The Dalhousie Mound Spring Complex as a guide to Martian Landforms, Processes, and Exploration

Jonathan Clarke[1], Mary Bourke[2], Peter Nelson[3], Michael Manga[3], and Julia Fonseca[4]

[1] Australian Centre for Astobiology/Mars Society Australia
jon.clarke@bigpond.com
[2] Planetary Science Institute, Tucson, Arizona
[3] Department of Earth and Planetary Science, University of California, Berkeley, California
[4] 15 E. Elm St., Tucson, AZ 85705

Abstract. Possible springs and their deposits are important targets for Martian exploration because of the information they contain about Martian landscapes and processes, provide indications for conditions in the Martian hydrosphere, are potential habitats for past (and present) Martian organisms, and their resource potential for human missions. The Dalhousie Mound Spring Complex (DMC) is one of largest groundwater discharge landforms known on Earth and is an excellent field laboratory to develop models of spring related landform evolution on both Earth and Mars. The DMC also allows development of recognition criteria for spring deposits at the scale of satellite, lander, and microscopic scales, and issues associated with their exploration.

Keywords: Groundwater, springs, geomorphology, regolith, modelling, Mars analogues

1 Introduction

1.1 Background

In 2001 Mars Society Australia evaluated a number of sites for their Mars analogue potential during the Jarntimarra expedition [1]. One site identified was the Dalhousie Mound Spring Complex (DMC). Results from the reconnaissance of the DMC were presented in 2003 at the Lunar and Planetary Science Conference in Houston [2]. As a result a NASA Mars Fundamental research grant was applied by for by the authors and awarded in 2004. Two field trips were under taken in 2005 and 2006. This paper presents the summary of work to date and its implications for understanding Martian landforms and processes, and for the selection of sites for future missions, both manned and unmanned.

Mound springs form where artesian water discharges at the ground surface and builds up a mound of deposited material. The height of the mound is equivalent to the hydraulic head of the artesian basin. They are widespread through the Great Artesian Basin (GAB) of Australia [3], and have been reported from Africa [e.g. 4, 5] and North America. Such 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. The DMC is significant because it is one of the largest and best expressed spring complexes on Earth and is relatively accessible

Fig. 1. Left - The location of the Dalhousie Mound Spring Complex and the Great Artesian Basin. Right - Oblique aerial view of the Dalhousie Mound Spring Complex (looking north) showing dark vegetated outflown channels and light coloured spring and channel deposits.

1.2 Setting

The DMC occurs at the margins of the GAB which underlies 22% of the Australian continent and covers 1.7 million km^2 (Figure 1). The complex consists of a cluster of more than 60 active springs formed by natural discharge from the GAB) [4]. A complex mosaic of active and ancient spring deposits and channels is spread over about 1500 km^2 of which the springs occur in a core zone of ~150 km^2 (Figure 1). Total measured discharge from the GAB is 1.74 GL per day, the unfocussed natural leakage through the aquaclude is thought be approximately equal to this figure. Some 54 ML per day are currently discharged by the DMC - 3% of the measured total. The discharged artesian waters are of low to moderate salinity (700 - 9400 ppm), near neutral pH (6.8-7.3) and warm (20-46^{o}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 ground water flow focused along a series of faults that breach the anticline's crest [5, 6].

1.3 Analogue significance

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 [7-9]. Terrestrial spring deposits have a wide range of morphologies yet, there are few published accounts on 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 DMC will greatly assist in recognition of such features on Mars. Lastly, given the considerable interest in thermal springs as favourable environments for life on the early Earth and perhaps on Mars [10], better characterization of spring sediments and textures, especially their microscopic fabrics and chemistry, will assist in the recognition of bio-signatures in Martian samples from putative Martian spring deposits.

Preliminary results

2.1 Active spring mound and channel morphology

We identified a range of morphologies associated with spring deposits and their outflows [11], Examples of these are illustrated in Figure 2. These include:

Depressions.
Springs at DMC likely begin as small negative relief features. According to information from the park ranger, one began forming 5 years before our field visit and had attained a width of 6 m and a depth of 30 cm. The desiccated clays at the surface overlie saturated muds at shallow depth. The presence of circumferential tension cracks indicate that sagging, rather than deflation is the primary formation mechanism. The initiation of springs through sagging and collapse is a feature of those in the DMC and a result of the partial dissolution of the shallow regolith by ascending groundwaters that are under-saturated with respect to some regolith components (see section 2.3).

Pools.
Pools are circular to elongate in shape. Larger pools may form by coalescing. They vary in width from 30-160 m and reached a maximum depth of 10 m. They are found both at local surface elevation and on top of mounds.

Mounds.
Mounds are generally symmetrical, but may display 'bulging' on the flank where seepage zones occur. They are low features attaining heights of 6 m and widths of 180 m.

Spring channels.
The channels, close to source are heavily vegetated and this likely dominates their pattern and morphology. They are narrow, sinuous, leveed systems). Recently abandoned channels show evidence of piping indicative of active through-flow at depth. Downstream, the channels merge with other spring outflows to form wide, shallow, anastomosing channels, separated by carbonate-rich islands.

Fig. 2. *Left* - Aerial view of spring pool. Note the sinuous, vegetation-rimmed discharge channel. *Right* – Small mesa formed by erosion of a former pool leaving behind a carbonate cap.

Islands.
Mounds are located within the channels and are low (~1 m), circular to elliptical, vegetation free surfaces ~ 55 m wide. They are halite encrusted and appear highly susceptible to aeolian erosion once desiccated. However at depth, there are thick carbonate deposits which have higher preservation potential.

2.2 Spring Sediments

Composition.
The mounds are constructed of autochthonous materials precipitated by the spring waters and allochthonous materials. The first category consists of largely carbonates,

sulphates, and oxides-hydroxides of iron and manganese. The second consists of sand (mostly quartz with minor feldspar) and clay with some carbonate.
The allochthonous material is of two types. The first is quartz sand and clay and minor carbonate deflated from the hinterland and the channel outflows and trapped in the immediate vicinity of the spring by vegetation. The second consists of quartz and feldspar sands and clays released from the aquifer which transported vertically by the ascending spring waters, or liberated by granular disintegration of exposed rocks at the surface by weathering.

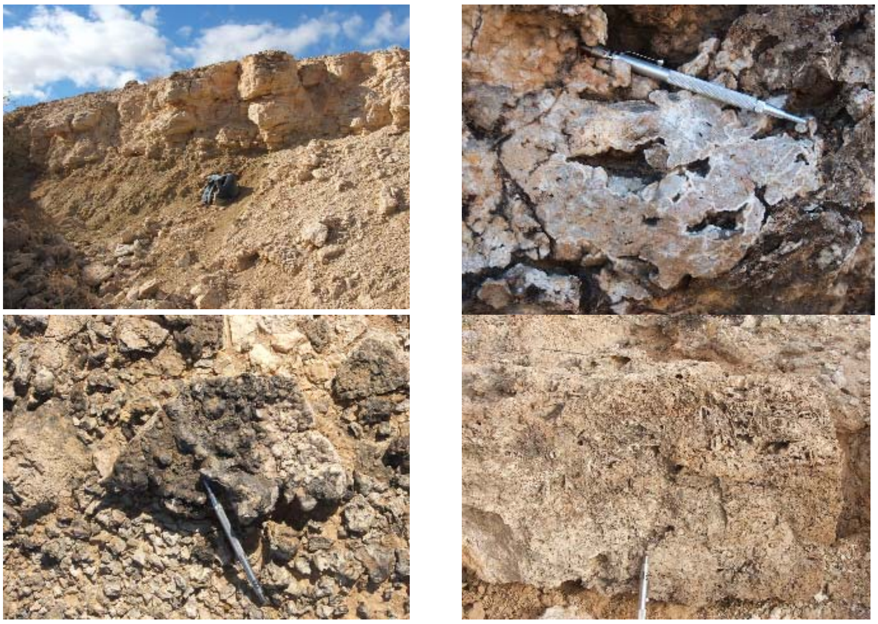

Fig. 3. Representative outcrop textures. *Top left* – gully exposure through Dalhousie rock pile with thermal vent deposits passing up to through pool and outflow channel deposits at top. Note rucksack for scale. *Top righ*t – brecciated and cavernous thermal vent limestone with internal cements and sediments, Dalhousie rock pile. Note scriber for scale. *Bottom left* – stromatolitic limestone formed on margin of former high temperature pool. Scriber for scale. *Bottom righ*t – moulds of aquatic plants in former channel deposit. Scriber for scale.

Large-scale features facies and depositional environments.

Spring limestone deposits show a wide range of morphologies, ranging from elongate to equi-dimensional in shape and in scale from metres to km. The tops of the deposits range from flat to sloping with angles of about 5^{o}. The limestones are typically featureless in outcrop and hand specimen, apart from variations in colour (white to dark grey) and varying amounts of cavities and quartz sand. There are exceptions, however. Some limestones contain well preserved impressions of aquatic plants. Deposits associated with high temperature vents show a range of features including cross cutting veins, crusts, stromatolites, breccias, ands multi-coloured cavity fills (Figure 3).

The fossil limestones can be assigned to a number of different depositional environments based on these features and by comparison with modern spring deposits [12]. These include: deposits of ambient temperature spring, cores, spring mound flanks, and channels, those of deposited in the cores and channels of warm springs, and hot spring vents.

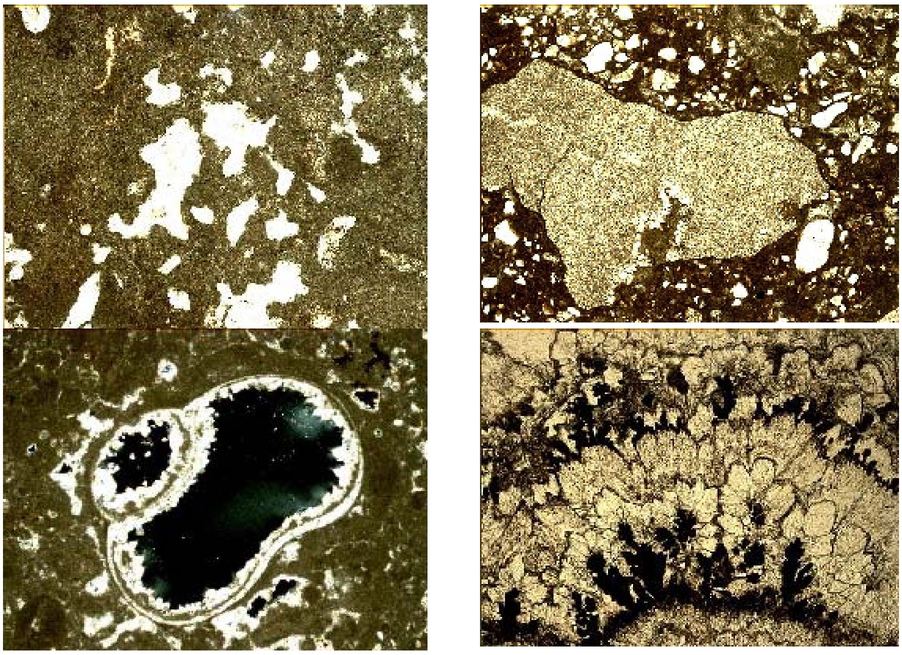

Fig. 4. Microscopic textures. Top left – Branching cavities formed by decay of vegetation in fine-grained spring limestone from top of mound. Top right – travertine fragment in sandy channel limestone. Bottom left – small gastropod on edge of abandoned channel, Dalhousie rock pile. Bottom right – Stromatolitic limestone. All photos have a field of view of 2.5 mm.

Microscopic textures and depositional environments.
A much wider range of textures is visible in thin sections of limestone samples. Three basic textural types are evident, related to water temperature: very fine-grained deposits (tufa), precipitated from ambient temperature springs, Coarse-grained deposits (travertine), precipitated by hot springs at temperatures above 50 degrees, and mixed travertine-tufa deposits, formed by springs of temperatures of 40-50 degrees. Within these categories it is possible to distinguish deposits formed in swamps, open pools, open channels, vegetated channels, and vents (Figure 4).

The different cement textures indicates they form both above the water table in the zone of partial water saturation, and beneath it in fully saturated materials. This is consistent with the model of upward mound growth with the saturated zone transgressing through mound sediments formerly above the water table. During the waning of the mound water flow can be expected to stagnate and fall. As a result the solute load of the mound may increase due to evaporative concentration, resulting in a final phase of gypsum precipitation. Some vadose carbonate cements may also occur during this phase.

2.3 Modelling of spring activity

Preliminary approaches have been made to the modelling of spring discharge dynamics [13]. Discharge from the aquifer into the springs is governed by Darcy's Law. :

$$Q = \frac{-\rho g \kappa A_{sub}}{\mu} \frac{dH}{dz}$$

Where g is gravitational acceleration, ρ is the density of water, μ is the dynamic viscosity of water, κ and *Asub* characterize the permeability and areal extent of the region though which the water is flowing, d is the depth to the aquifer, and dH/dz is the gradient of hydraulic head. The quantity $\rho g \kappa Asub/\mu$ can be thought of as a transmissivity of the fracture system or conduit through which water flows from the aquifer to the spring.

Figure 5 shows a conceptual sketch of the modelled spring system. In the model we assume a constant artesian pressure head, *Part*. We further assume that there is a characteristic velocity in the pool U which can be approximated as $U = R/T$, where T is the average residence time of water in the pool ($T \approx R2h/Q$). Because the existence of a pool depends upon the ability of the flow to remove sediment (which may be supplied through aeolian processes or upwelled from the subsurface) as suspended load, we assume that the pool dimensions will be set by this characteristic velocity such that it is equal to the settling velocity *Ws* of the largest particles evacuated from the pool: $U = Ws = Q/Rh$. If we assume the pool retains a self-similar shape throughout the evolution of the spring, such that the depth-to-width ratio remains constant, i.e. $h/R = \beta$, where β is a constant, we can arrive at an expression for the height of the mound η as a function of pool radius R:

$$\begin{cases} \eta(R) = (P_{art} - d) - AR^2 \\ A = \dfrac{W_s \mu \beta d}{\rho g \kappa A_{sub}} \end{cases}$$

Modelling was also carried out on historic measurements of water chemistry. The modelling showed that the water is under-saturated with respect to gypsum, but saturated with respect to calcite. This explains two observations of the surface materials. Firstly, the prevalence of calcite as the primary spring deposit (gypsum is only present distally or in dormant spring deposits through evaporitic concentration). Secondly, the formation of a collapse pool during the initial stages of spring evolution is due to dissolution of subsurface gypsum, which is a common component of the weathering profile.

It should be noted that since this model is a physical description of processes that occur chemically (e.g. precipitation of calcite) and because these chemical processes are temperature-dependent, we are neglecting the effects of temperature on precipitation and therefore are assuming isothermal conditions. We examined this assumption by developing a model relating spring outflow temperature with discharge. The model calculates the heat lost from the spring to the surrounding rock as the water flows to the surface. Results from this model suggest that the DMC springs' discharges are large enough to remain essentially isothermal throughout most of their evolution.

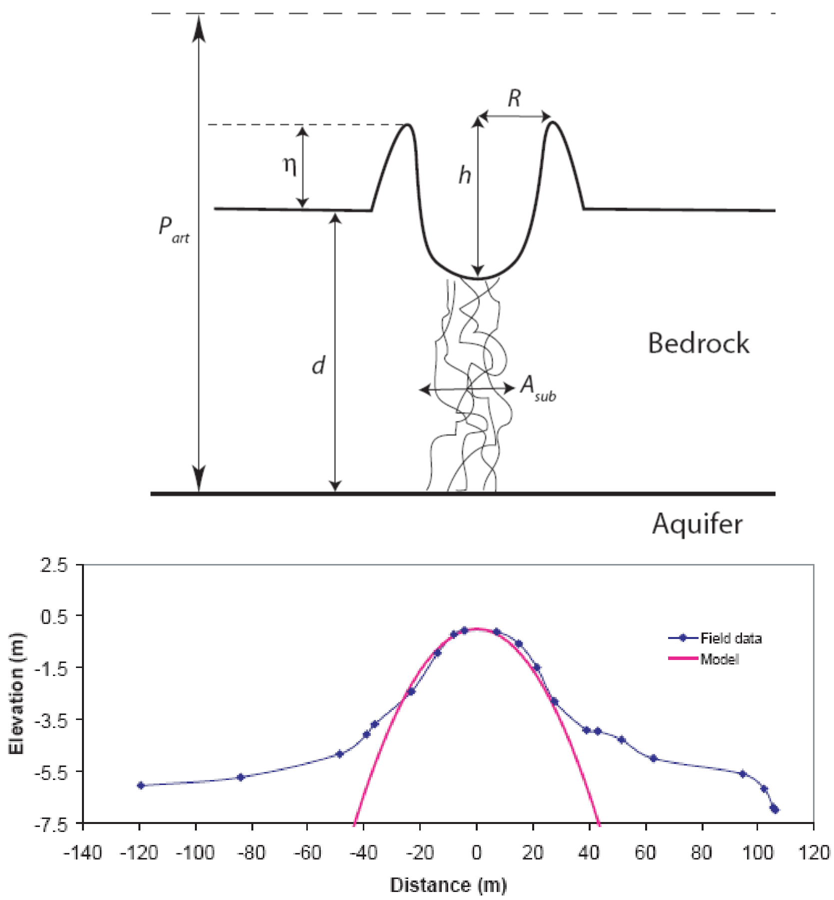

Fig. 5. Modelling of spring behaviour. Top - .the modelled system. Bottom- Example model calculation ((Part – d) = 0 m, A = 0.004 m-1) plotted against field data from a DMC mound.

2.4 Landscape evolution

Based on field and laboratory studies we propose a 6-stage conceptual model that illustrates the evolution of DMC mound springs (Figure 6). 1) Pressurized groundwater flows through fissures to the surface. The undersaturated spring water dissolves the bedrock gypsum. 2) This coupled with local weathering and deflation results in a depression which fills with water. 3) The saturated springwater precipitates calcite along the pool margin and the mound grows. 4) The hydraulic gradient is reduced with mound growth and the pool shrinks. 5) The pool continues to reduce in volume with mound growth and seepage may occur along the mound flank. 6) Mound pool is closed at the surface and seepage occurs along flank.

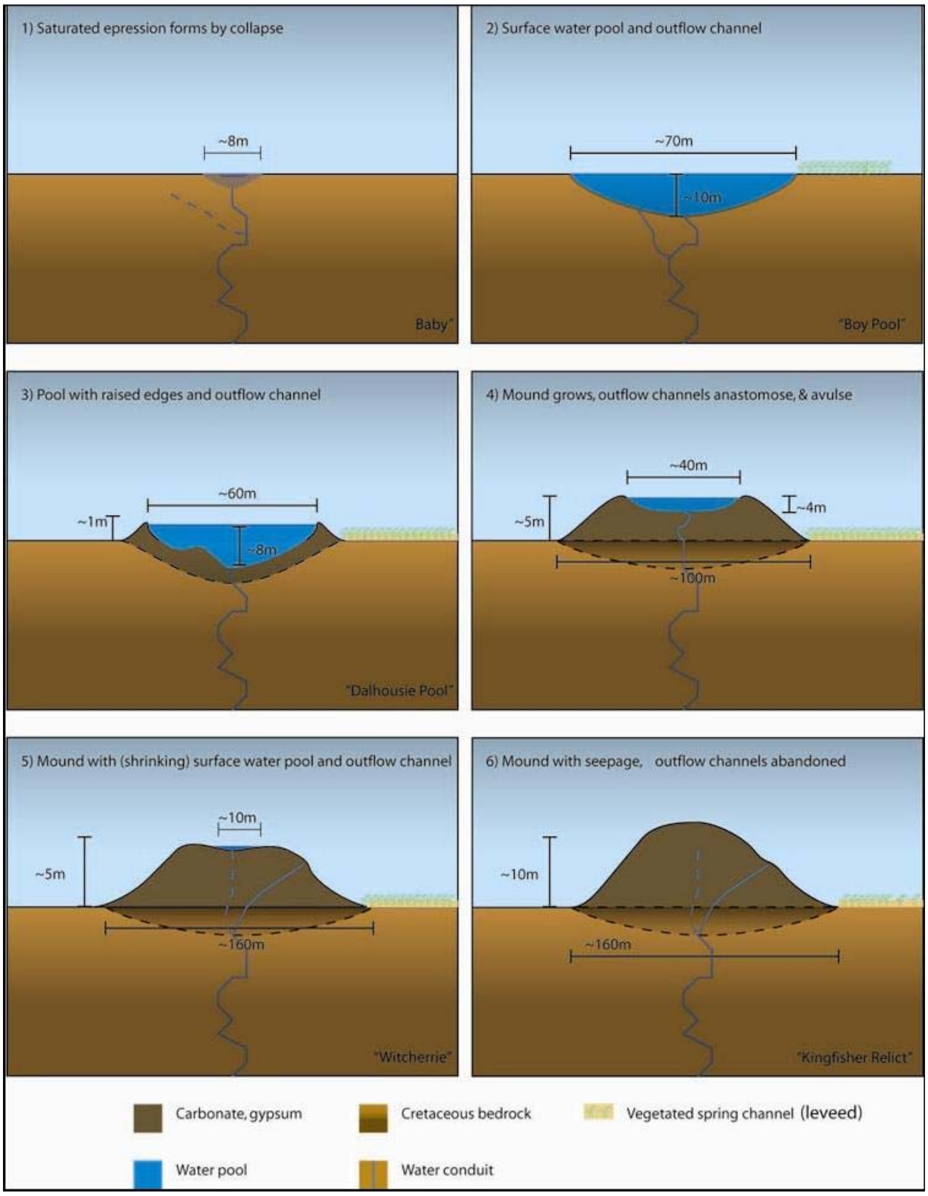

Fig. 6. Conceptual model of mound spring formation at the DMC. See text for details.

Relict spring deposit morphology and degradation.

There are several mesas and mounds in the field area, some date to the Early Neogene. The flat-topped mesas can be extensive (The largest, Dalhousie Rock Pile, is 4.7 km long and 15 m high). Others form low (< 2 m), flat-topped ridges or mounds. Spring deposits cap the circular and elongate bedrock mesas. The carbonate strata are generally < 2 m thick and petrographic analysis indicate shallow pool and channel facies. Source mound morphologies for these deposits were not preserved. In fact, no fossil mounds composed entirely of spring deposits were found at DMC. This would suggest that weathering and erosion significantly impact the preservation potential of mound spring form on planetary surfaces.

The mesas are currently degraded by local runoff, aeolian erosion, mass movement and weathering. In some locations, erosion by runoff and weathering has removed the protective carbonate cap, leaving a conical-shaped mound with a large depression. These are similar to the pitted cones and domes observed on Mars (Figure 7). Other mound springs are degraded to asymmetrical hills that have the appearance of streamlined islands. The variability of relict spring deposits found at Dalhousie has not been previously reported in the literature and will enable a more rigorous assessment of Martian landforms.

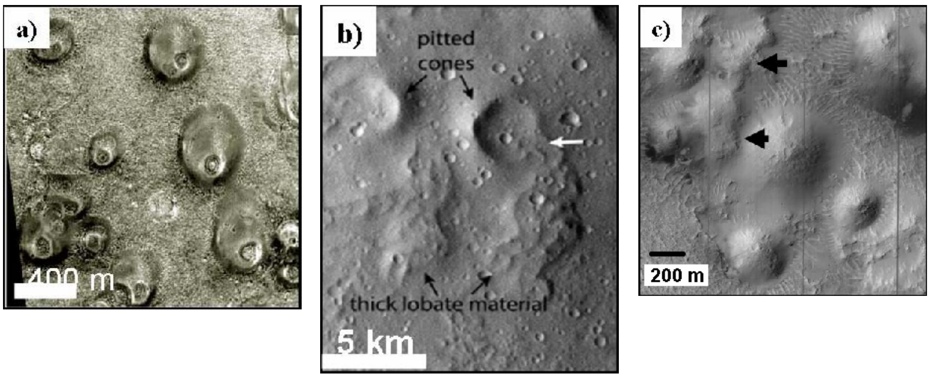

Fig. 7. Possible spring mounds on Mars. *Left* -located at 37.89 N, 65 W. From [8]. *Centre* – Pitted cones in SW Utopia. From [9]. *Right* - Cerebrus plains HiRISE image 10.3 N, 162.3 E, TRA_000880_1905 (50 cm/px). Note juxtaposition of mounds and mesas (black arrows). These Martian features are similar in scale to those at DMC.

3 Implications for the future

3.1 Landscape evolution

The morphometric data presented here on both active and fossil springs will improve our ability to identify potential spring deposits on Mars from satellite platforms. We show that the preserved form can be as domes, pitted cones, or mesas. This suggests that the range of morphologies assigned to potential spring deposits on Mars can now 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 sediment 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.

3.2 Modelling

Modelling exercises indicate that the parabolic shape predicted by the model does a reasonable job approximating the top and upper slopes of extinct mound springs surveyed at the DMC field site (Fig. 4). The field data suggest that further refinements to the model incorporating evaporation and mineral precipitation on the side slopes of mounds may improve its performance. We are continuing to adjust the model design in accordance with insights gained from field data collected at DMC and other mound springs in New Mexico, USA. Using only surface topographic data and a few assumptions about soil hydraulic properties, this model is able to infer a region's hydrogeological history. It therefore has potentially useful applications on Mars. Although Martian features are unlikely to be carbonate deposits like most of the spring mounds on Earth, they may represent other water-soluble minerals such as sulphur, sulphides, or other iron-rich minerals for which the generic processes described by this model still apply. With the continuing acquisition of relatively high resolution topography and imagery, we intend to apply this model to some of the Martian features that have been hypothesized to be spring deposits. This will allow us to estimate the hydrologic discharges and hydraulic potentials that would have been necessary to create these features. In particular, it should be possible to determine the height of the hydrostatic head in Martian aquifers from the height of the spring mounds.

3.3 Recognition of spring deposits

Given the significance of potential springs for Mars exploration it is important to develop criteria for their recognition. We suggest the following:

1. At a scale of tens of metres to kilometres, spring deposits may be topographically raised because they have constructed mounds or because the well cemented deposits have become elevated through landscape lowering.
2. Dramatic compositional contrasts between the surrounding rocks and the spring deposits are likely.
3. At scales of metres to tens of metres, spring deposits will be generally conformable to the surface but locally cross-cutting.
4. At scales of centimetres to metres, vein stock works, cavities, internal sediments, laminated botryoidal, and mamillated crusts and cavity fills, vugs are common.
5. At scales ranging from tens microns to centimetres, spring deposits show high complex internal textures with cross cutting stratigraphic relationships.

3.4 Limitations of orbital and *in situ* investigations

Orbital imagery is essential to providing the regional context of Mars surface features. Much can be achieved on the surface of Mars to test hypotheses generated from orbital data using rovers, as the outstanding successes of the Spirit and Opportunity missions have shown [14]. However, such remotely operated observations have their limitations. In studying a Dalhousie-like deposit on Mars, present and future rovers are likely to be hampered by the steep (in some cases precipitous) nature of the outcrop, and the difficult slopes which can be both very rocky and very soft at the same time. Robot rovers may be restricted to examining allochthonous blocks on the slopes surrounding ancient spring deposits, rather than accessing *in situ* material.

Furthermore, much of detailed fabric of strong limestones can only be identified on a scale where the field of view is a few millimetres or less and the resolution is a few microns. This is an order of magnitude higher than can be obtained using the microscopic imager of current rovers [15], which are, of course, black and white only. While higher resolution images are expected from the colour microscopic imager and the atomic force microscope of the 2007 Phoenix mission [16] they will still suffer from the limitations to being able to examine the surface only and have limited compositional control. Even if linked with a tool such as the RAT carried by the MER rovers[15], the microscopes will only be able to examine rough-cut surfaces. By contrast, petrographic thin sections offer micron scale textural and compositional data, but their manufacture is beyond the capabilities of even the most advanced robotic rovers conceived.

Once spring deposits have been identified on Mars through a combination of remote sensing and robotic rover exploration their further study will require the capabilities of sample return missions and, eventually, human visits. As was the case with the Moon, there is no substitute for returned samples to elucidate the nature and history of complex rocks[17].

Acknowledgments.
This work was funded by NASA grant NNG05GL37G. We would like to thank the Irrwanyere Aboriginal Corporation, the Eringa Native Title claimants, the Wankanguru Native Title claimants, the Department of Aboriginal affairs and reconciliation. The manuscript was improved thanks to the efforts of two anonymous reviewers.

References

1. Mann, G. A.., Clarke, J. D. A. Gostin, V. A. Surveying for Mars Analogue Research Sites in the Central Australian Deserts. Australian Geographical Studies. 30(2004): 116-124
2. Clarke, J. D. A. Stoker, C. Mound spring complexes in central Australia: an analogue for Martian groundwater-fed outflow channels? Abstracts of the 34th Lunar and Planetary Science Conference, abstract #1504, 2003.

3. Habermehl, M. A. Hydrogeology and. environmental geology of the Great. Artesian Basin, Australia. Geological Society of Australia Special Publication 21 (2001) 127-144.
4. Roberts, C. R., Mitchell, C. W. Spring mounds in southern Tunisia. In Frostick, L., Reid, I.(eds), Desert Sediments, Ancient and Modern. Geological Society Special Publication 35, 321-334 (1987).
5. Renaut, R.W, Morley, C. K., Jones, B. Fossil hot-spring travertine in the Turkana Basin, northern Kenya; structure, facies, and genesis. Renaut, R.W. and Ashley, G. M. (eds.). In Sedimentation in continental rifts. Special Publication, Society for Sedimentary Geology. 73, 123-141 (2002).
4. Smith, P. C. Hydrogeology. In Zeidler, W. and Ponder, W. F (eds.). Natural history of Dalhousie Springs. South Australian Museum, Adelaide, p27-40. 1989.
5. Krieg, G. W. Geology. In Zeidler, W. and Ponder, W. F (eds.). South Australian Museum, Adelaide, p 19-26. 1989
6. Krieg, G. W. Dalhousie explanatory Notes. Geological Atlas of South Australia 1:250,000 Series, 1985
7. Crumpler, L. S. Physical characteristics, geologic setting, and possible formation processes of spring deposits on Mars based on terrestrial analogs. Sixth International conference on Mars, pp. abstract.#3228, 2003.
8. Farrand, Gaddis, W. H. ,L. R., Keszthelyi, L. Pitted cones and domes on Mars: Observations in Acidalia Planitia and Cydonia Mensae using MOC, THEMIS, and TES data Journal of Geophysical Research (Planets), 110 (2005), E05005, doi:10.1029/2004JE002297,
9. Skinner, J.A., Tanaka, K.L. Evidence for and implications of sedimentary diapirism in the southern Utopia highland-lowland boundary plain, Mars. Icarus 186 (2007) 41-59, doi:10.1016/j.icarus.2006.08.013
10. Pirajno, F., Van Kranendonk, M. J. Review of hydrothermal processes and systems on Earth and implications for Martian analogues. Australian Journal of Earth Sciences, Volume 52 (2005) 329 – 351
11. Bourke, M. C., Clarke, J., Manga, M., Nelson, P., Williams, K., Fonseca, J., Fobar, B. Spring mounds and channels at Dalhousie, central Australia. Abstracts of the 37th Lunar and Planetary Science Conference, abstract #2174, 2007.
12. Ford, T. D., and Pedley, H. M. A review of tufa and travertine deposits of the world. Earth-Science Reviews 41 (1996) 117-175.
13. Nelson, P. A., Manga, M. Bourke, M. C., Clarke, J. D. A. A model for mound spring formation and evolution. Abstracts of the 37th Lunar and Planetary Science Conference, abstract #2111, 2007
14. Squyres, S. W., Arvidson, R. E., Baumgartner, E. T., Bell, J. F. III, Christensen, P. R., Gorvan, S., Herkenhoff, K. E., Klingelhoffer, G., Madsen, M. B., Morris, R. V., Reider, R., and Romero, R. E. 2003. The Athena Mars Rover Science Investigation. *Journal of Geophysics Research* 108(E12), 8062, doi:10.1029/2003JE002121
15. Squyres, S. W. Roving Mars: Spirit, Opportunity, and the Exploration of the Red Planet. Hyperion Books, New York, 384p., 2005
16. Shirbacheh, M., Hecht, M., Bell, J.L., and Mogensen, C. Microscopy, electrochemistry, and conductivity analyzer (MECA) payload on Mars '07 Phoenix lander. Proceedings 2005 IEEE Conference, 279- 291, 2005.
17. Taylor, S. R., Pieters, C. M., and MacPherson, G. J. 2006. Earth-Moon System, Planetary Science, and Lessons Learned. Reviews in Mineralogy and Geochemistry 60 (2006), 657-704.