AN EXTRATERRESTRIAL PERSPECTIVE ON TERRESTRIAL REGOLITH

Jonathan D. A. Clarke[1]

[1]CRC LEME, Geoscience Australia, GPO Box 378 CANBERRA ACT 2601 Australia

INTRODUCTION

Why should a conference on Australian regolith pay attention to the significance of extraterrestrial regolith? There are several reasons. First, historically regolith geology has never been tied to one planet and has received considerable developmental impetus from studying the regolith of other planets. Secondly, terrestrial regolith can provide an analogue for that found on other planets, especially Mars. This is particularly true for the Australian regolith, with its long history, which is increasingly drawing the attention of overseas planetary scientists. Lastly, extraterrestrial regolith has a number of lessons for those working in terrestrial regolith geology. This paper describes these lessons, with particular reference to the relevance of terrestrial regolith science to understanding other planets, how regolith landform mapping methodologies can be extended to extraterrestrial regolith, the application of terrestrial analogues to understanding of extraterrestrial regolith, especially on Mars, and the lessons extraterrestrial regolith has for terrestrial geoscientists.

THE SIGNIFICANCE OF REGOLITH STUDIES TO PLANETARY SCIENCE

Merill (1897) applied the term "regolith" to the surface mantle of unconsolidated material. The term languished in obscurity through the first half of the 20th century but gained currency with the development of astrogeology as space missions revealed the presence of fragmental materials mantling the surfaces of the Moon, Mars, Venus, Mercury, comets and the ice moons of the outer planets. "Regolith" was a generic term tailor-made for this material and was subsequently reapplied with increasing frequency to terrestrial situations. Regolith geology may have been conceived on earth, but was raised on the surface of the Moon and Mars before returning to its home planet (Clarke 2003). Planetary regolith is closely linked to an understanding of planetary geomorphology, a useful summary of which can be found in Greeley (1994).

Detailed understanding of planetary regolith compositions and properties is also critical to many applied areas as well. The designer of landing systems such as pads, airbags, and braking rockets needs to understand how these technologies will interact with the regolith. For example, braking jets will disturb the surface causing billowing of dust and other loose materials that may damage spacecraft. The wheels of rovers needed to be designed with reference to the bearing strength and roughness of the surfaces to be traversed, while protection of moving surfaces against regolith fines is a major challenge for operations on both the Moon and Mars. Regolith may also present a health hazard to crews when regolith fines enter the spacecraft via the airlock during surface operations (Beaty *et al.* 2005). Lastly, planetary regolith may be a source of useful resources, in particular water and oxygen, as well as construction materials. Use of *in situ* resources, including those in the regolith, is a key to minimising the mass and therefore cost of human missions to the Moon and Mars (see Lewis *et al.* (1993) for a compendium of papers on possible extraction of resources such as oxygen and solar wind volatiles from the lunar regolith, water from the subsurface of Mars, and the use of regolith materials for construction purposes).

ANALOGUE RESEARCH

Analogue research is investigation of terrestrial features that may provide analogues to extraterrestrial counterparts. In addition to comparisons, terrestrial analogues may also provide contrasts, illustrating how divergent superficially similar processes may be on other bodies in the solar system compared to those on Earth. Most analogue research has focused on comparisons between Earth and Mars, because of many similar processes that operate or are believed to have operated on the two planets as the action of both ice and liquid water, physical and chemical weathering and wind. Analogue research can also include investigation of extremophile habitats to constrain the possible locations for life elsewhere in the universe. This section will focus on analogue research that has been conducted in Australia to illustrate the scope of research that is possible and the opportunities that exist. The reader is urged to investigate the cited literature for more details of this research.

The Australian landscape has a diversity of impact craters ranging in size from the smallest 6 m diameter crater at Henbury in the NT to the Acraman astrobleme in SA which may be 90 km across, and range in age from a few thousand years (Henbury) to Mesoproterozoic (Teague Ring, WA). Target rocks vary from unconsolidated sediments (Yallallie WA) to metamorphics (Darwin Tas) and volcanics (Acraman). There is an extensive literature on impacts and astroblemes extending for more than 70 years, the two most recent and most important compendia are those of Glikson (1996) and Glikson & Haines (2005). These craters provide important insights not only into the consequences of terrestrial bombardment by asteroids and comets, but also more general clues about the impact process. In particular, they provide insight into the post-impact evolution of craters and how they are eroded, infilled, buried and exhumed. This is especially relevant to the study of crater evolution on other bodies with atmospheres, such as Mars and Venus, and those with past or present surface liquids, like Mars. Specific examples of study into Australian analogues to extraterrestrial surface processes conclude the paper.

The unusually long Quaternary basaltic flows and associated lava tubes at Undara, northern Queensland, have been used as analogues for lunar lava flows, collapse features and fills (Steven & Atkinson 1972, Atkinson 1991). Other Australian features that have been used as a lunar analogue are the Henbury crater group, formed by the low altitude breakup of a large iron meteorite. These craters are extremely youthful; one preserves a ray structure (Milton & Michel 1965). As the only reported example of a terrestrial rayed crater, the Henbury crater provided a unique opportunity to examine the nature of such features.

Because Mars has experienced the most Earth-like of environmental conditions, the greatest potential for terrestrial planetary analogues is for Mars (e.g. Thomas *et al.* 2005). Investigation of Australian Mars analogues is at a very early stage; most published research has served to draw the initial parallel with very little follow-on investigation. These studies are valuable not only for their extraterrestrial significance but because they also enable investigation of specific areas of terrestrial regolith, for example Dalhousie Springs, that might not otherwise be studied.

Proposed analogues include a range of aeolian deposits including parna (Greeley & Williams 1994) and dunes (Bishop 1999). Central Australian palaeoflood deposits were proposed as a Mars analogue by Bourke & Zimbelman (2000, 2001) and Dalhousie springs by Clarke & Stoker (2003). Acid salt lakes are a common feature of the more arid environments of southern Australia, in particular on the southern Yilgarn, Eyre Peninsula and the Wimmera region of Victoria. Acid saline lakes are, however, rare elsewhere in the world and have been proposed as an analogue for the arid evaporite deposits of Meridiani Planum. Initial research on these features has been started by Benison & Bowen (2006) and Australia is probably the best location in the world to study these lakes. The diagenetic histories of channel ironstones in the Pilbara region have also been proposed as possible Mars analogues (Heim *et al.* 2006). Also, in areas of minimum weathering, such as the Mt. Painter region and the Pilbara, hyperspectral studies of alteration associated with fossil hydrothermal systems have been carried out with the aim of developing recognition criteria for such features on Mars because of the their significance as possible habitats for past Martian life (Brown *et al.* 2005, Thomas & Walter 2002).

Lastly, in addition to their scientific value, sites that provide analogues to the Moon and Mars can serve as training and test areas for instruments and methods that may one day be use used on actual missions. Logistic constraints mean that areas that combine a diversity of analogue features are more attractive than those with one or two. One such area that has been identified is the Arkaroola region in the northern Flinders Ranges and the adjacent areas (Mann *et al.* 2004, Clarke *et al.* 2004). Research into the documenting the regolith geology to provide the background for analogue research has just begun (Waclawik & Gostin 2006).

LESSONS FOR TERRESTRIAL REGOLITH

In many respects the terrestrial environment is very different to that encountered on other bodies of the solar system. However, just as terrestrial features and processes can serve as analogues for those on the Moon, Mars and elsewhere, so understanding extraterrestrial regolith and processes may inform understanding of terrestrial features and the processes that shape them. One such example that is already well developed is the use of cosmogenic isotopes, formed by space weathering from cosmic ray bombardment, to date the terrestrial regolith (Pillans 2005). In general, the role of extraterrestrial processes in shaping the regolith is under-appreciated. This may be because few, if any, geoscientists are exposed to meteorites, impactites (glasses and breccias) and impact structures in the course of their training. There is a high likelihood that any such materials and features they encounter in the course of their careers will be overlooked.

There are more than 30 known impact structures on the Australian continent (Glikson 1996). While comparatively uncommon, impact structures are locally very important. They intensely modify the local geology and influence groundwater flow systems, sulphide mineralisation, hydrocarbon migration (Grieve 2005) and locally control local biogeography (Cockell & Lee 2002). However, few studies examine the role of impacts in Australian geology. For example, neither Whitbread (2004) nor Agnew (2005) mention that the world class Century zinc deposit occurs within the Lawn Hill impact structure (Shoemaker and Shoemaker 1996) or that the structure has extensively modified the ore body extent and distribution, and has been a prime factor in its preservation. While less than 10 craters or crater groups less than 1 km across are presently known from Australia (Bevan 1996), many more are likely to exist and are too degraded or infilled to be readily identified. Some may be confused with pits and depressions formed by other processes, such as deflation or collapse. The structural and geophysical expression of impacts may also be confused with those of diatremes and ring dykes and of domes and basins, an important consideration when using air- or space-borne imagery and geophysical surveys for reconnaissance and mapping.

A second area for consideration is that, although the amount of meteoritic material that descends on Australia is small (~78 tonnes per annum, by extrapolation from Love & Brownlee 1993), not all the material descends in the form of particulates. A proportion of the cosmic material arrives as meteorites, some of which are of nickel-iron alloy. On weathering these may be easily confused with gossans associated with magmatic ore deposits. While the probability of finding a meteorite is small, several anecdotal examples of putative gossans proving to be weathered meteorites are known to the author. Recognition of meteoritic material in both hand specimen and in lag (Tilley & Bevan 1998) could be critical in the correct assessment of geochemical sampling programs. Development of criteria for the recognition and elimination of such fragments in lag sampling would be valuable. This is especially because few, in any, geoscientists are trained to recognize meteorites in the field.

A third area where understanding of where extraterrestrial processes may assist in terrestrial regolith studies is that of stratigraphy and dating. The 790 Ka age of the Australasian tektite field provides a potential marker horizon in the study of the stratigraphy of soil topo-sequences and Quaternary sediments and can provide helpful controls when other forms of dating are absent (Pillans 2005), provided appropriate care is taken in the interpretation of their stratigraphic context. The mere presence of tektites in a deposit means that the deposit cannot be older than 790 Ka. The distribution and preservation of tektites can also shed valuable light onto rates of erosion and deposition, for example the scarcity of tektites in northwestern Australia (Fudali *et al.* 1991) may provide supporting evidence for high levels of Quaternary denudation suggested by the absence of thick weathering profiles across parts of the region.

Finally it is worth noting that impact craters are often occupied by central lakes. As a result they can provide significant palaeoenvironmental records. Significant examples in Australia are the Mid-Late Quaternary record in the Darwin crater in Tasmania (Colhoun & van der Geer 1988), and the Pliocene record in Yallalie crater, Western Australia (Dodson & Ramrath 2001). The Yallalie succession is particularly important for palaeoenvironmental reconstruction, given the paucity of detailed Pliocene palaeoenvironmental records in Australia during the critical period when the climate shifted towards a more arid regime.

CONCLUSIONS

The knowledge of extraterrestrial regolith will increase in the coming decades as the surfaces of more planets, satellites, asteroids, and comets are studied in detail. Furthermore, the amount of data being returned by missions to date greatly exceeds the numbers and ability of the existing planetary research community to process and interpret. The Mars Reconnaissance Orbiter is imaging the surface of Mars at sub-metre resolution, and new rover missions to Mars are in the planning stage. Further lunar rovers and possible new manned missions may be expected to the Moon within the next 20 years. Terrestrial applications are also important, with analogue studies providing valuable data on both terrestrial and extraterrestrial regolith and the high likelihood than there are still many impact structures at all scales waiting to be identified on the Australian continent. The sky is literally the limit for regolith studies, and Australian regolith scientists are very well placed to be at the forefront of research.

REFERENCES

AGNEW, P. D. 2005. Century Zn-Pb-Ag deposit, northwest Queensland. *In* BUTT, C. R. M., ROBERTSON, I. D. M., SCOTT, K. M., and CORNELIUS, M. (eds.). Regolith expression of Australian ore systems. CRC LEME, Perth, p.132-134.

ATKINSON, F. A. 1991. The Undara lava tube system, North Queensland, Australia; updated data and notes of mode of formation and possible lunar analogue. *Geo2*, 19(1), p.23, Sixth international symposium of vulcanospeleology.

BEATY, D.W., SNOOK, K., ALLEN, C.C., EPPLER, D., FARRELL, W.M., HELDMANN, J., METZGER, P., PEACH, L., WAGNER, S.A., AND ZEITLIN, C., (2005). An Analysis of the Precursor Measurements of Mars

Needed to Reduce the Risk of the First Human Missions to Mars. Unpublished white paper, 77 p, posted June, 2005 by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.jpl.nasa.gov/reports/index.htmlUTH.

BENISON, K. C. AND BOWEN, B. B., 2006. Acid saline lake systems give clues about past environments and the search for life on Mars. *Icarus* 183, 225–229.

BEVAN, A. W. R. 1996. Australian crater-forming meteorites. *AGSO Journal of Australian Geology and Geophysics* 6(4): 421-430.

BISHOP, M. A. 1999. Comparative geomorphology of seasonally active crescentic dunes: Nili Patera, Mars and Strzelecki Desert, Earth. Fifth International Conference on Mars Abstract #6069. *LPI Contribution* 972, Lunar and Planetary Institute, Houston.

BOURKE, M. C. AND ZIMBELMAN, J. R. (2001) The Australian paleoflood model for unconfined fluvial deposition on Mars. Proceedings of the XXXII Lunar and Planetary Science Conference.

BOURKE, M. C. AND ZIMBELMAN, J. R. (2000) Australian paleoflood systems: An analogue for Martian channel systems. Proceedings of the XXXI Lunar and Planetary Science Conference, Abstract #1393.

BROWN, A. J., WALTER, M. R., AND CUDAHY, T. J. 2005. Hyperspectral imaging spectroscopy of a Mars analogue environment at the North Pole Dome, Pilbara Craton, Western Australia. *Australian Journal of Earth Sciences* 52, 353–364.

CLARKE, J. D. A. 2003. The nature of regolith: a planetary scale perspective. *In* Advances in Regolith, Proceedings of the CRC LEME regolith symposium 2003, p74-77.

CLARKE, J. D. A., THOMAS, M., AND NORMAN, M. 2004. The Arkaroola Mars analog region, South Australia. *Abstracts of the 34P*[*thP*] *Lunar and Planetary Science Conference* Abstract #1029.

CLARKE, J. D. A. AND STOKER, C. 2003. Mound spring complexes in central Australia: an analog for Martian groundwater-fed outflow channels? Abstracts of the 34P[thP] Lunar and Planetary Science Conference, abstract #1504.

COCKELL, C. S. AND LEE, P. 2002. The biology of impact craters – a review. *Biology review* 77, 279-310.

COLHOUN, E. A. AND VAN DER GEER, G. 1988. Darwin Crater, the King and Linda valleys. *In* Colhoun, E. A. (comp.) Cainozoic vegetation of Tasmania. University of Newcastle, N.S.W., Australia, p.30-71.

DODSON, J.R. AND RAMRATH, A., 2001, An Upper Pliocene lacustrine environmental record from south-Western Australia – preliminary results: *Palaeogeography, Palaeoclimatology, Palaeoecology* 167, 309-320.

FUDALI, R. F., MILLER, A. J. AND, BEVAN, A. W. R. 1991. Australites from northern Australia. *Meteoritics* 26, 153-155.

GLIKSON, A. Y. 1996 (ed.). Australian impact structures. *AGSO Journal of Australian Geology and Geophysics* 16(4), 371-619.

GLIKSON, A. Y. AND HAINES, P. W. 2005 (eds.). Shoemaker Memorial Issue on the Australian impact record: 1997–2005 update. *Australian Journal of Earth Sciences* 52(4-5), 475-798.

GREELEY, R. 1994. Planetary landscapes. Chapman and Hall, New York, 2P[ndP] edition, 286p.

GREELEY, R. AND WILLIAMS, S. H. 1994. Dust deposits on Mars; the "Parna" analog. *Icarus* 110(1), 165-177.

GRIEVE, R. A. F. 2005. Economic natural resource deposits at terrestrial impact structures. *In* McDonald, I., Boyce, A. J., Butler, I. B,, Herrington, R. J., and Polya, D. A. (eds.). Mineral deposits and Earth evolution. *Geological Society Special Publication* 248, 1-29.

HEIM, J. A., VASCONCELOS, P. M., SHUSTER, D. L., FARLEY, K. A., AND BROADBENT, G. 2006. Dating paleochannel iron ore by (U-Th)/He analysis of supergene goethite, Hamersley Province, Australia. *Geology* 34(3), 173-176.

LEWIS, J. S., MATTHEWS, M. S., AND GUERRIERI, M. L. 1993 (eds.). Resources of near-earth space. The University of Arizona Press, Tucson, Arizona.

LOVE S. G. AND BROWNLEE D. E. (1993). A direct measurement of the terrestrial mass accretion rate of cosmic dust. *Science* 262, 550–553.

MANN, G. A., CLARKE, J. D. A. AND GOSTIN, V. 2004. Surveying the Mars Analogue Research Sites in the Central Australian Deserts, *Australian Geographical Studies* 30, 116-124.

MERRILL, G. P. 1897. A treatise on rocks, rock weathering and soils. MacMillan, New York, 411p.

MILTON, D. J. AND MICHEL, F. C. 1965. Structure of a ray crater at Henbury, Northern Territory, Australia U. S. Geological Survey Professional Paper 525-c p.c5-c11.

PILLANS, B. 2005. Geochronology of the Australian regolith. *In* Aanand, R. R. and de Broekert, P. (eds.). Regolith landscape evolution across Australia. CRC LEME, Perth, p.41-52.

SHOEMAKER, E. M. AND SHOEMAKER, C. S. 1996. The Proterozoic impact record of Australia. *In* GLIKSON, A. Y. 1996 (ed.). Australian impact structures. *AGSO Journal of Australian Geology and Geophysics* 16(4), 379-398.

STEVEN, N. S. AND ATKINSON, F. A. 1972. The Undara lava tubes, north Queensland, Australia. *In Proceedings of the International symposium on vulcanospeleology and its extraterrestrial applications* 29, 58-63.

THOMAS, M., CLARKE, J. D. A. AND PAIN, C. F. 2005. Weathering, erosion and landscape processes on Mars identified from recent rover imagery, and possible earth analogues. *Australian Journal of Earth Sciences* 52(3): 365-378.

THOMAS, M. AND WALTER, M. R. 2002. Application of Hyperspectral Infrared Analysis of Hydrothermal Alteration on Earth and Mars, *Astrobiology* 2, 335-351.

TILLEY, D. AND BEVAN, A. W. R. 1998. Prolonged weathering of iron and stony-iron meteorites. *In* TALYOR, G. and PAIN, C. (eds.) Proceedings of Regolith 98: new approaches to an old continent. CRC LEME, Perth, p.77-88.

WACLAWIK, V. AND GOSTIN, V. 2006. Significance of remnant gravel lags as landscape evolution indicators, Arkaroola Mars analogue region geology. *In* CLARKE, J. D. A. (ed.) Mars analogue research. *American Astronautical Society Science and Technology Series* 111, 107-114.

WHITBREAD, M. A. I. 2004. Lithogeochemical alteration around the Century and Elura Zn-Pb-Ag deposits: detecting alteration expressions in deep and near surface environments. Unpublished PhD thesis, University of Canberra.

Acknowledgements: Brad Pillans, Duncan Steel, Ross Taylor, and Matilda Thomas supplied useful advice. I also would thank the editorial panel for the invitation to contribute a paper on this topic to the conference. This paper is published with the permission of the CEO's of CRC LEME and Geoscience Australia.