significant fill of sedimentary carbonate rocks that preserve the stratigraphic record within the floor of the crater. In a similar way, eolian sediment on Mars is trapped inside impact craters. If water resources were present, the floors of such craters on Mars may have in the past acted as suitable habitats for life. Lindsay and Brasier (2006) note that numerous small to medium impact craters like the Lawn Hill Structure exist on Mars and have clearly defined flat floors, suggesting they contain a sedimentary record. If this were so, such craters would be among the best locations to drill in search of evidence of a martian biosphere, if it is there to be found (Cockell and Lee, 2002).

4. Analogues of hydrothermal systems

4.1. Mount painter, South Australia

The Mount Painter hydrothermal system (Coates and Blissett, 1971) is located in the Arkaroola region of the Flinders Ranges, South Australia. The site is of particular value because of its close association with several significant Mars analogue terrains that are collectively known as the Arkaroola Mars Analogue Region (Clarke et al., 2004). Mount Painter is a Paleozoic hematite hydrothermal system with excellent surface and vertical exposure (Foster et al., 1994). Many of the systems are radioactive and could provide niches for radioactive resistant extremophiles, similar to those at the modern Paralana hot springs (Anitori et al., 2002). Stromatolitic horizons are located in the Neoproterozoic sediments (Coates and Blissett, 1971) in the surrounding region and veins containing possible microfossils of deep-Earth microbes (Bons et al., 2009) have been reported.

4.2. The Pilbara region, Western Australia

The Pilbara Craton of Western Australia is one of the oldest and best-preserved sedimentary and volcanic successions in the world. The rocks of the Warrawoona Group were deposited between 3.2 and 3.5 billion years ago and are dominated by well-preserved thoeleitic and komatiitic volcanic successions, which have been suggested as an analogue for the flood basalts of Mars (Brown, 2004, Brown et al., 2004a–c). The minimal tectonic metamorphism makes these rocks very attractive for searches for biosignatures. In addition, the presence of Earth's earliest convincing biosignatures in the abundant stromatolites, microfossils and isotopic signatures at North Pole Dome (Schopf et al., 2007; Walter et al., 1980; Allwood et al., 2006, 2007; Van Kranendonk, 2006) makes it an ideal proving ground for strategies to find past life on Mars.

The hydrothermal activity at North Pole Dome is characterised by low-temperature, low-pressure epithermal fluid flow and is most pervasive at the top of the Dresser Formation. Brown et al. (2005) note that epithermal alteration events, such as that at North Pole Dome, on the flanks or distal regions of high-temperature hydrothermal sites would have been suitable to nurture biological activity on Mars. The search for biosignatures in hydrothermally altered terrains on Mars will focus upon regions that include contacts between varying alteration mineralogies such as veins or lineaments of specific alteration types. Examples on the surface of Mars of such hydrothermal activity include crater rims, volcanic edifices, gullies created by hydrothermal activity and shallow intrusions exposed by cratering (Oehler and Allen, 2008; Squyres et al., 2008). North Pole Dome is a good example of a shallow hydrothermal system and has proved to be a useful analogue for testing several detection techniques, which are discussed further below.

4.3. Hyperspectral mapping of hydrothermal systems

For the purpose of analogue studies, there are many remote sensing techniques that can, and are being used to study and map Mars' geology. Testing these methods on analogues on Earth allows protocols to be developed that can be applied to future robotic or manned Mars missions. Previous analogue studies include the application of spectral remote sensing techniques and hyperspectral methods to map the geology and characteristics of hydrothermal systems (Thomas and Walter, 2002; Thomas et al., 2002). Such systems can be detected and mapped using spectroscopy and in particular hyperspectral methods, since their weathering products usually have good exposure and are spectrally distinctive. For example, the Australian-built Portable Infrared Mineral Analyzer (PIMA) has been used to ground truth hyperspectral data obtained by the airborne HyMap instrument at both Mt Painter and North Pole Dome (Brown et al., 2004a, b; Storrie-Lombardi et al., 2004). These datasets have been augmented with satellite derived LandSAT and ASTER data.

At Mount Painter the resulting hyperspectral maps show distinctive areas of mineralisation commonly associated with the Paralana Fault zone (Thomas and Walter, 2002; Thomas et al., 2002; Brown, 2004). The Paralana fault zone is still likely to be the most prolific and active hydrothermal fluid conduit in the region, but mineralogical and hyperspectral evidence suggest it is not the only hydrothermal system present. Both the HyMap and PIMA hyperspectral data give evidence for two different hydrothermal fluids being responsible for the interpreted mineral variations. These hydrothermal fluids have resulted in ore-grade mineralisation, both here and at the nearby Mt Gee, and may be good analogues for similar hydrothermal mineralisation recently postulated for Mars (West and Clarke, 2010). Similarly, hyperspectral mapping has revealed new details about the nature of hydrothermal alteration within the Dresser Formation of North Pole Dome (Brown et al., 2004a, 2005, 2006) and work in both these regions has demonstrated techniques that can be adapted to hyperspectral datasets currently being acquired at Mars by the *OMEGA* and *CRISM* instruments (Ehlmann et al., 2008).

5. Relief inversion analogues

Inversion of relief on Earth occurs when a low part of the landscape is in some way protected from erosion or becomes resistant to erosion. As the landscape evolves the unprotected and less resistant parts are eroded to leave the more resistant lower parts standing higher in the resulting landscape. Pain and Ollier (1995) reviewed inversion of relief as a component of landscape evolution on Earth and provided many examples.

On Earth, relief inversion commonly occurs when a valley floor becomes a ridge or flat-topped mesa. This can occur in volcanic areas when lava flows down a valley, filling it partially or completely. Drainage re-establishes itself as twin lateral streams flowing down each side of the lava flow, and the lava that was once on the valley floor becomes a ridge or elongated mesa between two valleys. Usually, alluvial deposits on the original valley floor are preserved beneath the lava flow, and are exposed on the sides of the ridge or mesa. If enough time has elapsed since the flow, the former valley floor may be preserved only as isolated lava-capped hills.

In all landscapes, elements are taken into solution and move in subsurface flow down slopes and depressions to the lowest parts of the landscape. Some environments favour the precipitation of these elements in valley floors, and when this occurs, the materials on valley floors and other low areas become cemented to form duricrusts. Duricrusts cemented by calcium carbonate are called calcretes; by iron, ferricretes; by gypsum, gypcretes; and by silica, silcretes. Note that the cementing is a modification of the material present in the valley floors. Most commonly this will be alluvium, but adjacent weathered bedrock and slope deposits are also often cemented.

5.1. *Australian relief inversion analogues*

There are many terrestrial examples of calcareous or iron-cemented alluvium leading to inversion of relief (Pain and Ollier, 1995). In semiarid regions, such as in central Australia, calcium carbonate may be deposited along stream lines. When this is hardened into a calcrete, it may act like a lava flow, becoming less erodable than the neighbouring valley sides. New streams then form lateral to the calcrete, and eventually cause inversion of relief. The same happens with iron and silica cementing. Ferricrete and silcrete are especially resistant to erosion, and the inverted channels can persist either as ridges or as isolated mesas long after the surrounding landscape has completely changed its character (Fig. 4A). Fig. 5 shows one of the most visually stunning examples of inverted relief in Australia, the mesas of the Painted Desert near Arkaringa, South Australia (McNally and Wilson, 1995).

In many cases, inverted channels contain information about environments that existed in the past, but are not present today. For example, Macphail and Stone (2004) and Morris and Ramanaidou (2007), studying the inverted channel deposits in the Pilbara region (Fig. 4A), show that the climate may have been wet subtropical rather than dry as it is at present.

5.2. *Relief inversion on Mars*

Relief inversion is also common on Mars (Pain et al., 2007). Although it is difficult to be sure, at least some inverted channels may be explained by lava flows. Others (e.g. Fig. 4B) appear to be caused by cementing of valley floor deposits, although the cementing agent is unknown. Explanations of inversion of relief on Mars are drawn largely from analogues on Earth. This is because, in common with many other features on Mars, the identification of materials is not yet possible at an appropriate scale except for the very limited areas visited by landers and rovers. However, it seems likely that, in common with Earth, some channels on Mars have been filled with lava flows, after which twin lateral streams formed. Similarly, valley floor materials on Mars have become cemented, and later eroded giving rise to landforms very similar to those on Earth.

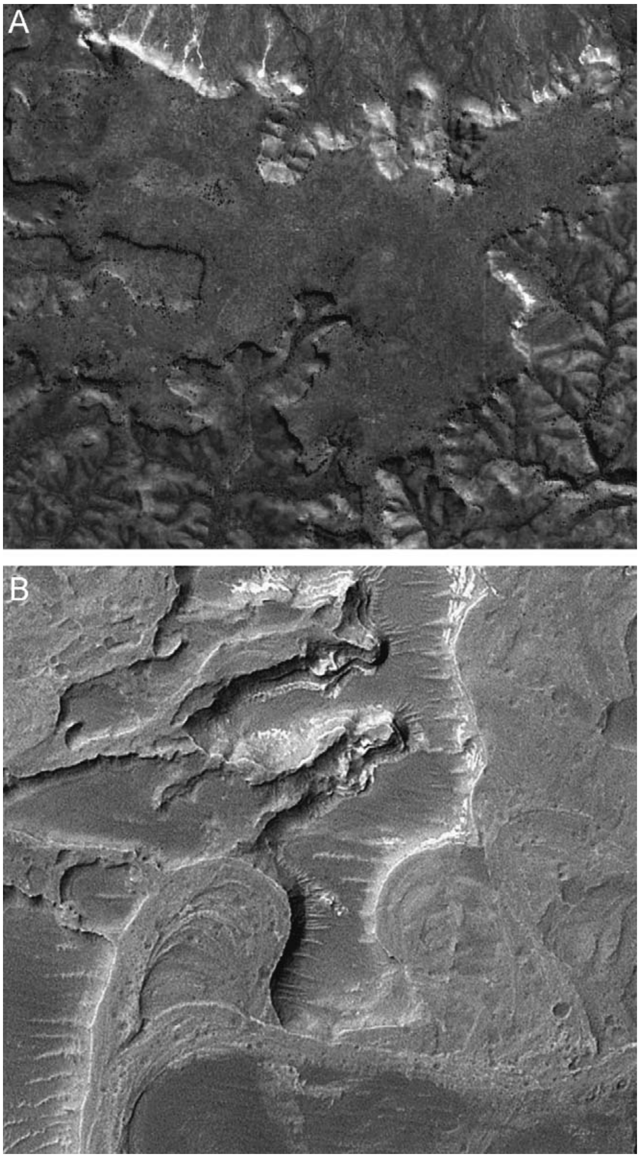

Fig. 4. (A) An example of an inverted channel from Western Australia (21°46′S, 115°59′E). According to Macphail and Stone (2004) and Morris and Ramanaidou (2007), the cementing agents are goethite and hematite, which results in broad mesas covered in ferricrete where the former river flowed. The mesas is now being eroded by slope processes and material is being removed by streams. (Image from Google Earth, Image copyright 2008 Digital Globe.) (B) An example of inverted channels from the Eberswalde delta on Mars. Stream channel features can easily be seen on the tops of the mesas that are now in inverted relief. The cementing agent is unknown, but the mesas are likely to be eroded by slope processes, and the material is probably being removed by wind (Pain et al., 2007). (Image from MGS MOC Release No. MOC2-1225, 20 September 2005, subset of image MOC2-1225a.)

Fig. 5. The mesas of the Painted Desert near Arkaringa.

Fig. 6. Stromatolites in the intertidal zone of Hamelin Pool, Shark Bay, Flagpole Landing. Photographs courtesy of Falicia Goh.

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 (Arp et al., 2001; Burns et al., 2004) and the relatively thin atmospheric ozone layer contribute to a high ambient UV irradiance (Palmisano et al., 1989). This relatively low ozone contributes to the value of Shark Bay stromatolites as modern analogues of early life on Earth and possible former life on Mars (Walter and Des Marais, 1993; Des Marais and Walter, 1999). Abundant fossilised stromatolite reefs, formed in ancient hypersaline embayments, can also be found in the Pilbara region of Western Australia mentioned earlier (Schopf et al., 2007; Walter et al., 1980; Allwood et al., 2006, 2007; Van Kranendonk, 2006).

7. Acid lake analogues

7.1. Potential acidity on Mars

Burns (1987) speculated that acid waters on Mars were responsible for the spectral signatures of jarosite ($(KFe_3(OH)_6(SO_4)_2)$) and schwertmannite ($Fe_{16}O_{16}(OH,SO_4)_{12-13} \cdot 10-12H_2O$). He later suggested (Burns, 1993) that acidic groundwater in southern Australia (Mann, 1983; McArthur et al., 1991) might be valuable analogues for such environments, as was the history of that acidity in the context of the long-term landscape evolution from humid to arid environments (Clarke, 1998). This insight was supported by the theoretical work of Clark (1994) and verified by the discovery of jarosite by the Mars Exploration Rover *Opportunity* at Meridiani Planum (Klingelhofer et al., 2004). Despite the early recognition of Australian acidic Mars analogues, it was more than 10 years before the first systematic studies explored their significance.

7.2. Western Australian acid lake systems

Detailed studies have been carried out on a group of small, acid lakes on the Yilgarn Craton. The lakes have pH values of between 1.7 and 4. Sand and mud flats, formed at low points in the landscape, are flooded by surface runoff and groundwater discharge. On the surface and in the sedimentary pore spaces these sand and mud flats precipitate a mineral assemblage that consists of halite, gypsum, kaolinite, iron oxides, jarosite, and alunite (Benison et al., 2007a, b). Benison and Bowen (2006) and Benison et al. (2007a, b) suggest that these sediments are close analogues to the depositional and diagenetic facies of the Burns Formation studied by the Mars Exploration Rover *Opportunity* on Mars (Grotzinger et al., 2005). Mormile et al. (2003, 2007), Benison and Laclair (2003) and Benison et al. (2007a, b) investigated the biota in these lakes and their preservation potential as analogues for possible life on Mars. They were particularly interested in how such biota might be recognised by future explorers. Schaefer et al. (2003) has also suggested that the formation of hematite concretions in these lakes could be compared with iron minerals found on Mars, such as the hematite concretions of Meridiani Planum (Benison et al., 2007a, b; Bowen et al., 2007, 2008).

In addition to the studies cited above, a hyperspectral survey of the Yilgarn Craton has been carried out using the airborne HyMap instrument and supplemented by ASTER imagery (Brown and Cudahy, 2006). Large deposits of gypsum were detected remotely in the evaporite deposits of the dry lakes that criss-cross the region. These results have been compared to measurements made by the *OMEGA* instrument of sulfate deposits in the martian North Pole region. Since the ultramafic-mafic volcanic flows of the Yilgarn Craton are a good analogue for the volcanic flood basalts of Mars, detection of sulfate deposits against this backdrop is important to understanding what the most likely minerals are in a basaltic acid weathered region and how to detect them on Mars with orbiting instruments.

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).

Fig. 7. Ironstone precipitates and iron-stained acid seeps along the shores of Lake Tyrrell, Victoria. The lake floor is essentially the outcropping groundwater surface of the regional aquifer (Long et al., 1992a, b).

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 carbonate minerals and active acid weathering processes can coexist in close proximity. As the actual mineral paragenetic sequence in the complex sediments of Meridiani Planum is still unknown, much may still be gained in understanding the martian surface from studying the precipitation sequences of sedimentary and weathering environments in the acid lake systems of southern Australia.

8. Mound spring complexes

Mound springs form when artesian water discharges at the surface and builds up a mound of deposited material. The height of the mound is equivalent to the hydraulic head of the artesian basin. Such mounds are widespread through the Great Artesian Basin (GAB) of Australia (Krieg, 1985) and their deposits provide important insights into the past and present hydrology and climates of artesian basins and preserve records of the environments at the point of discharge.

8.1. Dalhousie springs complex

The Dalhousie Springs Complex (DSC) is significant because it is one of the largest and best expressed spring complexes on Earth and is relatively accessible compared to the springs of the Canadian High Arctic, for example (Pollard et al., 1999; Grasby et al., 2003). The DSC occurs at the margins of the GAB which underlies 22% of the Australian continent and covers 1.7 million km^2. The complex consists of a cluster of more than 60 active springs formed by natural discharge from the GAB (Habermehl, 2001). A complex mosaic of active and ancient spring deposits and channels is spread over about 1500 km^2 and the springs occur in a core zone of $\sim$150 km^2. The discharged artesian waters are of low to moderate salinity (700–9400 ppm), near neutral pH (6.8–7.3) and warm to hot (20–80 °C). The elevated temperatures are due to passage of the groundwater through deeply buried (up to 3 km) aquifers. The waters also contain high levels of dissolved iron and H_2S and <1 ppm dissolved oxygen. The main aquifers of the GAB are the Late Jurassic Algebuckina Sandstone and earliest Cretaceous Cadna-owie Formation, confined by the aquaclude of the Cretaceous Bulldog Shale. The aquifers are brought near the surface by the mid-Cainozoic Dalhousie anticline and the groundwater flow focused along a series of faults that breach the anticline's crest (Krieg, 1985).

Springs begin as rimmed pools with outflow channels (Fig. 8A) and evolve through sediment baffling and precipitation into

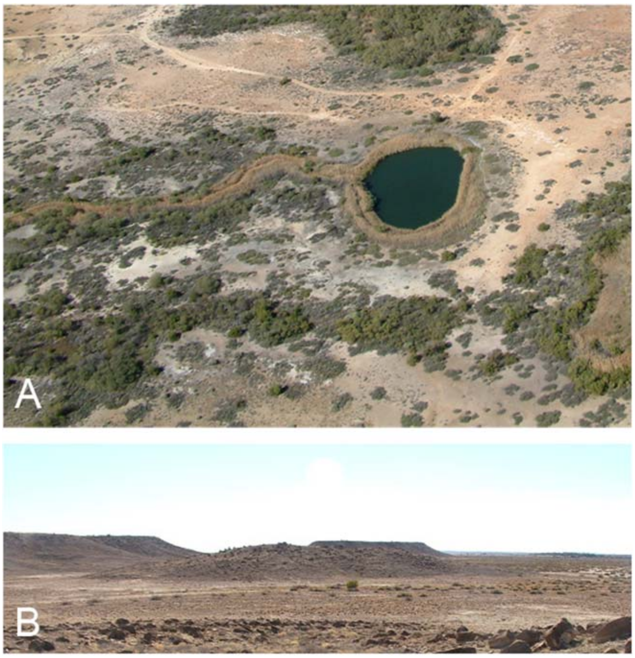

Fig. 8. The Dalhousie springs complex. (A) Aerial view of a spring pool. Note the sinuous, vegetation-rimmed discharge channel. (B) A small mesa formed by the erosion of a former pool leaving behind a carbonate cap.

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 and groundwater environments. Possible Australian analogues include the magnesite deposits at Kunwarara, Thuddungara and Arthur and Lyons Rivers which formed via the precipitation of magnesite from magnesium carbonate rich waters sourced from the weathering of local ultramafic rocks (Milburn and Wilcock, 1990; Diemar, 1990; Dickson, 1990).

10. Future work

Australia also contains examples of other features relevant to Mars such as polygonal landforms, debris taluses and aprons, gully forms and a variety of volcanic fields. To date no work has been undertaken to assess their Mars analogue potential and these should be pursued by future researchers. The Arkaroola Mars Analogue Region in particular contains a wide variety of features and geological systems that require further study. These include the major alluvial fan systems that occur along the range front of the Flinders Ranges and drain into the surrounding salt lakes and the dune fields on the margins of the Strezlecki Desert. Some preliminary geomorphological investigations have been undertaken by Waclawik and Gostin (2006) but further work is required as these surfaces, duricrusts and sediments provide analogues for many complex landforms likely to be found on Mars. Preliminary work by Heldmann et al. (2006) has used remote sensing data sets and ground-truthing measurements collected on site to investigate 11 springs and water holes in the Arkaroola Mars Analogue Region. Given the importance of water to the geomorphology of Mars' surface, to the past and present possibility of life and the availability of resources for human exploration, further studies of the radioactive Paralana Hot Spring mentioned above, the aquifers of Lake Frome that contain uranium deposits and the numerous salt lakes formed by the combination of run-off and shallow ground water discharge would be beneficial. Other investigations in the region could search for extremophile populations in the radioactive minerals of the Mt Painter complex, in the high temperature ($>90\,^{\circ}$C) artesian bores of the region or the surrounding salt lakes, which are all unexplored. All these studies could shed light on the dynamics of such systems and how possible equivalents could be identified on Mars.

11. Conclusion

Australia has many locations and landforms that can be studied to understand the geological processes observed or inferred on Mars. Australia's unique combination of aridity and ancient terrains have preserved numerous impact structures that are type examples for understanding impacts as a geological process, whether that be on Mars or in the Solar System generally. The deserts of central Australia host many examples of stony pavements and duricrust plains similar to those imaged on Mars' surface and large dune fields and desert flood outs like those imaged from Mars orbit. The sandy and dusty ground and dune field sands also have a visual and compositional likeness to Mars' regolith and provide insights into aeolian processes on Mars.

Several Australian examples of relief inversion have been identified and their value as analogues of relief inversion on Mars outlined. Recent studies, including hyperspectral mapping by remote sensing instruments, of the Mt Painter and North Pole Dome hydrothermal systems have been reviewed and parallels between these systems and those postulated on Mars made. The analogue potential of hypersaline embayments such as Hamelin Pool in Shark Bay and the acid lake systems of Western Australia and other Australian acid and salt lakes has been discussed and areas for further research identified. The geology of the Dalhousie Springs Complex, one of the largest and best examples of a spring complex on Earth, has been reviewed and the implications for Mars analogue research, including the evidence for such systems on the surface of Mars, have been discussed. Deep weathering of mafic and ultramafic rocks has produced weathering profiles that may mimic those formed in earlier, wetter epochs of martian history. Finally, opportunities for future research have been detailed including in the Arkaroola Mars Analogue Region.

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