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FOLLOW THE WATER: APPLYING A MARS EXPLORATION STRATEGY TO THE ARKAROOLA ANALOG REGION, SOUTH AUSTRALIA

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The current governing mantra for NASA's Mars robotic exploration strategy is "Follow the Water". The Arkaroola Mars Analog Region (AMAR) served as the field site for Expedition Two in August 2004, a multidisciplinary Mars analog research campaign. The AMAR is an ideal site to assess, in a terrestrial environment that provides a range of useful parallels to Mars, the validity of a "Follow the Water" strategy. Information was gathered on the geologic and hydrologic history of the Arkaroola region from both remote sensing datasets and ground-truthing measurements collected on-site during the Expedition. Based on the experiences of Expedition Two and comparisons with past, present, and future missions to Mars, conclusions are drawn regarding issues such as site selection, mobility, and exploration strategies to most effectively "Follow the Water" on Mars. Landing site selection criteria should focus on landing site safety and also regions with a high probability of past and/or present water. Substantial mobility capability is required for robotic and human missions to characterize the surrounding geology and hydrologic history due to site accessibility, availability of water (if present), and diversity of samples. Mineralogic studies (orbital, airborne, and in situ) are also extremely useful for assessing the potential past and/or present habitability of a region.

INTRODUCTION

The past and present distribution of water on Mars in all three states is of prime interest to researchers interested in the history of the Martian environment, the past and present possibility of life, and the availability of resources for human exploration. For this reason a "Follow the Water" strategy has been evolved as the guiding principle of NASA's robotic Mars missions since the 1990's. This proved spectacularly successful at the Meridiani Planum site explored by the Opportunity rover which has been demonstrated as the site of a former saline lake or sea[1]. Results from the Spirit rover have proved more ambivalent[2], although at Gusev crater too there is evidence for

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possible aqueous weathering based on the volcanic rock textures[3]. Orbital reconnaissance of Mars has also proven successful by using the "Follow the Water" approach as the Mars Global Surveyor (MGS) spacecraft has discovered sites of recent fluvial activity on the Martian surface in the form of gully features[4], surface ice has been detected in the Martian polar caps[5, 6], and the Mars Odyssey spacecraft has detected evidence of massive deposits of near-surface ground ice in the polar regions of Mars[7, 8].

The Arkaroola Mars Analog Region (AMAR) was selected by Mars Society Australia (MSA) in 2001 as its prime site for multidisciplinary Mars analog research[9, 10]. It is therefore an ideal site to assess, in a terrestrial environment that provides a range of useful parallels to Mars, the validity of a "Follow the Water" strategy. The data in this paper was collected largely during Expedition Two organized jointly by MSA, its Canadian counterpart Mars Society Canada (MSC), and other society members from the United States during MSA's earlier Jartimarra-1 expedition[10] and by one of us (Thomas) for an Honours thesis at the Australian Centre for Astrobiology, the main results of which have been published previously[11].

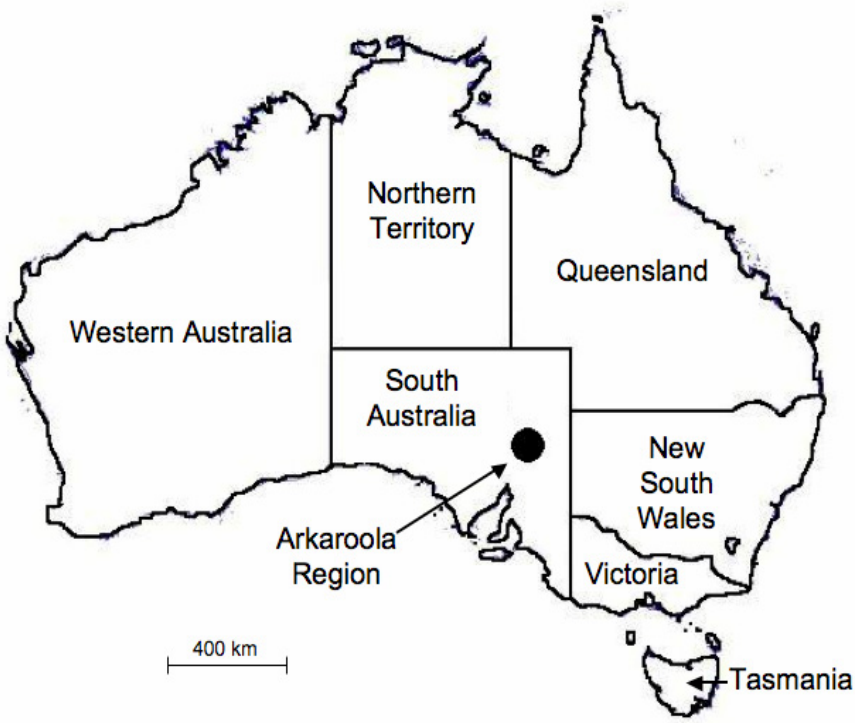

Figure 1 Location of Arkaroola within South Australia.

"FOLLOW THE WATER" AS AN EXPLORATION STRATEGY

The current governing mantra for NASA's Mars robotic exploration strategy is "Follow the Water". This guiding principle requires that spacecraft missions search for scientific evidence that water was present in the past or is still present today on Mars. Liquid water is not abundant in the present epoch on the surface of Mars because the temperatures and pressures on the Martian surface are generally too low for liquid water to be stable with respect to freezing and boiling, respectively[12]. Therefore many investigations search for evidence of past water activity and/or subsurface reservoirs of ice or liquid water.

The rationale for the "Follow the Water" approach to exploration is four-fold. Water is critical for 1) determining if life arose on Mars, 2) characterizing the climate of Mars, 3) characterizing the geology of Mars, and 4) preparing for human exploration of Mars. Each of these categories is explicitly addressed in the MEPAG (Mars Exploration Program Analysis Group) document which helps to guide NASA's mission selection process[13]. Each category is discussed in more detail below as in relation to the "Follow the Water" strategy. All NASA missions flown to Mars must trace the mission goals, objectives, and investigations back to the MEPAG recommendations. Additionally, with the new U.S. Presidential Vision for Space Exploration[13], the goals of detecting potential liquid water reservoirs on Mars has increased importance both in terms of assessing the possibilities of forward and back contamination from a planetary protection perspective as well as the use of pre-existing water deposits for in situ resource utilization purposes.

1. LIFE. As a first step in the search for life on Mars we therefore seek locales on Mars that are *habitable*, or able to sustain life. All life as we know it requires liquid water to survive and so we seek habitable niches on Mars which may be environments that can support life. Based on our understanding of terrestrial life, a habitable environment requires liquid water, organic molecules, and an energy source. Determining where on Mars liquid water may persist (past or present) is therefore critical for determining where to search for evidence of extinct or extant life.

2. CLIMATE. We seek to understand the processes that have shaped the climatic evolution of Mars and to understand how Mars has evolved to its present state. Of prime importance is determining the processes that control the present distribution of water, carbon dioxide, and dust in the Martian atmosphere by considering daily, seasonal, and solar cycle trends on present-day Mars as well as atmospheric escape rates. We also search for micro-climates where unusual concentrations of volatiles (especially H_2O) may indicate exceptionally or recently wet and/or warm locales. The past history of Mars climate is also important as the geologic record (including geomorphic and chemical signatures) can yield insights into conditions on an earlier Mars. The former presence of surface water deposits on Mars[14] along with the existence of vast canyon and valley systems[14] are just examples of evidence supporting past wet conditions on Mars with implications for climatic conditions different from today.

3. GEOLOGY. Understanding the evolution of the surface and interior of Mars is meritorious in its own right but has also gained additional significance in terms of the search for life on Mars. The geologic nature of the planet is extremely informative regarding several aspects of life including early Martian history, volatile distribution, and geothermal energy sources. There are a wide variety of geologic investigations to be conducted including (but not limited to) determining the 3-dimensional distribution of water on Mars, studying fluvial, subaqueous, and subaerial sedimentary processes, evaluating igneous processes, characterizing surface-atmosphere interactions, examining mineralogy and hydrothermal alterations, understanding interior processes and thermal evolution, etc.

4. HUMAN EXPLORATION. Sustained human exploration of Mars will ultimately rely on the use of in situ resources. Of utmost importance is the use of in situ water for a variety of purposes including life support, crop growth, and propulsion/fuel cell power systems. We must therefore determine the locations of water deposits on Mars which may be a driver for site selection of the first human base. We must also determine the accessibility of such deposits (near surface ice, subsurface aquifers, etc.) which will drive the technological development for extracting this resource from the ground. Likewise, understanding the potential habitability on Mars is important for assessing the potential for both forward and back contamination in terms of planetary protection issues[15].

CURRENT MARTIAN NEAR SURFACE WATER SOURCES

There are three potential sources of near surface water on Mars that may contain habitable zones to sustain life and/or provide in situ resources to support human exploration. Spacecraft observations and theoretical modeling suggest that water exists today in 1) near surface ground ice deposits, 2) subsurface aquifers, and 3) polar ice cap deposits. We shall discuss each of these locales and the scientific evidence supporting the existence of these resource deposits.

1. NEAR SURFACE GROUND ICE DEPOSITS

Vast deposits of near surface ground ice have been detected by the Gamma Ray Spectrometer (GRS) instrument aboard the Mars Odyssey spacecraft[8]. The GRS instrument detects gamma rays and neutrons produced via interactions of cosmic rays with the Martian subsurface[7]. Due to the cosmic ray bombardment, a large number of secondary neutrons are produced. A deficit of high-energy neutrons at some regions on Mars may indicate the presence of water in the subsurface, because neutrons become moderated down to thermal energies in the presence of hydrogen[7]. GRS specifically detects water by measuring these secondary neutrons. In addition, the neutrons interact with atomic nuclei of atoms within the Martian subsurface and emit gamma rays with a unique set of lines which allows for spectroscopic identification of the subsurface composition[7]. From this data the abundance of hydrogen present is inferred. Since the hydrogen is most likely present in the form of water ice, the spectrometer is able to measure the concentrations of ice. The GRS instrument is sensitive to the upper 1-2 meter(s) of the subsurface and so only detects ice to this depth[7].

The global distribution of near-surface water ice is shown in Figure 1[13]. Note that most equatorial regions generally have relatively low concentrations of water ice whereas more poleward regions become more ice-rich. Regions shown in blue and violet are likely to comprise 50% water ice by volume[13].

Ice may also be present in the near-surface environment of Mars in the form of (rock) glaciers and possibly rafted ice deposits. The detection of such glaciers has been reported in several regions of Mars including Western Arsia Mons[16], the Vallis Marineris region[17], and Arabia Terra[18]. High Resolution Stereo Camera (HRSC) images from the European Space Agency Mars Express spacecraft may be suggestive of near-surface pack ice deposits in the southern Elysium region of Mars[19].

All of these findings show that significant amounts of water ice likely exist on Mars in some form. Such water could be extracted from the ground and used to support a human mission as an input to an ISRU (in situ resource utilization) architecture. Such ice deposits may also provide regions of preserved extinct and/or extant life on Mars. Liquid water can exist at grain contacts as thin films above about -20°C and organisms isolated from Siberian permafrost can still metabolize at such low temperatures[20]. At obliquities above 40º, Mars polar and high-latitude temperatures rise above -20°C and so these high-latitude ice deposits may provide habitable abodes at opportune times in Martian history[20].

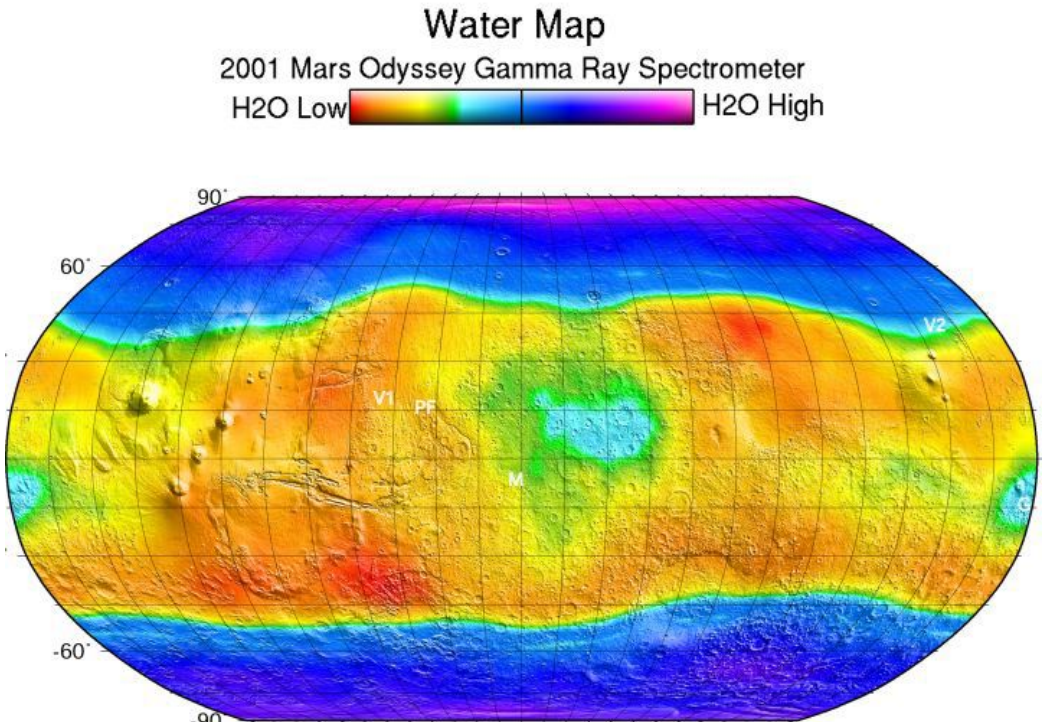

Figure 2 Map of Mars showing global concentrations of near-surface water ice[13]. Locations marked with white letters indicate landing sites of robotic missions to Mars [V1 = Viking 1, V2 = Viking 2, PF=Pathfinder, M=Meridiani Planum (Opportunity rover), G=Gusev crater (Spirit rover)].

2. SUBSURFACE AQUIFERS

The discovery of recent gullies on Mars from the Mars Global Surveyor (MGS) Mars Orbiter Camera (MOC) provides evidence for geologically recent liquid water activity on Mars[4, 21-27]. Generally, gully morphology can be divided into alcove, channel, and depositional-apron regions as shown in Figure 3[4, 26]. The superposition of the gullies on geologically young surfaces such as dunes and polygons as well as the extreme scarcity of superposed impact craters indicate the relative youth of the gullies, suggesting that the gullies formed within the past few million years[4, 26].

There has been much debate regarding the source of this recent water feeding the gullies. Hypotheses have ranged from melting ground ice[21, 22], snowmelt[23], and groundwater[24], although at present a shallow subsurface aquifer source is the most likely candidate[4, 25, 26]. This would imply that deposits of liquid water may currently exist in the subsurface of Mars.

A shallow aquifer can occur where competent rock layers can trap water below ground upslope from the ridge[4], while maintaining an overlying dry and thermally insulating soil layer[25]. The dry insulating overburden allows geothermal heat to maintain liquid water within the confined aquifer at only a few hundred meters depth. An ice-cemented-soil plug between the aquifer and slope surface develops where ground ice is generally stable. Freezing cycles induced by obliquity variations cause increased fluid pressure in the aquifer to fracture the ground ice plug and allow liquid water to emerge from the side of a slope to create the gully.

The shallow aquifer theory has been tested against observational data from the Mars Global Surveyor spacecraft[26]. One interesting result is that temperature-pressure conditions at the observed depths of the gully alcoves (which would correspond with the depth of an aquifer) are generally within the liquid water regime, implying that liquid water could exist at these locations[26]. An aquifer would be located beneath the upslope plateau located behind the gullies and so should be sites of future investigation. Techniques such as ground penetrating radar may prove useful for positively identifying subsurface water deposits as well as mapping their horizontal extent. If aquifers are found in regions suitable for human landing, drilling into these reservoirs may provide adequate water to support the human settlement.

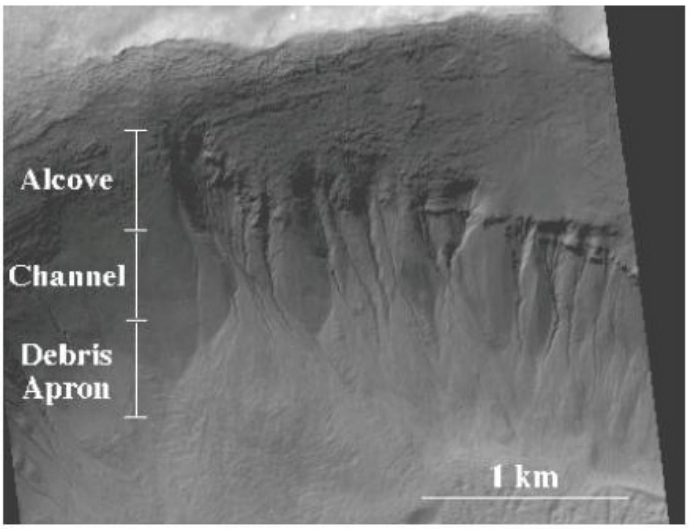

Figure 3 Portion of MOC image M17-00423 located at 200.86°W, 39.16°S showing the alcove, channel, and debris apron structures of recent gullies on Mars. Scale bar is 1 km.

3. POLAR ICE DEPOSITS

Both the northern and southern hemispheres of Mars have both permanent polar caps and polar layered deposits composed at least partially of water ice[28, 29]. The polar ice caps are surficial ice units that persist throughout the summer at both poles and appear to lie directly upon the layered deposits[29]. The permanent caps are slightly off-center and reach as far as 10° from the north pole and 6° from the south pole (since the southern summer is warmer than in the north)[30]. The caps themselves undergo variations in size and composition throughout the year as the seasonal component of the cap is largely carbon dioxide ice[31].

The polar layered deposits (PLDs) are also found in both the northern and southern polar regions (Figure 4). The PLDs are composed of a mixture of water ice and dust deposited in stratigraphically delineated profiles[29]. The layers most likely represent a depositional record of dust and condensing carbon dioxide and water ice formed over climatic timescales[32]. In the north, PLD outcrops are primarily found within the margin of the residual ice cap whereas in the south the PLDs also extend to lower latitudes.

The polar terrains on Mars are among the youngest surfaces on the planet. In the north, Viking high-resolution images failed to reveal any craters with diameters >300 m within the ~10^6 km^2 covered by the deposits which suggests the surface is less than about 10^5 years old[33-36]. In the south, the presence of ~15 craters with diameters >800 m[37] suggests a surface age of 7 -15 million years, depending on the recent Martian cratering flux[36]. The surfaces may therefore be experiencing a deposition of fresher material and/or a reworking of the preexisting surface[29].

Studying the polar regions of Mars is therefore important for understanding the hydrologic cycle on Mars, deducing climatic variations over Martian history, and examining the potential for life to exist in thin films of melted water[20] and/or as remains of life preserved in ice deposits. The polar regions are also possible sources of near-surface and surface water resources to support human exploration. The polar regions contain deposits of water ice which may be one of the most accessible deposits of water on Mars.

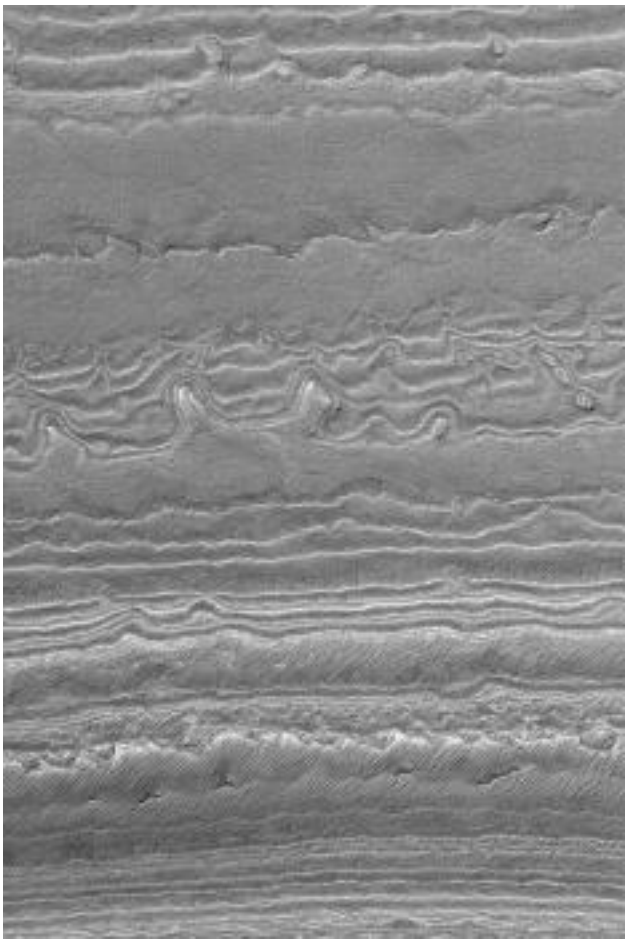

Figure 4 Portion of MOC image MOC2-548 located near 86.0°S, 182.4°W showing south polar layered deposits. Image is ~3 km wide and slope goes uphill towards the bottom of the image.

REMOTE SENSING OF PAST AND PRESENT HYDROLOGICAL ACTIVITY AT ARKAROOLA

The value of the AMAR is four-fold: a diversity of sites that provide useful analogs for Martian rocks, environments, and processes, diverse terrains that allow field testing of a range of technologies, controllable isolation for social-psychological research, and comparative easy access for logistics. Lastly, MSA plans to establish the MARS-OZ simulated base at Arkaroola as a platform to support a range of Mars analog research[10].

The mapping of large-scale hydrothermal systems presents difficulties of scale and scope to the individual researcher on the ground. In a Martian environment, the scientist on the ground will be guided by an extensive array of remote datasets currently being collected by such instruments as the Thermal Emission Spectrometer (TES) onboard the Mars Global Surveyor spacecraft and the Gamma Ray Spectrometer (GRS) aboard Mars Odyssey. Future missions will involve hyperspectral VNIR spectrometry from instruments such as the Compact Reconnaissance Imaging Spectrometers for Mars (CRISM) which was launched in August 2005 with the Mars Reconnaissance Orbiter. Experience in applying these types of remote datasets to Earth-bound problems will assist the future Martian explorers by formulating techniques and best practices to capitalize on the strengths of each particular dataset type.

Hydrothermal mineral assemblages typically display certain spectral characteristics due to vibration of the hydroxyl (OH-) anion in the near infrared[38]. These properties allow detection by satellite-borne infrared spectrometers[39]. Hyperspectral equipment, such as the Australian-built HyMap airborne system and the PIMA II field spectrometer, collect detailed spectral information, often in contiguous wavelengths, which can be analyzed and interpreted for making detailed mineralogical and alteration maps[40].

During Expedition Two, a variety of remote mapping techniques were bought to bear on resolving the problem of mapping hydrothermal alteration in the Mt. Painter district near Arkaroola. Remote mapping of alteration mineralogy was compared with established geological mapping to place the hydrothermal events in a geological context and timeframe.

Over the period 15-20 Aug 2004, an investigation was carried out using infrared instruments to search for indications of metamorphic activity in Neoproterozoic rocks surrounding the Mt Painter Inlier. Hyperspectral data used in this study included spectra collected using a Portable Infrared Mineral Analyzer (PIMA), a hand-held Short Wave Infra Red (SWIR at 1300-2500nm) instrument and a HyMap airborne dataset covering the Visible and Near-Infrared (VNIR at 400-1300nm) and SWIR regions of the electromagnetic spectrum. The HyMap dataset was collected in 1998. The HyMap instrument has undergone several improvements since the collection of this dataset and hence this investigation found some problems with the spectral accuracy of the data. Nonetheless, extremely useful variations could still be detected in both outcrop and regolith mineralogies.

Testing and sampling was carried out at various locations chosen via analysis of the HyMap airborne instrument. A sample Hymap image is shown in Figure 5. The airborne hyperspectral sensor can samples only the top 1-2 millimeters of the surface material and thus is sensitive to coverings such as desert varnish and transported cover such as scree slopes and sediment deposits. Samples collected from the field were analyzed at the base camp where both weathered and freshly broken surfaces were compared to enable a comparison between HyMap detected mineral-

ogy and PIMA analysis of the fresh mineralogy. Preliminary results indicate that iron oxide rich dust had minimal effects on the ability of the HyMap to distinguish between significant mineralogical variations. Iron indurated samples displayed a strong Fe^{2+} curve in the SWIR region when analyzed with the PIMA. Interference from other widespread surface coatings such as lichen appeared to be minor, although pervasive iron or calcium induration produced a strong spectral response which could mask other diagnostic mineral absorption features. Due to this effect, markedly indurated sediments were avoided except for comparison with nonindurated samples.

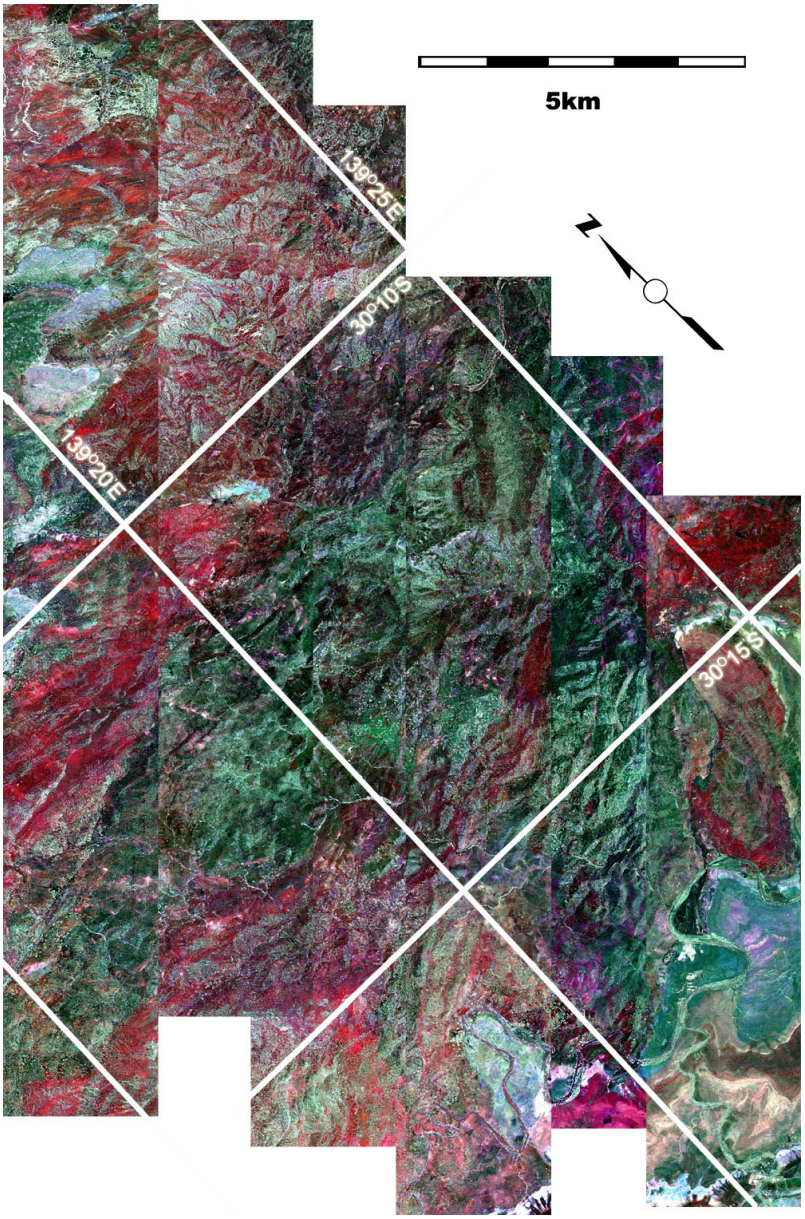

Figure 5 False color map of the Mt Painter Inlier, as imaged by the airborne HyMap instrument. Red areas are granitic, green are sedimentary and blue are basaltic rocks.

A comparison of the HyMap results from around Mt. Painter and Mt. Gee (in swathe 3 of the HyMap dataset) revealed that the quartz breccias of the famous Mt. Gee hydrothermal system were largely impenetrable using the VNIR-SWIR HyMap sensor. This contrasted with the contact metamorphosed mica-rich sedimentary rocks and basaltic volcanics of the Lower Callanna Group, covered by swathe 1 and swathe 6. Areas covered by swathe 6 were investigated on the second day of the study, but this data was not optimal since swathe 6 covered extremely rugged terrain with variations in height from 300-500 m and was two hours from the base camp. For this reason our work concentrated on ground analysis of swathe 1 in the time available.

Hand samples were collected from all accessible rock types in swathe 1 and the mineralogy was compared between HyMap and PIMA measurements. Due to the lack of spectral contrast (discussed earlier), the HyMap mineralogy is relatively imprecise. Results of the survey are presented in Table 1.

Table 1
MINERALOGY DETECTED BY HYMAP, PIMA, AND HAND SAMPLES

	Detected Mineralogical Phases		
Geologic Unit	**HyMap**	**PIMA**	**Hand Sample**
Woodnamooka Phyllite	Al and Fe-OH		
Humanity Seat Formation	Al-OH		
Wooltana Volcanics	Mg-OH or carbonate	Mg-Chlorite	Chlorite
Whywyana Formation	Mg-OH or carbonate	Actinolite	
Paralana Quartzite	Al-OH	Muscovite	
Mount Neill Granite Porphyry	Al-OH and Mg-OH		"Cats Eye" Quartz, Feldspar

This study has investigated variations in the rocks of the early Neoproterozoic Lower Callanna Group and the intrusive Mt. Neill Granite porphyry. The survey has shown the ability of the two infrared instruments, the PIMA and HyMap, to determine differing mineralogy in highly metamorphosed sedimentary and volcanic rocks. The ability of the HyMap to provide region wide targets and possible survey points for higher resolution spectral analysis using the PIMA shows what can be achieved in a short period using such synergistic instruments. Complementing remote sensing with surface hand sample analysis by astronauts on Mars would provide a worthwhile strategy for efficient geological survey of resources by human explorers and may increase the likelihood of finding niches for fossilized or extant signs of life on Mars.

GEOLOGICAL CONTEXT AND SPRING CHARACTERISTICS OF WATER SITES AT ARKAROOLA

There are a number of permanent or semi-permanent water sources in the Arkaroola area. There are four types of springs or waterholes:

- Radioactive hot springs (Paralana)
- Weakly radioactive cold springs (Old Paralana, Black Springs)
- Non-radioactive springs, both warm and cool pools (Nepouie Spring)
- Pools in creek beds (Arkaroola, Bolla Bollana, and Munyallina Springs, Nooldoonooldoona, Arkaroola, Echo Camp, and Barraranna Waterholes)

These water occurrences are of two types. The first are springs from deep, fracture controlled bedrock aquifers that are either elevated in temperature or radioactivity or both. Weak artesian pressure is associated with these, suggesting either recharge from the surrounding highlands, mixing with waters of the Great Artesian Basin, or both. The elevated temperature and radioactivity both indicate interaction with the radiogenic granites of the Mt. Painter igneous complex and circulation of water to depths of at least 1 km. Relationship of the thermal springs to past hydrothermal activity in the area is uncertain[11].

The second type of water occurrence is water associated with shallow creek aquifers. Although the creeks in the Arkaroola region flow rarely, typically every 2-10 years, the bedrock-confined channels and gravel beds of the creek gorges contain significant and permanent shallow aquifers, as indicated by the stands of River Red Gums (*Eucalyptus camaldulensis*) along their length. The shallow aquifers are exposed either where constrictions in the bedrock channel and rocky bars force the aquifer near the surface, or in scours in the gravel bed. The creek aquifer is also associated with localized deep water holes associated with plunge pools in intermittent rapids and waterfalls.

The climate is arid within the study area. Rainfall occurs throughout the year and peaks during the summer months. Mean annual rainfall has ranged from 23 mm in 1902 to 714 mm in 1974 with a median of only 164 mm, at the Arkaroola rainfall recording station[41]. Mean maximum temperatures at Arkaroola can exceed 30°C during the months of November to March and mean minimum temperatures may fall below 10°C during July through August. As a result there are no permanent watercourses, other than springs, within the area studied. However, ephemeral watercourses flow occasionally after major precipitation events. At the time of our study, the area was experiencing an extended drought and so no water was flowing.

Surface hydrology is limited to springs and waterholes within the valleys of this section of the Flinders Ranges. This existing surface water contained in small depressions within the valley is associated with groundwater sources. The Flinders Ranges are comprised of fractured rock aquifers and discharge water to these existing surface water impoundments. Paralana Hot Springs is an example of this type of water source. It is also suspected that discharge into surface water impoundments occurs by under flow into sedimentary aquifers (water table or unconfined aquifers) thereby filling those surface depressions that fall below the water table. These two types of groundwater sources are primarily responsible for the springs and waterholes that exist in the ephemeral creeks within the study area.

A total of 11 springs and waterholes were studied. Exact coordinates of sites were determined using a Garmin *e*trex GPS unit (see Table 2) and sites were sampled for water chemistry (see Table 3) and aquatic life. All sites identified are within a 40 km radius from the MARS-OZ habitat site. The following is a brief characterization of each of our study sites.

Arkaroola Springs

The springs consist of outcropping creek bed aquifers in deep channel scours in the bed of Arkaroola Creek. The channel is constricted by a gorge cut through the resistant Wortupa Quartzite[42, 43]. The temperature of the water (12.1°C) is relatively cold, probably due to the combination of its location and the source of the water. The waterhole is located at the foot of a very high cliff that provides shade for most of the day. The conductivity level measured (2101µs) at Arkaroola Springs indicates a high concentration of dissolved ionic matter. This high conductivity level is

probably a result of the elemental ions that enter the waterhole via erosion (after precipitation events) and rock weathering. Dissolved materials are subsequently being left behind as water evaporates. The above neutral pH reading (8.32) confirms these assumptions because it indicates the presence of cations such as calcium, magnesium and iron. The surrounding landscape has been overgrazed and is mostly composed of large boulders, large River Red Gum, and some small vegetation growing in between rock boulders.

Arkaroola Waterhole

The water hole consists of the creek aquifer where it is forced to the surface by the scoured bedrock channel of Arkaroola Creek. The channel forms a gorge along the contact between the evaporitic quartz sandstones of the Humanity Seat Formation and the sandstones and siltstones of the Woodnamoka Formation, all of Neoproterozoic age[42, 43].

This waterhole is very murky and has steep muddy edges and no vegetation or gravel immediately surrounding it. The silt sediment taken is very dark and odorous, indicating organic matter decay from the surrounding upland and riparian plant communities. Radiation measured is slightly above background. Water chemistry indicates high levels of dissolved ionic matter (1457µs) with a base pH (8.81) and cold temperature (16.3°C). The pool is only partly shaded throughout the day. Loss of water from the waterhole is evident by watermarks on large rocks adjacent to the waterhole and the soft wet mud at the edges.

Barraranna Waterhole

At Barraranna Gorge there are two waterholes about 150 m apart. The water holes occur where creek aquifers are forced to the surface by exposed scoured bedrock in a narrow gorge cut through the Neoproterozoic Humanity Seat Formation of evaporitic sandstones[42, 43].

The water in these two waterholes is visibly very different even though they are relatively close to each other and come from the same underground source. The difference in elevation is suspected to account for the differences observed in these waterholes. Because the second waterhole is at a lower elevation we believe that it is still receiving water from the source. This continual discharge from groundwater provides freshwater and accounts for the better water quality. Additionally, the lower waterhole also contains zooplankton that feed on algae. This algal-grazing by the zooplankton also explains the differences in water quality and clarity between the two waterholes. The high cliffs did not allow us to explore beyond the second pool therefore we were not able to determine if more waterholes exist further downstream.

The first waterhole at Barraranna receives sunlight throughout the morning until about mid-afternoon (around 2:00 pm). The bottom of this pool cannot be seen due to excess algal growth. The substrate sample is silt, sand, and small gravel. Water temperature is cold (11.7°C) and pH (8.77) is alkaline. A high conductivity reading (751µs) is consistent with the turbid water.

The second waterhole in the Barraranna Gorge is much clearer and cleaner than the first waterhole observed. We believe the clarity of the water was due to the zooplankton (*Daphnia*) grazing on the algae (no *Daphnia* were found in the first pool). The visible substrate is composed of silt, sand, and gravel with some attached algae. However, most of the pool bottom is bedrock. The pool is very long (about 150 m was visible) and due to the sheer rock wall we could not get to the other end of the pool. By mid-afternoon the pool is completely shaded. There is no vegetation

except for a few Yacca plants (*Xanthorrhoea quadrangulata*) growing from the benches located on the rock wall. The water quality in this pool is much better than the first pool. Water temperature (10.1°C) is slightly colder and pH (8.36) is slightly closer to neutral. The lower conductivity (491µs) is consistent with the colder, clearer water.

Black Spring

Black Spring is a very small (1 x 2 m) and shallow (16-20 cm deep) spring that is shaded most of the day by the surrounding River Red Gum and wattle trees (*Acacia* ssp.). The spring occurs in the bed of a small creek that has eroded into relict Pleistocene gravel fans, which are a common feature of this part of the Flinders Ranges[44]. The gravels have been cemented by carbonate which in the vicinity of the spring has a highly porous texture suggestive of tufa. The spring is located close to the range front and is probably localized by bedrock reverse faults associated with the rising range front[45]. Radioactivity in the area is slightly above background level. The substrate is composed of organic matter, sand and small angular gravel. Water measurements indicate cold water (13.7°C), neutral pH (7.1), and relatively high conductivity (1342 µs), indicative of the carbonate.

Bolla Bollana Spring

This spring is an outcropping creek aquifer in bed of Arkaroola Creek where it cuts through the sandstones and minor dolostones of the Neoproterozoic Wortupa Quartzite[42, 43]. Bolla Bollana is a very murky spring and the turbidity observed is possibly due to algal growth; however, algae counts were not conducted. The bottom of this pool is not visible but a sample retrieved contains sand and gravel material. It appears that the pool is shaded throughout the morning by the surrounding rock cliffs. This waterhole is about 4-5 kilometers from Arkaroola Village and is probably more heavily impacted by human intrusion than some of the more remote waterholes. Even though the waterhole receives sunlight part of the day the water temperature is 8.4°C, colder than all the other sites. Like Nooldoonooldoona Waterhole, it sits on the bed of Arkaroola Creek and contains very high conductivity levels (5060µs) and pH is basic at 8.67. These readings indicate a very high presence of dissolved ionic matter. Although the waterhole substrate is composed of sand and small gravel it sits on a large bedrock outcrop. The high conductivity reading may be due to the chemical weathering of the dolomite present and erosion during precipitation events. Receding water level, due to evaporation, is evident by watermarks on the outcropping creek bed. The plant community is dominated by River Red gum and, upland, Cypress Pine.

Echo Camp Waterhole

Echo Camp water hole is an outcropping aquifer of Arkaroola Creek exposed in channel scours in a gorge. The gorge follows the contact between the granite porphyries of the Mesoproterozoic Mount Neil Granite and the Neoproterozoic sandstones of the Humanity Seat Formation[43, 46].

This waterhole is very turbid; the bottom was not visible due to algae growth. The edges of the pool are very wet and soft indicating a rapidly receding water level. Sediment samples are composed of sand, organic debris, and gravel about 3-5 cm in diameter. The area appears to be heavily disturbed by wildlife and human intrusion. Compared to the other waterholes sitting in the Arkaroola Creek bed, conductivity is much lower (860µs) and pH is neutral. Water temperature (15.5°C), however, is very similar to the other waterholes.

Munyallina Spring

This spring is formed from an outcropping creek aquifer in gravel bed of Munyallina Creek where it is forced to the surface by the constriction of a narrow valley cut through tillites of the Neoproterozoic Bolla Bollana Formation[42, 46].

This spring consists of a series of very small pools. Pools are very shallow and contain sand and gravel-substrate, about 2-4 cm in diameter. Presence of cows and kangaroos is very evident (odor, tracks, droppings and sightings). These small pools contain cold (12.6° C) water with a pH (7.57) slightly above neutral. Conductivity levels (3071µs) are very high as expected because surrounding soils contain a saline crust left behind after higher water levels have receded due to infiltration and evaporation.

Nepouie Spring

Nepouie spring emerges from karst-enlarged fractures in the Balcanoona Limestone. This formation consists of oolitic and stromatolitic limestone of Neoproterozoic age[43]. No evidence of faulting is evident. The spring waters mix with outcropping shallow aquifers of Nepouie Creek where they are forced to the surface by the constriction of the gorge.

Nepouie Spring is situated in a notch cut through uplifted ancient bedrock that includes Nepouie Peak. The spring waters mix with outcropping shallow aquifers of Nepouie Creek where they are forced to the surface by the constriction of the gorge. These two different sources of water produce two different waterholes with differing water characteristics.

The first (Nepouie Creek) waterhole contains cold water (14.5°C) containing large algal mats and substrate composed of sand and gravel. Conductivity and pH measure 2265µs and 8.03, respectively. These readings are indicative of high concentrations of dissolved matter and a limestone bedrock.

Water from Nepouie Creek Waterhole flows and mixes with Nepouie Spring. The water temperature of 28.6°C (at the ground source) suggests the water discharges from much deeper within the Earth than the first pool. These water sources create a flowing stream. Most small pools within the flowing stream have small fish and therefore it is believed to be a perennial stream.

Nooldoonooldoona Waterhole

This waterhole occurs in deep plunge pools scoured into the bed of Arkaroola Creek where it cuts a gorge through the granitic porphyries of the Mesoproterozoic Mount Neil Granite[42, 46]. The waterhole is partly residual surface water and partly fed by the stream aquifer forced to the surface by the bedrock.

The Nooldoonooldoona Waterhole site is composed of three successive waterholes within a 400 m reach. High cliffs dotted with Cypress Pine (*Callitris glaucophylla*) surround all three waterholes. River Red gum dominates the riparian areas. The upper two waterholes are shallow (about 0.5 m) and are mostly covered with mats of algae. The third waterhole is deeper (about 1.5 m), does not have any algal mats and contains relatively clear water. Substrate is composed of angular gravel about 3-5 cm in diameter. Temperature (12.5°C) at this site is very cold possibly because it is shaded most of the day, the water depth (~1.5 m), and the source of water. Conductivity (2818µs) and pH (8.41) are indicative of high ionic content.

Old Paralana Homestead Spring

The spring is located in a channel island within the bed of a tributary of Paralana or Hot Springs Creek. The creek has cut down through the carbonate-cemented Pleistocene gravel fans[44] and into underlying weathered granite, probably the Mount Neil Granite[42] of the old pediment. Reasons for the spring location are uncertain, but may be controlled by basement faults[45]. The pool is higher than the creek bed, suggesting low levels of artesian pressure.

The artesian spring is surrounded by imported date palms (*Phoenix dactylifera*), which once served as both markers of civilization and as a food source for the homestead occupants. The entire area has radiation levels slightly above background. The water being forced out of the ground is not contained by a depression but rather it flows for about two meters before infiltrating back into the ground. Water measurements indicate a cold-water (17.6°C) spring with high conductivity (2112µs) and slightly above neutral (7.47) pH. Even though temperature at this site is slightly warmer than Black Spring, it is suspected that the same underground source is providing water for both springs. These sites are north south of each other and are only several kilometers apart. Elevation at Black Spring (165 m) is slightly higher than Old Paralana (159 m).

Paralana Hot Springs

The spring discharges up through the bed of Paralana or Hot Springs Creek at the down stream end of a gorge cut through fractured and altered Mesoproterozoic Terrapinna Granite[42, 46]. The spring position is likely to be controlled by active range front reverse faults[11, 45].

Paralana is a radioactive hot spring with radiation levels approximately three times above background levels and water temperature of about 56.5°C. This hot spring consists of two small pools that form a small stream of running water. Both pools contain large floating algal mats and epibenthic algae. The flowing water forms a narrow stream and stretches for a variable distance (over at least four kilometers). Water temperature at 0.5 kilometer from the source of the spring decreases to 14.7°C and radiation levels are undetectable. This stream winds through a thick stand of Red River Gums, White Tea-tree (*Melaleuca glomerata*) and other vegetation favoring wetland habitat. The area does not appear to be overgrazed nor perturbed by livestock. However, there are signs of tourists and wildlife activity.

DISCUSSION

Current and future landed missions to Mars are targeted on sites with a high probability of past and/or present water based on available data and modeling efforts. For example, both Mars Exploration Rover (MER) landing sites were believed to have once harbored significant quantities of surface water. The TES instrument detected crystalline hematite (α-Fe_2O_3) in the Meridiani region which provided mineralogic evidence for probable large-scale water interactions[47]. The subsequent analysis of the region by the landed rover Opportunity confirmed this hypothesis[1]. Likewise, Gusev Crater was selected as a landing site for the rover Spirit in large part due to the hypothesis that Gusev was once a crater lake filled with liquid water in the past and may still harbor clues about the nature and behavior of liquid water on Mars[48, 49]. Opportunity quickly found several lines of evidence supporting the hypothesis of near-surface water on Mars at Meridiani[1] whereas the results from Spirit have proven more elusive in terms of detecting evidence of liquid water[2]. To better understand these surprising results, terrestrial analog research in similar settings on Earth (such as Arkaroola) are needed to provide a better baseline understanding of how to in-

terpret orbital data and the implications for ground-truthing studies. Such work was begun during Expedition II and should continue through future expeditions to the Arkaroola region. For example, hydrous minerals have been identified via remote sensing data in the Arkaroola region and ground truthing investigations have been critical for deciphering the geologic and hydrologic history of the region as described in this paper. Therefore the study of several regions identified via remote sensing as likely candidates for water activity can also be studied from the ground and these datasets can then be critically evaluated to determine which remote sensing clues are most valuable in selecting sites for landed investigations. Such knowledge is necessary for future site selection for landed Mars missions.

Table 2
GEOGRAPHIC INFORMATION

Site	Geographic Coordinates	Elevation
Arkaroola Springs	54 J 0349869 6644509 (WGS 84)	131 m
Arkaroola Waterhole	54 J 0339727 6648738 (WGS 84)	309 m
Barraranna Waterhole (1)	54 J 0345690 6647766 (WGS 84)	202 m
Barraranna Gorge (2)	54 J 0345617 6647700 (WGS 84)	230 m
Black Spring	54 J 0350344 6657575 (WGS 84)	165 m
Bolla Bollana Spring	54 J 0334852 6647920 (NAD 27)	429 m
Echo Camp Waterhole	54 J 034028 6649835 (WGS 84)	262 m
Munyallina Spring	54 J 0344868 6630546 (WGS 84)	130 m
Nepouie Spring (cold pool)	54 J 0342418 6627953 (WGS 84)	134 m
Nooldoonooldoona Waterhole	54 J 0335297 6649749 (WGS 84)	369 m
Old Paralana Homestead Spring	54 J 0351371 6657701 (WGS 84)	159 m
Paralana Hot Springs	54 J 0349937 6660787 (WGS 84)	218 m

Mars analog field work in regions such as Arkaroola also yield important insights regarding issues of mission mobility. Before humans are sent to Mars there will likely be a Mars Sample Return (MSR) mission to assess potential toxicology of the Martian soil to humans, to better understand the nature of the Martian regolith and dust for engineering mitigation against corrosion, abrasion, cohesion, etc. on mission surfaces, and to assess the potential for back contamination in terms of planetary protection. Given these objectives then likely a landed mission which collects a sample from any location on Mars will be sufficient. This is only true assuming that the surface materials around Mars are homogenous due to planetary-scale mixing from atmospheric winds and/or other geologic processes. However, if the MSR mission has a significant science component related to the search for evidence of liquid water on the Martian surface at some point in Mars' past, then mobility of the lander to allow for site analysis and ultimate site selection for the sample collection is required. For example, if the Opportunity rover were immobile we would not

be able to analyze in adequate detail even the nearby cliffs of Eagle crater where the rover initially landed. Likewise, the Spirit rover is uncovering more tantalizing evidence of past water activity only after roving on the Martian surface and examining numerous different sites. The science return of the MER mission would be greatly diminished in the absence of the ability to move around the planetary surface. We have come to similar conclusions regarding mobility during our studies in the Arkaroola region. As shown in Table 2, different outcroppings of water activity have been found at different distances from our initial home base in Arkaroola within a 40 km radius. The ability to move and examine these various sites has greatly increased our knowledge about the hydrologic history of this region. If we had been restricted to Arkaroola itself and did not have the ability to traverse and explore the land we would not have a complete view of the area. Even pedestrian astronaut EVAs only provide limited range and the use of a rover capable of transporting both humans and equipment to various field sites is highly desirable for increased science return. Therefore we are learning through both missions to Mars and analog missions on Earth that scientific investigations to understand the geology and hydrology of an area typically require substantial mobility capabilities. Such knowledge is critical for future mission planning activities.

Table 3
WATER CHEMISTRY DATA

Site	Date Sampled	Temp. °C *	Conductivity µs	pH
Arkaroola Springs	11 Aug 2004	12.1	2101	8.32
Arkaroola Waterhole	18 Aug 2004	16.3	1457	8.81
Barraranna Gorge (1)	19 Aug 2004	11.7	751	8.77
Barraranna Gorge (2)	19 Aug 2004	10.1	491	8.36
Black Spring	16 Aug 2004	13.7	1342	7.1
Bolla Bollana Spring	18 Aug 2004	8.4	5.06 ms	8.67
Echo Camp Waterhole	18 Aug 2004	15.5	860	8.12
Munyallina Spring	13 Aug 2004	12.6	3071	7.57
Nepouie Spring (cold)	14 Aug 2004	14.5	2265	8.03
Nepouie Spring (hot)	14 Aug 2004	28.6	2149	7.21
Nooldoonooldoona Waterhole	12 Aug 2004	12.5	2818	8.41
Old Paralana Homestead Spring	16 Aug 2004	17.6	2112	7.47
Paralana Hot Springs	10-11 Aug 2004	56.5	1991	6.81

* Pool temperatures were taken at different times during the day and no corrections have been made for diurnal variations or variations in environment (such as shading, weather conditions, etc.).

There are several issues driving this need for mobility in terms of science return including accessibility, availability of water, and diversity of samples. For example, areas on cliff faces such as gully alcoves on Mars are very inaccessible and likely to have low sample diversity but are excellent targets in the search for water. Martian polar deposits may have low sample diversity but rate highly for the possible detection of water and accessibility. The Viking 1 site had low sample diversity and low water potential but was reasonably accessible. The Viking 2 site had low sample diversity but was accessible and possibly had high water potential in the near surface. The Pathfinder site had diverse geology and was accessible, but water potential was low. The balance between scientific and engineering requirements must be optimized to ensure that the best sites are targeted for landed missions. Studies in diverse regions such as Arkaroola provide a terrestrial testbed for assessing the value of different types of environments and the requirements for accessibility along with the science return and measures of sample diversity and water availability.

Related to mobility, the exploration radii measured from a possible landing site must be considered (see Clarke, J. D. A. and Willson, D, "Exploration Strategies at the Arkaroola MARS-OZ Site: Implications for Mars," (this volume)). The MERs have a fairly unimpressive mobility compared to even a pedestrian astronaut. However, even an advanced rover might only cover 10-20 km in the time available, perhaps 50 km at the most, and still would not have access to regions such as alcoves unless it carries a small cliffbot or similar robot capable of scaling steep cliff walls. Our work at Arkaroola during Expedition II has shown that a greater understanding of the hydrologic history is obtained by widening the exploration radii which provides access to various different types of springs and water holes (see Table 2). If the crew was restricted to a more limited range of mobility then our datasets (and hence our understanding of the physical systems) would be correspondingly less complete.

The Arkaroola region has also proven to be a useful Mars analog site in terms of mineralogy and improving our understanding of past and present habitable conditions for life. Granite intrusions such as the Mt Painter Inlier had not been observed on Mars until recently. Remote sensing data from the TES instrument suggests the surface of Mars is unrelentingly basaltic[50]. Hints of more differentiated siliceous volcanism have been slow to be discovered, but a small crater near Syrtis Major has shown spectral characteristics of a granite intrusion[50]. Syrtis Major is relatively dust free and it is possible more Martian "granitic" intrusions may await discovery in the future. Hydrothermal activity around these intrusions is likely to share many geological characteristics with the Arkaroola Mars Analog Region.

In particular, the basalts of the Wooltana Volcanics which now bear the hydrothermal phyllosilicate mineral chlorite, would be a good analog for Martian hydrothermally altered basalts. Basalts on Earth and Mars flow far and fast, and can flow in subsurface lava tubes, creating important niches for life. Basalt flows intersecting structural lineaments are particularly interesting targets, due to the collection of fluids and heat at structural boundaries that can be exploited by biology.

Carbonate (dolomite) rich rocks are abundant in the Mt Painter Inlier. Carbonates are yet to be detected on the Martian surface, although this could be due to limitations of our remote sensing capabilities[51]. It should be born in mind that abundant sulfates have been found on Mars, suggesting low pH water may have been present on the surface of Mars in the past[52]. Sulfates are yet to be observed in the AMAR, however their discovery would be an important further link to Martian conditions.

CONCLUSIONS

The "Follow the Water" strategy has proven effective for exploration of both Mars analog sites on Earth and the surface of Mars. Landed missions to Mars rely on information gathered from previous missions to help guide site selection and work done in terrestrial analog settings such as the AMAR (Arkaroola Mars Analog Region) are providing important information regarding science return and operational procedures for exploration. The AMAR offers a wide variety of hydrologic sites which have been investigated from both remote sensing datasets and ground-truthing measurements collected on-site during Expedition II. Appropriate site selection (in terms of accessibility, availability of water, and diversity of samples) and exploration mobility for crews with instrumentation and/or robotic rovers are critical components in maximizing the science return of a mission destined to "Follow the Water"; similar strategies are proving effective on both planets. Eventual human missions to Mars will undoubtedly benefit from testing of such protocols on Earth through analog field campaigns.

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