ABSTRACT

The Moon is a promising science target, made a priority in recent space exploration plans. So far, polar landing sites have been preferred, but many promising scientific objectives lie elsewhere. Here we summarize the potential value of one such scientific target, northern Oceanus Procellarum, which includes basalts of a wide range of ages. Studying these would allow refinement of the lunar stratigraphy and chronology, and a better understanding of lunar mantle evolution. We consider how exploration of such areas might be achieved in the context of lunar exploration plans.

Full Moon exploration

Ian Crawford, Sarah Fagents and Katherine Joy make the case for exploring the basaltic lava flows of Oceanus Procellarum: valuable (non-polar) lunar science facilitated by a return to the Moon.

In January 2004 the US Administration announced a redirection of NASA's human space-flight activities away from Earth orbit and towards the Moon and Mars, with a manned return to the Moon possibly as early as 2018. This in turn has stimulated the development of a Global Space Exploration strategy, as other space-faring nations have begun to assess how they could contribute to, and benefit from, an expanded programme of lunar exploration (see discussion by Ball and Crawford 2006).

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 (e.g. bombardment history, interplanetary dust density and composition, solar evolution, and the near-Earth radiation environment; Spudis 1996, Crawford 2004, NRC 2006). Some of these objectives are astrobiological in nature as they will enhance our understanding of the cosmic conditions under which life first arose on Earth (Crawford 2006). While the current US exploration architecture is predicated on the establishment of a permanent lunar base at the south pole (NASA 2006), here we draw attention to the fact that many of these scientific objectives will require geological investigations at other locations on the Moon.

Oceanus Procellarum

A specific example, albeit only one of many, of an interesting target for exploration away from the poles is provided by the relatively young basaltic lava flows in northern Oceanus Procellarum (figure 1). This area consists of a patchwork of discrete lava flows with estimated individual ages ranging from about 3.5 to 1.2 Gyr (e.g. Wilhelms 1987, Hiesinger *et al.* 2003; figure 2). This is a far greater range of ages than any basalt samples collected by the Apollo and Luna missions, which occupy the narrow age range 3.8 to 3.1 Gyr, and while the currently identified basaltic lunar meteorites have a somewhat wider range of crystallization ages (3.9 to 2.4 Gyr; Korotev 2005, Fernandes et al. 2007) their provenance, and thus geological context, is currently unknown. Collecting samples from one or more of the Procellarum lava flows, and returning them to Earth for radiometric dating and geochemical analyses, would immediately yield two significant scientific benefits:

- it would greatly improve the calibration of the lunar cratering rate for the last three billion years; and
- it would yield information on the evolution of the lunar mantle to more recent times than is possible with the Apollo and Luna samples.

In addition, as the younger lava flows are superimposed on older ones, a third possibility suggests itself:

- layers of ancient regoliths ("palaeoregoliths") sandwiched between lava flows may preserve records of the early inner solar system environment not otherwise available (e.g. Spudis 1996).

We now briefly consider the scientific importance of all three of these records that are potentially preserved in the Procellarum lavas, before turning to the implications for the conduct of future lunar exploration.

The lunar cratering rate

The current calibration of the cratering rate, used to convert crater areal densities to absolute ages, is based on the Apollo and Luna sample collection, and is neither as complete, nor as reliable, as it is often made out to be (see Stöffler *et al.* 2006 for a review). Figure 3, taken from Stöffler *et al.*, shows the number of craters per square km larger than 1 km in diameter as a function of surface age as calibrated by samples returned by the Apollo and Luna missions. It will be immediately apparent that there are no points on this curve between 1000 and 3000 million years ago. Actually, the situation is even worse than is implied by figure 3, because neither of the craters Copernicus or Tycho, which are indicated as having ages of 0.8 and 0.1 Ga, respectively, have actually been directly measured. The former, in particular, is actually quite uncertain (e.g. Stöffler *et al.* 2006), and would itself be an important target for a future lunar sample return mission.

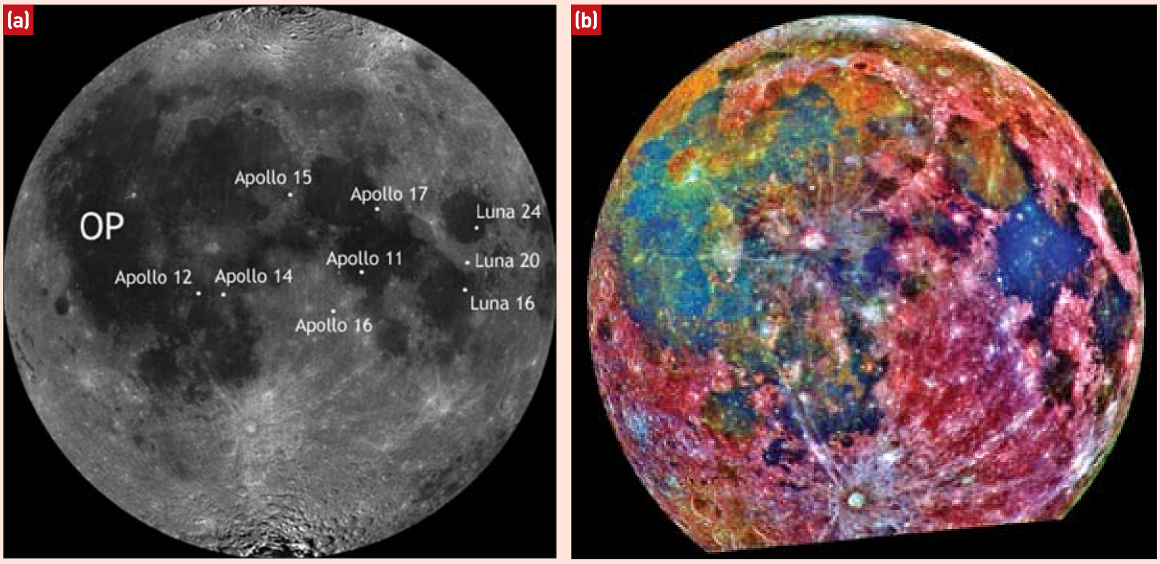
> **"The lunar cratering-rate curve is used, with assumptions, to date cratered surfaces throughout the solar system"**

It is important to realize that this uncertainty in the calibration of the lunar cratering rate for the last 3 billion years is not merely a limitation for constraining the Moon's later geological history. Of even greater significance for planetary science is the fact that the lunar cratering-rate curve is used, with assumptions, to date cratered surfaces throughout the solar system from Mercury to the icy moons of Jupiter and Saturn. Indeed, it is precisely the essentially uncalibrated part of the curve that is used to estimate dates for some of the most important dates in relatively recent ("Amazonian") martian history (e.g. Hartmann and Neukum 2001).

Radiometric dating of one or more of the relatively young Oceanus Procellarum basalt units with well-defined crater densities, such as those mapped by Hiesinger *et al.* (2003; figure 2), would place additional points in this critical part of the curve, with major benefits for the whole of solar system chronology.

Lunar mantle evolution

Basalts are derived from the partial melting of planetary mantles, and as such provide information of the geochemical and thermal evolution of planetary interiors not otherwise available. Our knowledge of lunar mantle evolution is derived mostly from geochemical and mineralogical studies of basalt and picritic glass bead samples returned by the Apollo and Luna missions



1(a): The near side of the Moon. The anorthositic highland crust has a relatively high albedo, while the basaltic lava flows are dark. Oceanus Procellarum (OP) is the large expanse of basalt near the north-western limb. Apollo and Luna sample-return landing sites are marked. (USGS) (b) In this false-colour image blue and orange areas within the maria indicate different chemical compositions. Note the diversity within Procellarum. (NASA-JPL)

(e.g. Shearer *et al.* 2006). However, as noted above, these samples all date from the period 3.1 to 3.8 Ga, which was the most active period of lunar volcanism. The youngest mare basalt samples to have been dated so far are lunar meteorites, including: LAP 02205 (2.95 Ga; Nyquist *et al.* 2005), NWA 773 (2.87 Ga; Borg *et al.* 2004) and the recently collected NEA 003 (2.38 Ga; Fernandes *et al.* 2007). However, as their provenance is (at least as yet) unknown, they lack the geological context required to usefully constrain models of lunar mantle evolution, and in any case do not extend to ages as young as are inferred for many of the Procellarum lava flows.

As discussed above, on the basis of their crater counts many of the Procellarum basalts date to much more recent times (Hiesinger *et al.* 2003; figure 2). Sampling these basalts would therefore allow us to build up a picture of lunar mantle evolution throughout the currently unsampled period extending from 2.9 Ga to perhaps as recently as 1 Ga. Among other things, this would help answer the question of whether the elevated concentrations of radioactive heat producing elements in the Procellarum KREEP Terrain (Jolliff *et al.* 2000) are responsible for magmatic activity continuing to relatively recent times in this region of the Moon (see, for example, the discussion by Wieczorek and Phillips 2000, and Rankenburg *et al.* 2007).

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 (e.g. Spudis 1996, Wieler *et al.* 1996, Levine *et al.* 2007). Galactic cosmic-ray particles may similarly be implanted, potentially leaving a record of high-energy galactic events such as nearby supernova explosions (e.g. Spudis 1996). It has also been suggested that samples of the Earth's early atmosphere may be preserved in the lunar regolith (Ozima *et al.* 2005), as well as samples of its early crust blasted off in large meteorite impacts (Armstrong *et al.* 2002).

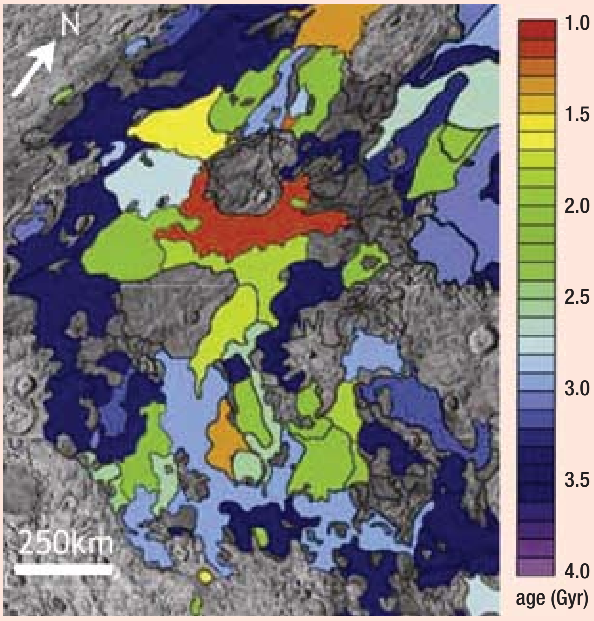
"Solar wind and galactic cosmic-ray particles should be fully preserved within palaeoregoliths at depths greater than 0.1 to 1 m"

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 (and thus protected from more recent geological processes), billions of years ago (figure 4). The lava flows of Oceanus Procellarum may provide us with just such an opportunity.

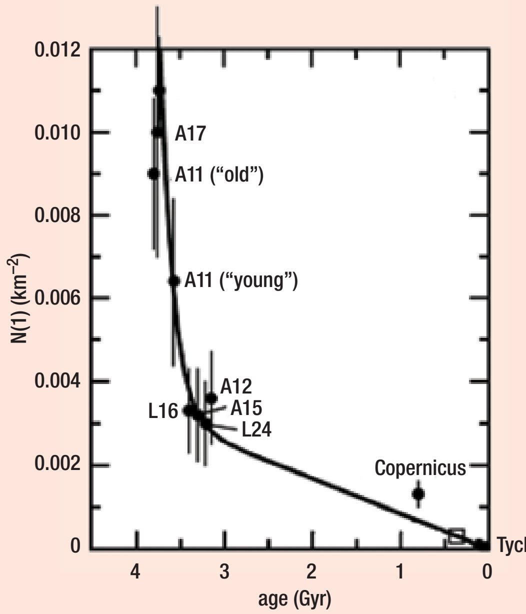
A regolith will form when a fresh surface is exposed to the flux of micrometeorites that constantly impinges on the lunar surface. The contemporary regolith formation rate is very low, of the order of 1 mm per million years (Horz *et al.* 1991). However, regolith is expected to have formed more quickly in the past, because impact rates used to be higher and because 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 (Horz *et al.* 1991). 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 overlying lava flow. In particular, solar wind-implanted ions are degassed from regolith grains if the latter are heated to temperatures of about 700 °C (Haskin and Warren 1991). 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 (Crawford *et al.* 2007, Fagents *et al.* in preparation). Figure 5 shows the results for a 1 m thick lava flow initially at a temperature of 1200 °C, in which case the 700 °C isotherm never penetrates deeper than about 7 cm into the underlying regolith. For a 10 m thick flow, comparable to the thicknesses of individual flows mapped from orbit (e.g. Hiesinger and Head 2006), the 700 °C penetration depth would be about 80 cm. However, evidence for metre-scale layering within lava flows exposed in the wall of Hadley Rille at the Apollo 15 landing site (figure 6) suggests that the thicker flows mapped from orbit are themselves likely to be built up from thinner flows. If so, as far as heating the underlying regolith is concerned, the results for the 1 m thick case may be most appropriate for these also. These results suggest that solar wind and galactic cosmic-ray particles should be fully preserved within palaeoregoliths at depths greater than 0.1 to 1 m, depending on the thickness of the overlying lava flow. Palaeoregoliths of the latter thickness may also be sufficient to preserve ancient terrestrial meteorites which will therefore also be protected from thermal alteration by the overlying lava.

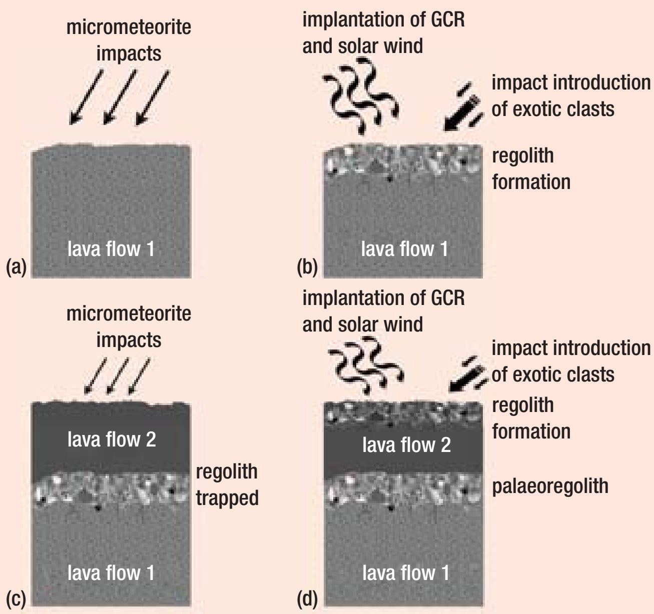
Given the regolith accumulation rates estimated for early lunar history (Horz *et al.* 1991),



2: Estimated ages of lava flows in Oceanus Procellarum (in billions of years) based on crater counts, as mapped by Hiesinger *et al.* (2003). (Image courtesy Dr H Hiesinger, ©AGU)



3: The lunar crater density (number of craters larger than 1 km in diameter per square km) as a function of surface age as calibrated by Apollo (A) and Luna (L) samples (Stöffler *et al.* 2006). Note the lack of points between 3 and 1 billion years ago; dating one or more of the Procellarum basalt flows will provide data points in this region of the curve. Note that the dates for the craters Copernicus and Tycho are also quite uncertain, as neither has been visited by a sample-return mission – as drawn here the former lies off the preferred curve by 500 million years! (Image reproduced with the kind permission of the Mineralogical Society of America. ©MSA)



4: Schematic representation of the formation of a palaeoregolith layer: (a) a new lava flow is emplaced and meteorite impacts immediately begin to develop a surficial regolith; (b) solar wind particles, galactic cosmic-ray particles and "exotic" material derived from elsewhere on the Moon (and perhaps elsewhere) are implanted; (c) the regolith layer, with its embedded historical record, is buried by a more recent lava flow, forming a palaeoregolith; (d) the process begins again on the upper surface.

individual lava flows would have to remain exposed for between 20 and 200 Myr to accumulate regoliths in the required thickness range. The ages of individual basalt flows mapped by Hiesinger *et al.* (2003) 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). 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.

Implications for exploration

Some of the above scientific objectives may be met by robotic exploration. For example, geochemical analyses of individual lava flows could be performed by *in situ* X-ray fluorescence spectroscopy using instruments like the X-ray Spectrometer (XRS) designed for Beagle 2 (Sims *et al.* 1999). However, much of the scientific interest of this area relies on dating individual lava flows, and while *in situ* methods of radiometric dating may be possible in principle, there is no doubt that the most accurate way of achieving this would be to return carefully selected samples to a terrestrial laboratory for analysis (Taylor *et al.* 2006). Sample return would also enable much more sensitive mineralogical and geochemical analyses than would be possible with robotic instruments *in situ*. For these reasons, in response to ESA's Call for Ideas for the Next Exploration Science and Technology Mission (NEXT), a lunar sample-return mission to Oceanus Procellarum has recently been proposed by a consortium led by Birkbeck College and EADS Astrium.

On the other hand, there seems little doubt that a really detailed geological investigation, and associated sampling, of a wide range of discrete lava flows in this region would be best achieved by human exploration, and the identification and sampling of buried palaeoregolith deposits would probably be infeasible otherwise (Crawford 2004). However, while these scientific benefits would be facilitated by renewed human exploration of the lunar surface, there are several implications for the exploration architecture proposed by NASA (2006). In particular, the architecture must:

- Support the ability to conduct "sortie-class" expeditions to non-polar localities far from the proposed base at the south pole.
- Provide adequate provision for sample collection and return capacity (roughly estimated at several hundred kg per sortie).
- Make provision for surface mobility – in the case of the basalt flows discussed above (figure 2) a range of order 250 km would permit access to several different units with a wide range of

"Sample return would enable much more sensitive mineralogical and geochemical analyses than with robotic instruments"

ages. This in turn would imply the provision of a pressurized rover (figure 7).
- Provide the means to detect and sample palaeoregolith deposits. For detection, ground penetrating radar would seem to be a suitable technique (see discussion by Sharpton and Head 1982). For access, provision of a drilling capability (perhaps to ~100 m depths) may be required, unless suitable outcrops can be found at the boundaries between flows.

Note that while, for all the reasons given above, we consider the scientific case for exploring Oceanus Procellarum to be extremely strong, there are without doubt other non-polar regions of the lunar surface that would also benefit from such a capability.

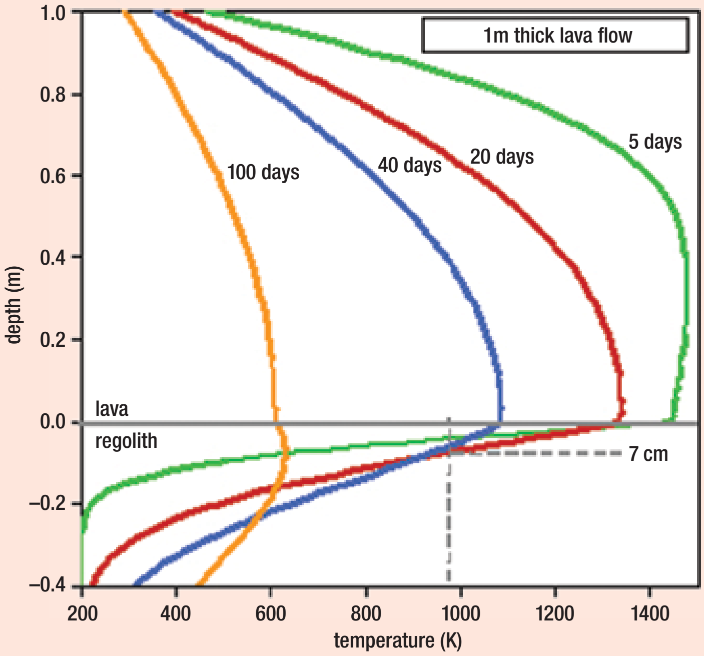
Conclusion

Geological field work in northern Oceanus Procellarum could address the following three scientific objectives:
- Better calibration of the lunar cratering rate for the last 3 billion years (with clear benefits to the dating of planetary surfaces throughout the solar system).
- Better understanding of the geochemical evolution of the lunar mantle to more recent times than possible using the Apollo samples.
- A search for buried palaeoregolith deposits 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 lunar exploration architecture be designed so as to permit such geological field activities at distances remote from the proposed lunar base at the south pole. ●

I A Crawford (i.crawford@ucl.ac.uk) and K H Joy (k.joy@ucl.ac.uk) are in the School of Earth Sciences, Birkbeck College, London, WC1E 7HX. S A Fagents (fagents@higp.hawaii.edu) is at the Hawaii Institute of Geophysics and Planetology, University of Hawaii, HI 96822, USA.

5: Temperature profiles through lava and regolith as a function of time after flow emplacement for a 1 m thick lava flow at 1473 K (1200 °C). The 973 K (700 °C) isotherm is represented by a vertical dashed line: the maximum penetration of this isotherm into the regolith is ~7 cm. (For details of the model see Crawford *et al.* 2007)



6: Discrete basaltic layers exposed in the far wall of Hadley Rille near the Apollo 15 landing site (individual layers are about 1 m thick). Palaeoregoliths sandwiched between mare lavas of different ages may preserve a unique record of conditions in the early solar system not otherwise available. (NASA)

7: A pressurized rover, having a range of several hundred km, would permit the efficient exploration and sampling of diverse geological terrains, such as the basaltic lava flows of Oceanus Procellarum shown in figure 2. (NASA)

References

Armstrong J C *et al.* 2002 *Icarus* **160** 183–196.
Ball A J and Crawford I A 2006 *A&G* **47** 4.17–4.19.
Borg L E *et al.* 2004 *Nature* **432** 209–211.
Crawford I A 2004 *Space Policy* **20** 91–97.
Crawford I A 2006 *Internat. J. Astrobiol.* **5** 191–197.
Crawford I A *et al.* 2007 *LPSC* **38** Abstract #1323.
Fernandes V A *et al.* 2007 *LPSC* **38** Abstract #1611.
Hartmann W K and Neukum G 2001 in *Chronology and Evolution of Mars* eds Kallenbach R *et al.* (Kluwer) 165–194.
Haskin L and Warren P 1991 in *The Lunar Sourcebook* eds Heiken G H *et al.* (CUP) 447.
Hiesinger H *et al.* 2003 *JGR* **108** E7 1–27.
Hiesinger H and Head J W 2006 *Rev. Min. & Geochem.* **60** 1–81.
Horz F *et al.* 1991 in *The Lunar Sourcebook* eds Heiken G H *et al.* (CUP) 90.
Jolliff B L *et al.* 2000 *JGR* **105(E2)** 4197–4216.
Korotev R L 2005 *Chemie der Erde* **65** 297–346.
Levine J *et al.* 2007 *Geochim. Cosmochim. Acta* **71** 1624–1635.
NASA 2006 *Lunar Architecture Team: Overview* available at http://www.nkau.gov.ua/pdf/NASA_Lunar_Architecture_Team_Status_December_2006.pdf.
NRC 2006 *The Scientific Context for Exploration of the Moon – Interim Report* (National Research Council, Washington D.C.).
Nyquist L E *et al.* 2005 *LPSC* **36** Abstract #1374.
Ozima M *et al.* 2005 *Nature* **436** 655–659.
Rankenburg K *et al.* 2007 *Geochim. Cosmochim. Acta* **71** 2120–2135.
Sharpton V L and Head J W 1982 *JGR* **87** 10983–10998.
Shearer C K *et al.* 2006 *Rev. Min. & Geochem.* **60** 365–518.
Sims M R *et al.* 1999 *Adv. Space Res.* **23** 1925–1928.
Spudis P D 1996 *The Once and Future Moon* (Smith. Inst. Press).
Stöffler D *et al.* 2006 *Rev. Min. & Geochem.* **60** 519–596.
Taylor S R *et al.* 2006 *Rev. Min. & Geochem.* **60** 657–704.
Wieczorek M A and Phillips R J 2000 *JGR* **105(E8)** 20417–20430.
Wieler R *et al.* 1996 *Nature* **384** 46–49.
Wilhelms D E 1987 *The Geologic History of the Moon* USGS Prof. Pap. 1348.