EXPLORING THE BASALTIC LAVA FLOWS OF OCEANUS PROCELLARUM: VALUABLE (NON-POLAR) LUNAR SCIENCE FACILITATED BY A RENEWED HUMAN PRESENCE ON THE MOON.

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Introduction: One of the principal scientific reasons for wanting to resume *in situ* exploration of the lunar surface is the record it contains of the early geological evolution of a rocky planet, and of early Solar System history more generally [1,2,3]. Accessing this record will be greatly enhanced by a renewed human presence on the Moon, especially if supported by an exploration architecture designed to facilitate geological field activities (of which provision for long-range mobility, e.g, in pressurized rovers, will probably be the most important element). While the current US exploration architecture is predicated on the establishment of a permanent lunar base at the south pole, here we draw attention to the potential scientific benefits of conducting field geology at non-polar locations.

The case for Oceanus Procellarum: A specific example (albeit only one of many possible examples) of how future lunar science would benefit from the speed and efficiency of human explorers in the fielwould be the study of the young basaltic lava flows in northern Oceanus Procellarum. This area consists of a patchwork of discrete lava flows with estimated individual ages ranging from about 3.5 to 1.2 Gyr. [4,5]. This is a far greater range of ages than any basalt samples collected by the Apollo missions (which occupy the narrow age range 3.8 to 3.1 Gyr). Thus, collecting samples from a number of these different lava flows, and returning them to Earth for radiometric dating, would greatly improve the calibration of the lunar cratering rate for the last three billion years (see [6] for a review of the importance of such an improved calibration). Moreover, geochemical studies of these basalts would yield information on the evolution of the lunar mantle over this same time period. Finally, as the younger lava flows are superimposed on older ones, we may expect to find layers of ancient regoliths ('palaeoregoliths') sandwiched between them, the importance of which we now consider.

Importance of palaeoregoliths: Studies of Apollo samples show that solar wind particles are efficiently implanted in the lunar regolith, which may therefore contain a record of the composition and evolution of the solar atmosphere [1,7]. Galactic cosmic ray particles may similarly be implanted, potentially leaving a record of high-energy galactic events such as nearby supernova explosions. It has also been suggested that samples of the Earth's early atmosphere may be preserved in the lunar regolith [8], as well as samples of its early crust blasted off in large meteorite impacts [9].

Clearly, this record provides a potentially very valuable window into the history of the early Solar System. However, as the present surficial regolith has been subject to comminution and overturning ("gardening") by meteorite impacts for the last three to four billion years, the record it contains will be an average over most of Solar System history, weighted towards relatively recent times. From the point of view of accessing ancient Solar System history, it will be desirable to find palaeoregoliths that were formed, and buried, billions of years ago. The lava flows of Oceanus Procellarum may provide us with just such an opportunity. The archival value of such palaeoregoliths will be enhanced by the fact that both the under- and overlying basalt layers will lend themselves to radiometric dating, thereby precisely defining the age of the material and the geological record they contain.

Palaeoregolith Formation: A regolith will form when a fresh surface is exposed to the flux of micrometeorites which constantly impinges on the lunar surface. The contemporary regolith formation rate is very low, of the order of 1mm per million years [10]. However, regolith is expected to have formed more quickly in the past, due to higher impact rates and the fact that a thickening regolith shields the underlying bedrock and thus slows its own formation. For example, the regolith at the Apollo 11 landing site is thought to have accumulated at the rate of 5 mm per million years when the underlying basalts were first emplaced at about 3.6 to 3.8 Ga [10]. Older lava flows are likely to have initially accumulated regolith at an even greater rate. As solar wind and galactic cosmic ray particles are implanted within the top few microns of exposed mineral grains, regoliths as thin as a few millimetres ought to be sufficient to retain a record of these, although thicker layers will be required to ensure survival.

A worthwhile geochemical record will only be preserved within a palaeoregolith layer if it survives the thermal consequences of burial by the initially molten overlying lava flow. In particular, solar wind-implanted ions are degassed from regolith grains if the latter are heated to a temperatures of about 700°C

[11,12]. We have recently developed a numerical solution to the one-dimensional heat conduction equation to describe the heat transfer from a hot, initially molten lava flow to the underlying particulate regolith [13]. We performed calculations for lava flow thicknesses of 1 and 10 m; the lower value is appropriate for the thinnest individual flows exposed in the wall of Hadley Rille (see, e.g. Fig. 1.22 in [14]), while many individual lava flows identified from orbit have thicknesses of the order of higher value [14]. For this range of lava flow thicknesses we found [13] that solar wind and galactic cosmic ray particles should be preserved in palaeoregoliths at depths greater than about 0.1m or 1.0m, respectively. Palaeoregoliths of the latter thickness may also be sufficient to presereve ancient terrestrial meteorites [9], which will therefore also be protected from thermal alteration by the overlying lava.

Given the regolith accumulation rates estimated for early lunar history [10], individual lava flows would have to remain exposed for between 20 and 200 Myr to accumulate regoliths in this thickness range. The ages of individual basalt flows in mapped by Hiesinger et al. [5] indicate that this is likely to have been a common occurrence, and that suitable palaeoregolith deposits likely await discovery in Oceanus Procellarum (and doubtless elsewhere, albeit not spanning such a large fraction of lunar history as in Procellarum).

Implications for the exploration architecture: In order to conduct a sufficiently detailed geological investigation of a range of discrete lava flows, and buried palaeoregolith deposits, in Oceanus Procellarum (or similar localities) the exploration architecture would have to support:

- The ability to conduct 'sortie-class' expeditions to non-polar localities far from the proposed lunar base
- Adequate provision for sample collection and return capacity (roughly estimated at several hundred kg per sortie)
- Provision for surface mobility – in the specific case of the Procellarum basalt flows mapped by [5] a range of order 250 km would permit access to a number of different units with a wide range of ages. This implies provision of a pressurized rover.
- Provision of the means to detect and sample palaeoregolith deposits. For detection, ground penetrating radar would seem to be a suitable technique (see discussion in [15]). For access, unless suitable outcrops can be found a the boundaries between flows, provision of a drilling capability (perhaps to c. 100m depths) may be required. This in turn implies provision for storage and transport of the drill cores.
- If a serious search is to be made for samples of the early Earth (i.e. terrestrial meteorites) during these traverses [9], infra-red equipment capable of identifying terrestrial materials through the spectral signatures of, e.g., hydrated minerals and/or carbonates, will be required [16].

Conclusions: Geological field work in northern Oceanus Procellarum could address the following three scientific objectives:

(1) Better calibration of the lunar cratering rate for the last 3 billion years (with clear benefits to the dating of planetary surfaces throughtout the Solar System).

(2) Better understanding of the geochemical evolution of the lunar mantle to more recent times than possible using the Apollo samples; and

(3) A search for buried palaeoregolith deposts throughout the age range 3.5 to 1.2 Gyr, which likely contain a record of the solar wind, galactic cosmic rays, and, more speculatively, samples of the Earth's atmosphere and crust, from these early times.

Taken together, this would be a very rich scientific harvest, and we recommend that the developing Exploration Architecture be developed so as to permit such geological field activities at distances remote from the proposed lunar base at the south pole.

References: [1] Spudis, P.D. (1996) *The Once and Future Moon*, Smith. Inst. Press. [2] Crawford, I.A. (2004) *Space Policy* 20, 91-97. [3] National Research Council (2006) *The Scientific Context for Exploration of the Moon*. [4] Wilhelms, D.E. (1987) *The Geologic History of the Moon*, USGS Prof. Pap. 1348. [5] Hiesinger, H., et al. (2003) *JGR*, 108, E7, 1-27. [6] Stoffler et al. (2006) *Rev. Min. & Geochem*., 60, 519-596. [7] Wieler, R., et al. (1996) *Nature*, 384, 46-49. [8] Ozima, M., et al. (2005) *Nature*, 436, 655-659. [9] Armstrong, J.C., et al. (2002) *Icarus*, 160, 183-196. [10] Horz, F., et al. (1991) in: *The Lunar Sourcebook*, eds. Heiken, G.H., et al., CUP; p. 90. [11] Haskin, L. and Warren, P. (1991) in: *The Lunar Sourcebook*, p. 447. [12] Spudis, P.D. (2003) Pers. Comm. [13] Crawford, I.A., Fagents, S.A. & Joy, K.H. (2007) *LPSC* 38, Abstract No. 1323. [14] Hiesinger, H. & Head, J.W. (2006) *Rev. Min. & Geochem*., 60, 1-81. [15] Sharpton, V.L. & Head, J.W. (1982) *JGR*, 87, 10983-10998. [16] Crawford, I.A. (2006) *Internat. J. Astrobiol.,* 5, 191-197.