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SIGNIFICANCE OF REMNANT GRAVEL LAGS AS LANDSCAPE EVOLUTION INDICATORS, ARKAROOLA MARS ANALOGUE REGION GEOLOGY

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A preliminary geological and geomorphological investigation of the Arkaroola Mars Analogue Region has revealed the presence of remnant stream gravels preserved at elevation in the landscape. These gravels indicate that streams and alluvial fans flowed through the region during the early Quaternary. Neotectonic activity along the Flinders Ranges uplifted these gravels and erosion has partly stripped these sediments from the surface leaving isolated pods of stranded stream gravels. The method of mapping surface gravel composition and characteristics has proved insightful at AMAR and would be a useful technique if applied to Martian exploration.

INTRODUCTION

In order to select a suitable site for Mars analogue research in Australia the Mars Society Australia (MSA) conducted the Jantimara-1 Expedition in 2001. Arkaroola was the chosen location for an analogue research site. In 2003 the MSA conducted Expedition-2 to the Arkaroola Mars Analogue Region (AMAR) (Figure 1). Part of this mission was to determine a location for the construction of a Mars analogue research station, or Hab site (Figure 2). Factors influencing this decision included ease of accessibility, location of resources and the closeness of biological, hydrological and geological features for future study. This paper reports on preliminary geological investigations at the chosen site.

The Arkaroola and Mt. Painter regions have been a focus of many geological studies due to the discovery of mineral ores of gold, copper and uranium, as well as a complex and interesting geological history. Significant regional studies include the Copley Geological Mapsheet[1] and Bulletin 43 of the geological Survey of South Australia[2]. These works provided a strong geological basis from which to select a suitable analogue site.

Considerations taken into account from a geological perspective included the necessity for the landscape to appear Martian-like but also to conform to similar known geological characteristics. At the time of site selection the surface of Mars was believed to consist predominantly of flows of basalt and related ash and sediments [3]. Subsequent investigation by the Spirit and Oppor-

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tunity rovers have located evidence of sub-aqueous deposits and aeolian deposits and soils[4 5]. In addition the Viking Orbiter, Mars Global Surveyor, and the Mars Exploration Rover missions have returned imagery of features interpreted as showing faults and faulted zones. As Mars does not possess true continental plates or plate tectonic activity, similar structural regimes in the terrestrial environment will be found only in continental interiors. In South Australia the Flinders Ranges, within which Arkaroola is situated, represents a highly active seismic zone with faulted margins between the Ranges and the topographically lower alluvial plains that surround them [6]. This zone of intra-continental deformation therefore provides an excellent analogue for faulted Martian features.

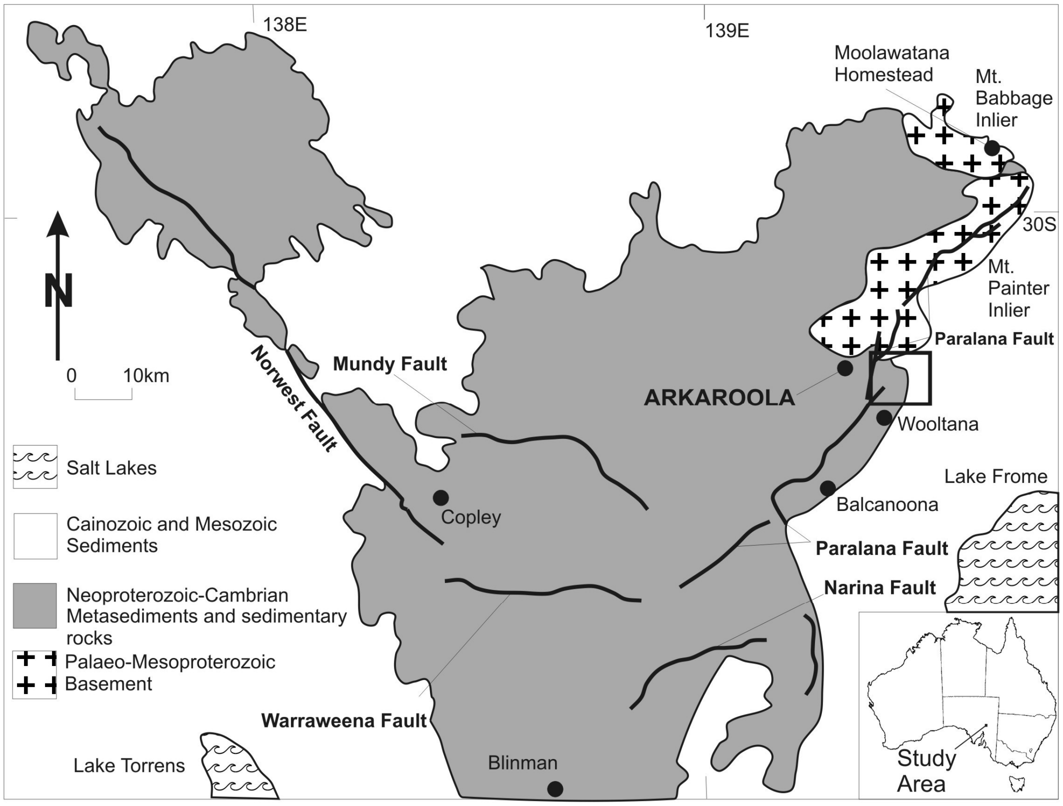

Figure 1: Location Diagram (after Paul *et al.* [7]). The rectangle indicates the location of the AMAR (Figure 2).

GEOLOGY AND STRUCTURE OF THE ARKAROOLA REGION

Extensive outcrops of Wooltana Volcanics occur within the AMAR (Figure 2). These volcanics, dated at around 830 Ma[8], are composed of grey and purple basalts that are amygdaloidal in part and contain minor rafts and lenses of rhyolite, red quartzites, tuffs and calc-silicate metasediments. Stratigraphically younger sedimentary rocks ranging in age from Proterozoic to Quaternary surround these basalts. Proterozoic sediments are located to the south and west of the Wooltana Volcanics. These consist dominantly of quartzites, tillites and conglomerates with minor shales. They become stratigraphically younger to the west. This sequence has been folded, tilted and eroded prior to the deposition of the Jurassic Parabarana Sandstone. This latter unit is composed of quartzitic kaolinitic sandstone and conglomerate. Tertiary silicification has occurred on the flanks of the Parabarana Sandstone forming discontinuous pods of silcrete. Other Tertiary deposits include white limestones, dolomites and marls that flank the ranges to the south, where they have been upturned along faults prior to the Quaternary. Later Quaternary deposits are low-level Telford Gravel consisting of rounded to subangular cobbles and pebbles with cross-bedded channel sands; high-level Pooraka Formation consisting of yellow to red-brown fine grained sand and angular cobbles and pebbles derived from Proterozoic sources in the ranges; and modern alluvial sediments of streams and alluvial plains composed of sands, gravels, clays and gypsum.

The Paralana Fault defines the eastern boundary of the northern Flinders Ranges, separating the ranges from the lowlands of the Frome Embayment to the east. The difference in elevation is approximately 700m. The Paralana Fault is a zone of sub-parallel faults, splays and offsets trending approximately northeast-southwest and extending over 150km. It has been active since the Proterozoic[9].

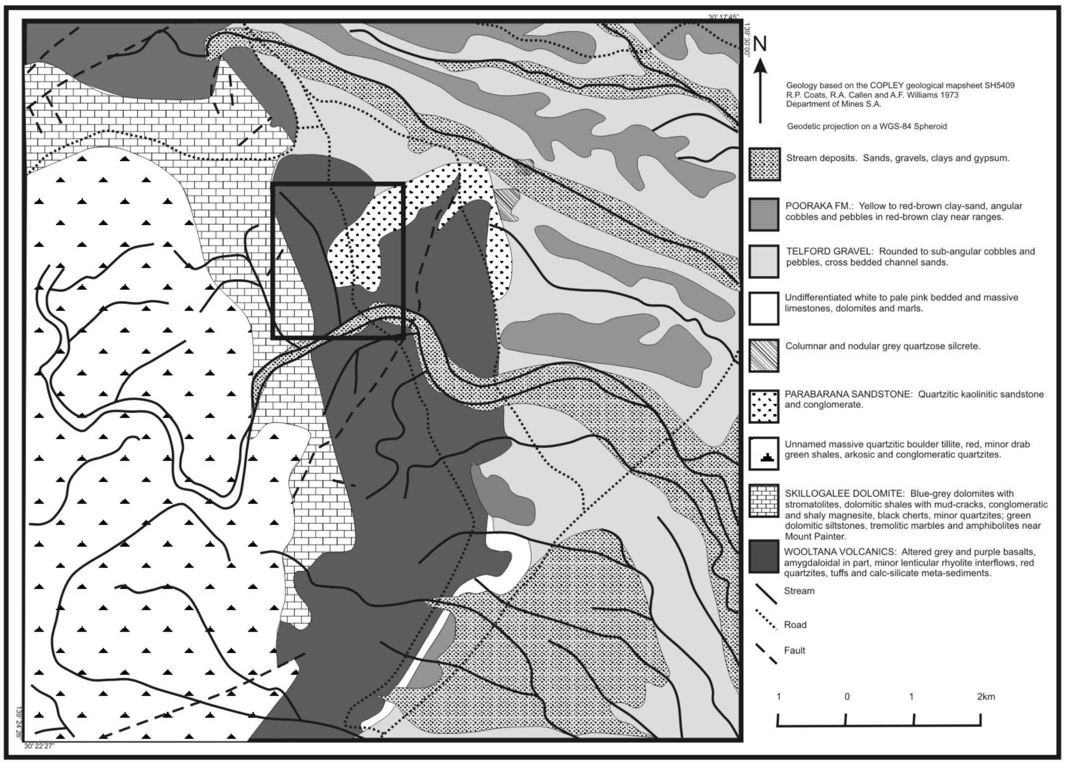

Figure 2: Geology of the AMAR in the Arkaroola Region showing the arrangement of geological units particularly the extent of the basaltic Wooltana Volcanics. The rectangle indicates the location of the AMAR Hab site (Figure 3).

GEOLOGY/GEOMORPHOLOGY RELATIONSHIPS

Although the regional geology has been characterised, to determine the landscape evolution of a region requires an interaction between the geology and the geomorphology. In this case there is a strong difference between the geomorphology of older units and that of the Quaternary units. The Proterozoic sediments and volcanics all possess high relief with deep, steep sided valleys. Tertiary deposits tend to hug the edge of the ranges and possess moderate to subdued relief. Quaternary sediments form the lowland areas surrounding the ranges and are composed of two layers the topographically higher but stratigraphically older Pooraka Formation and the lower Telford Gravel. The Telford Gravel is exposed at the base of broad valleys with the Pooraka Formation forming remnant highland mesas and plains. These sediments were deposited by alluvial fans flanking the ranges and represent different stages of tectonism. Tectonic uplift along the margins of the ranges has resulted in the deposition of the two distinct gravel units[10]. Encroaching aridity associated with climate change has subsequently caused stream incision producing the upland mesas. Modern alluvium flows down through the active drainage system within the ranges and debouches onto the lower plains forming broad alluvial fans. The region is in a semi-arid environment that receives an average annual rainfall of around 300mm/a[11]. The Arkaroola region receives the bulk of its rainfall from winter rains of the Southern Oscillatory System. Tropical depressions in the north of Australia also feed rains into the region from the northwest of the continent as troughs of low pressure, usually during summer[12]. Intense rainstorms in the ranges may occur that cause episodic flooding that flows out into the lowlands across the alluvial fans.

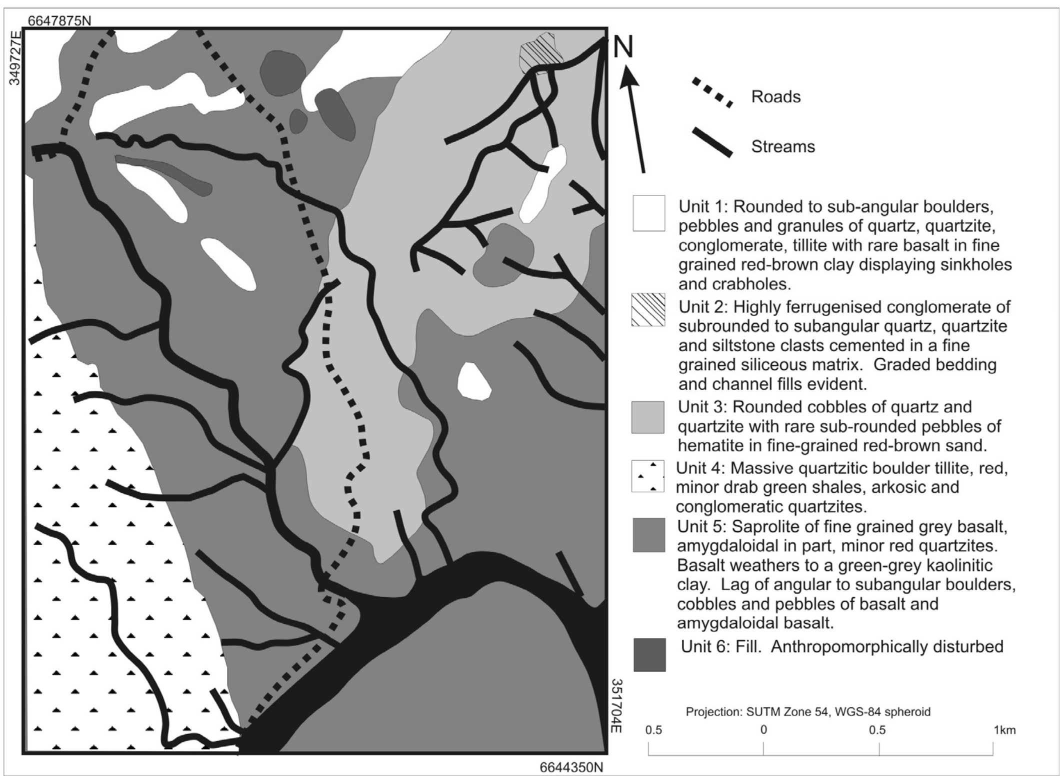

Figure 3: Surficial Geology of the AMAR Hab site showing remnant deposits of river gravels stranded at the tops of hills.

GRAVEL LAGS

Different gravel lags have been identified associated with each of the geological units (Figure 3). In the case of lags derived from Quaternary sources, these are located at significant elevation above the surrounding landscape and are interpreted as evidence of neotectonic activity and resulting erosion.

The basalts form two styles of lag depending on the degree of weathering of the parent saprock. In most cases the basalts are slightly weathered to saprock, and form angular to subangular boulders, cobbles and pebbles of basalt and amygdaloidal basalt (Unit 5: Figure 3 & Figure 4). Where the basalt is highly weathered the resulting saprolite forms a green-grey kaolinitic clay resulting in subrounded pebble lags of the parent material. These units form a distinct dark lag across the landscape (Unit 5: Figure 3).

Figure 4: Photograph of a rubbly surface exposure of Wooltana Volcanics. The size of the scale is 10cm.

Where Jurassic Parabararana Sandstone has been identified, the soil is covered by rounded cobbles of quartz and quartzite with rare subrounded pebbles of hematite in fine-grained red-brown sand (Unit 3: Figure 3). These lags outcrop along a crescent shaped ridge and are derived from the underlying conglomerate unit (Unit 4: Figure 3). Outcrops on the northern margin of this unit have been ferrugenised and silicified. The final weathered product may appear as a coarse-grained rounded cobble lag that may incorrectly be interpreted as a beach deposit. The clast roundness, however, is due to prior working within the stream system that deposited the conglomerates and not due to action along a shoreline.

Lags derived from Quaternary sediments are associated with hilltops. They are composed of rounded to subangular boulders, pebbles and granules of quartz and other lithologies present within the ranges in a fine-grained red-brown matrix (Unit 1: Figure 3 & Figure 5). They often display crab-hole and sink-hole soil structures indicating efflorescent soils commonly rich in gypsum.

The location of these lags at the tops of hills is a strong indicator that they have been topographically inverted, possibly as a result of uplift. Within the Hab site there are several flat-topped hills that display these gravels preserved on their peaks. The gravels directly overlie basalt substrate and are thin and not laterally extensive. From observation they appear also to occur at a constant elevation, however, no topographic measurements have been conducted to confirm this. If this is the case these gravels represent the preserved remnants of a much more extensive palaeosurface. Given the nature of the gravels it is likely that they were derived from debris flow and braided stream reworking of alluvial fan systems that formed on the flanks of the rangefront, most likely in the Early Pleistocene[13].

The gravels have been dissected and also truncate stratigraphically older units. This is particularly evident to the east of the Hab site. Here a patch of red-brown gravels of the Pleistocene alluvial fans (Unit 1: Figure 3) overlies the dominantly white gravels (Unit 3: Figure 3) derived from the Jurassic conglomerates (Unit 2: Figure 3). Up slope there is a change from rounded quartz gravels to polymictic gravels containing boulders of tillite and other basement lithologies.

Another patch of red-brown Pleistocene gravel is located at the top of a peak to the east of the Hab site. Polymictic gravels (Unit 1: Figure 3) grade downslope into basalts (Unit 5: Figure 3) that entirely surround this peak.

Figure 5: Photograph of a remnant stream gravel showing a wide variety of well rounded to sub-angular clasts. The size of the scale is 10cm.

LANDSCAPE EVOLUTION

Reconstructing the landscape evolution of this region is assisted by acknowledging the role played by each of these different gravels within the landscape's history. All of these lags are likely of Quaternary age, however, they are derived from different sources. It is the interpretation of the origin of these geologic sources that enables refinement of the landscape evolution model.

The interpretation of Proterozoic sedimentary environments is well-documented elsewhere and the deposition of the volcanics and sedimentary strata will only be briefly covered here. The sequence begins with the Wooltana Volcanics deposited as basaltic flows. Various quartzite and meta-sediment inclusions indicate that these lavas flowed over and draped the surrounding landscape. Deposition of the dolomite, conglomerate, tillite and sandstones of the Proterozoic sedimentary units followed this. These units were deposited in marine, glacial and fluvio-glacial environments. Four phases of folding, deformation and tilting occurred from the Cambrian through to the Ordovician resulting in the deformation of the Proterozoic sediments with movement along the Paralana Fault. Uplift since the Ordovician has resulted in the erosion of the Proterozoic sediments and the volcanics, redepositing them in nearby areas[14]. During the Jurassic deposition of fluvial conglomerates and sandstones occurred on the flanks of the ranges. Subsequent lacustrine environments in the Oligocene-Miocene deposited white limestones, dolomites and marls around the edges of the ranges prior to another phase of deformation at the end of the Miocene. This uplift raised the Jurassic sediments above the water table allowing silica-rich groundwaters to result in induration and silicification[15]. The uplift caused the alluvial fan systems to begin forming on the flanks of the ranges depositing debris flow and braided stream sediments. During the Pleistocene the onset of aridity[16] resulted in significant incision of the ranges. This incision removed large volumes of sediment throughout the ranges and resulted in the exposure of the basaltic rocks and Jurassic sediments. Subsequent re-activation of tectonism resulted in significant uplift of the ranges and the deposition of the Pooraka Formation alluvial fans.

Throughout the remainder of the Quaternary the landscape became more eroded and produced the remnant lags described here. In the case of exposed Jurassic sediments, this resulted in the reworking of fluvially rounded pebbles forming well-rounded white quartz lags.

CONCLUSIONS

The gravel lag deposits within the AMAR are a consequence of a complex landscape evolution history. This history involves deposition of mantling alluvial fan sediments that were subsequently stripped leaving only small patches of remnant lags. The mapping of different surficial lags allows a reconstruction of the landscape evolution from the geology and the geomorphology by paying particular attention to the gravel lag composition, spatial distribution and topographic elevation.

A similar methodology is likely to yield worthwhile results when applied to Martian exploration. The distribution of gravel lags may also indicate provenance given that evidence exists for a range of different rock types on Mars. If future discoveries do lead to the identification of true fluvial or fluvial-like sediments, landscape evolution reconstructions may be possible.

The expression and observation of basalt lags on Mars will be an important indicator of landscape evolution. Gravel lags should not be dismissed as a late stage product of little importance overlying the more important features of “true” basement geology.

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REFERENCES

[1] Coats, R. P., Callen, R. A., and Williams, R. F. "Copley 1:250 000 Geological Mapsheet." Geological Survey of South Australia, Department of Mines Adelaide, 1973.

[2] Blisset, A. H. and Coats, R. P. "Regional Geology and Mineral Resources of the Mount Painter Province" Geological Survey of South Australia Bulletin 43, Department of Mines Adelaide, 1973.

[3] Cattermole, P. "Mars: the story of the red planet" Chapman & Hall. London, 1992.

[4] Soderblom, L. A., Anderson, R. C., Arvidson, R. E., Bell, J. F., Cabrol, N. A., Calvin, W., Christensen, P. R., Clark, B. C., Economou, T., Ehlmann, B. L., Farrand, W. H., Fike, D., Gellert, R., Glotch, T. D., Golombek, M. P., Greeley, R., Grotzinger, J. P., Herkenhoff, K. E., Jerolmack, D. J., Johnson, J. R., Jolliff, B., Klingelhofer, G., Knoll, A. H., Learner, Z. A., Li, R., Malin, M. C., McLennan, S. M., McSween, H. Y., Ming, D. W., Morris, R. V., Rice, J. W., Richter, L., Rieder, R., Rodionov, D., Schroder, C., Seelos, F. P., Soderblom, J. M., Squyres, S. W., Sullivan, R., Watters, W. A., Weitz, C. M., Wyatt, M. B., Yen, A. and Zipfel, J. Soils of eagle crater and Meridiani Planum at the Opportunity Rover landing site. *Science* **306**(5702), 1723-1726, 2004

[5] Squyres, S. W., Grotzinger, J. P., Arvidson, R. E., Bell, J. F., Calvin, W., Christensen, P. R., Clark, B. C., Crisp, J. A., Farrand, W. H., Herkenhoff, K. E., Johnson, J. R., Klingelhofer, G., Knoll, A. H., Mclennan, S. M., Mcsween, H. Y., Morris, R. V., Rice, J. W., Rieder, R. and Soderblom, L. A. "*In situ* evidence for an ancient aqueous environment at Meridiani Planum, Mars" *Science* **306**(5702), 1709-1714. 2004.

[6] Drexel, J. F., Preiss, W. V. and Parker, A. J. "The Geology of South Australia, Volume 1, the Precambrian" Adelaide, Geological Survey of South Australia, 1993.

[7] Paul, E., Flöttmann, T., and Sandiford, M. "Structural geometry and controls on basement involved deformation in the northern Flinders Ranges, Adelaide Fold Belt, South Australia" *Australian Journal of Earth Sciences* **46**, 343-354, 1999.

[8] Drexel *et al.*, *op cit.*

[9] Celerier, J. "Neotectonics and intraplate deformation in the northern Flinders Ranges , South Australia" Honours Thesis (unpublished), School of Earth Sciences, University of Melbourne, 2002.

[10] Celerier *op cit.*

[11] Schwerdtfeger, P. and Curran, E. "Climate of the Flinders Ranges" *In* Davies, M., Twidale, C. R. and Taylor, M. J. (eds.) Natural History of the Flinders Ranges. *Occasional Publications of the Royal Society of South Australia.* Royal Society of South Australia Incorporated. Adelaide, pp. 63-75, 1996.

[12] Nanson, G. C., Callen, R. A. & Price, D. M. "Hydroclimatic interpretation of Quaternary shorelines on South Australian playas." *Palaeogeography, Palaeoclimatology, Palaeoecology* **144**, 281-305, 1998.

[13] Blair, T. C. and Mcpherson, J. G. "Alluvial Fan Processes and Forms. Geomorphology of Desert Environments" Abrahams A. D. and Parsons, A. J. (eds.) Chapman & Hall , London, pp. 354-402, 1994.

[14] Drexel, J. F. and Preiss, W. V., eds. "The Geology of South Australia. Volume 2, The Phanerozoic" *Geological Survey of South Austalia Bulletin 54*, Geological Survey of South Australia, 1995.

[15] Drexel and Preiss, *op cit.*

[16] Nanson, G. C., Price, D. M. and Short, S. A. Wetting and drying of Australia over the past 300ka. *Geology* **20**, 791-794, 1992.