



estec

European Space Research
and Technology Centre
Keplerlaan 1
2201 AZ Noordwijk
The Netherlands
T +31 (0)71 565 6565
F +31 (0)71 565 6040
www.esa.int

DOCUMENT

PROSPECT User Requirements Document

Prepared by	James Carpenter, Elliot Sefton-Nash
Reference	ESA-LEX-PRO-URD-0001
Issue	2
Revision	1
Date of Issue	09/08/2018
Status	Issued
Document Type	RS - Requirement Document / Specification (System, Subsystem, Unit, Equipment level)



APPROVAL

Title PROSPECT User Requirements Document	
Issue 2	Revision 1
Author James Carpenter, Elliot Sefton-Nash	Date 8/9/2018
Approved by	Date

CHANGE LOG

Reason for change	Issue	Revision	Date
Updated based on work performed since last issue	2	0	26/09/2016
Updated based on work performed since last issue: Removed possibility of fluorine reactant. Updated max drill depth to 1.2m. Note other requirements may require further updates to reconcile with recent developments.	2	1	09/08/2018

CHANGE RECORD

Issue	Revision		
Reason for change	Date	Pages	Paragraph(s)
Updated based on work performed since last issue	26/09/2016	Whole document	
Updated based on work performed since last issue	09/08/2018	Whole document	



Table of contents:

1	INTRODUCTION	4
2	LUNAR VOLATILES: ORIGINS PROCESSES AND POTENTIAL RESOURCES	7
2.1	Cold trapped (physisorbed) water and volatiles at the lunar poles	8
2.1.1	Objectives for cold trapped (physisorbed) volatiles	15
2.1.2	Requirements for investigations into cold trapped (physisorbed) volatiles	16
2.1.2.1	Sample Requirements.....	16
2.1.2.2	Volatile extraction and measurement requirements.....	20
2.1.2.3	Isotopic analysis requirements	21
2.2	Chemisorbed and Solar wind implanted volatiles	27
2.2.1	Objectives for chemisorbed and Solar Wind implanted volatiles.....	29
2.2.2	Requirements for investigations into chemisorbed and Solar Wind implanted volatiles	30
2.2.2.1	Sample Requirements.....	30
2.2.2.2	Volatile extraction and measurement requirements.....	32
2.2.2.3	Isotopic analysis requirements	33
3	OXYGEN EXTRACTION FROM MINERALS IN REGOLITH	35
3.1	Objectives for oxygen extraction of minerals in regolith.....	37
3.2	Requirements for oxygen extraction of minerals in regolith	37
3.2.1	Sample Requirements.....	38
3.2.2	Oxygen extraction and measurement requirements	38
3.2.3	Isotopic analysis requirements	39
4	THE ORIGINS OF TERRESTRIAL VOLATILES	40
4.1	Objectives for the origins of terrestrial volatiles.....	42
4.2	Requirements for investigations into the origins of terrestrial volatiles	42
4.2.1	Sample requirements.....	42
4.2.2	Volatile extraction and measurement requirements.....	43
4.2.3	Isotopic analysis requirements	44
5	PREBIOTIC CHEMISTRY	45
5.1	Objectives for prebiotic chemistry.....	48
5.2	Requirements for investigations into prebiotic chemistry.....	48
5.2.1	Sample Requirements.....	48
5.2.2	Organic Compound extraction and measurement requirements	49
5.2.3	Isotopic analysis requirements	50
6	MEASUREMENT CONTEXT REQUIRMENTS	51
7	OPERATIONAL EXPERIENCE REQUIREMENTS	54
7.1	Objectives associated with Operational Experience	54
7.2	Requirements associated with Operational Experience.....	54
8	OUTREACH & COMMUNICATIONS USER REQUIREMENTS	56
8.1	Objectives associated with Outreach & Communications.....	56
8.2	Requirements associated with Outreach & Communications.....	56
9	SUMMARY OF REQUIREMENTS	59
9.1	Sample Requirements.....	59
9.1.1.1	Oxygen from minerals; extraction and measurement requirements	60
9.1.1.2	Volatile extraction and measurement requirements.....	60
9.1.1.3	Organic Compound extraction and measurement requirements	60
9.1.1.4	Isotopic analysis requirements	61
9.1.1.5	Measurement Context Requirements	61
9.1.1.6	Requirements associated with Operational Experience	62
9.1.1.7	Requirements Associated with Outreach & Communications.....	63
10	REFERENCES	64

1 INTRODUCTION

Establishing the utilization potential of resources found in-situ on the Moon may be key to enabling sustainable exploration in the future. PROSPECT has been defined to support the identification of potential resources, to assess the utilization potential of those resources and to provide information to help establish their broader regional and global distribution.

Volatile in this context refers to chemical compounds that are evolved from solid samples of regolith as gas at temperatures up to around 1000°C (assumed to be generated by an oven). The term “Volatiles” for the purposes of defining requirements in this document includes the following compounds: H₂, H₂O, OH, CO, CO₂, CH₃OH, Hydrocarbons from C₁-C₆, H₂S, NH₃, SO₂, COS, CS₂, HCN, CH₃CHO, C₁₀H₈(+PAH), NO_x, N₂, O₂, Kr, Xe, Ar, Ne, He, Hg. The term may also be taken to include more organic compounds including carboxylic acids and amino acids.

PROSPECT will also perform investigations into resource extraction technologies that maybe applied at larger scales in the future and provide data with important implications for fundamental scientific investigations on the Moon related to Solar System history, astrobiology and the origins of terrestrial volatiles.

The development of PROSPECT should generate a number of benefits for future exploration by:

- Preparing technologies and capabilities for future exploration missions in the area of drilling, sampling, sample handling and analysis and resource utilisation.
- Generating knowledge on surface properties, in-situ resources, surface operations and fundamental science.
- Demonstrating a key exploration end to end capability to secure long-term roles for Europe in future international exploration scenarios.
- Engaging with the public and other stakeholders and increasing their awareness and understanding of lunar exploration and its benefits.

To achieve this PROSPECT will be operated at the lunar surface in the South Polar region of the Moon, where it is required to:

- Obtain samples from depths of up to 1.2m.
- Perform thermochemical extraction of water, oxygen and other chemicals of interest from these samples.
- Identify the chemical species extracted.
- Quantify the abundances of these species.
- Characterize isotopes such that origins and emplacement processes can be established.

In the lunar polar regions PROSPECT is able to target water ice. At all locations on the Moon PROSPECT is able to extract other volatiles released from regolith by heating. These



include physisorbed, chemisorbed and solar wind implanted volatiles. Oxygen extraction from minerals shall also be performed through resource processes that have been proposed in the literature as candidate extraction processes.

Benefits following on from the operation of PROSPECT will be achieved by the Users of the data and lessons learned products that will result from its application at the lunar surface. The products are envisaged in the following domains:

- **Scientific and engineering data products** which can be analysed to generate new knowledge of the Moon, its resources and the operation of systems at the surface
- **Experience and lessons learned products** which can be used to ensure that knowledge and experience gained during the project is transferred to later missions
- **Communications products** which can be used to engage the general public and other stakeholders in the project and increase awareness and interest in lunar exploration.

This document presents the objectives for PROSPECT and the requirements associated with meeting those objectives, from a user perspective. These requirements are the high level requirements for the package, which it must meet in order to allow the generation of products that meet User expectations and allow the realisation of the envisaged benefits. These requirements flow down into the definition of system requirements and the system specification.

Below are summaries of the functions of the PROSPECT package.

Drilling and sampling: PROSPECT includes a drill that is required to provide access to the subsurface to depths of up to 1.2m. Once at the required depth a sampling tool removes small regolith samples, whilst preserving sample volatile content. Samples must then be extracted and handled whilst minimizing alteration and contamination, including losses of volatiles due to thermal effects. Samples are then transferred to ovens where they are sealed for chemical extraction.

Sample heating and chemical extraction: Samples are sealed in ovens and heated to temperatures as high as $\sim 1000^{\circ}\text{C}$. Heating in vacuum extracts ices, chemisorbed volatiles, cosmogenic volatiles and implanted solar wind. Reacting gases may also be introduced to the ovens to extract additional chemistry of interest. A number of techniques are under investigation, based on a combination of flight heritage and laboratory investigations. These include combustion with oxygen and reduction using hydrogen and methane.

Chemical composition and abundance analysis: Evolved gasses are measured to determine the chemical composition and to establish the abundance of the chemicals which are evolved. This evaluation is performed using a combination of gas pressure determination and ion trap mass spectroscopy.



Gas chemical processing: The evolved chemicals require processing in order for their isotopic characteristics to be determined. Preparations can separate chemical species for analysis based on condensation properties and convert chemical species into those which are better suited to introduction to a magnetic sector or to remove isobaric interferences. The preparation is performed in a chemical processing system through a combination of refinement and chemical conversion.

Isotopic analysis: Isotopes of the elements of interest are separated for detection using a magnetic sector and measurements are then made and compared with real time measurements of standards. Using this technique accurate analysis is achieved, allowing direct comparison with laboratory measurements on Earth.

Supporting measurements: Instrumentation is under consideration to monitor the drilling and sampling process, to support operations, to provide measurements early in the sample chain and to establish the effects of the chain on samples. Measurements emphasise monitoring operations, assessing mineralogy and investigating water content and dynamic processes occurring during the drilling and sampling. Measurements may include optical imaging, infrared spectroscopy and electrical permittivity.

2 LUNAR VOLATILES: ORIGINS PROCESSES AND POTENTIAL RESOURCES

For ESA the Moon is considered to be the next destination for human exploration, beyond Low Earth Orbit and on the way to the ultimate goal of a human missions to Mars. This emphasis on the Moon represents a realisation of the scientific and technical challenges associated with deep space exploration by humans and the need for an incremental approach to overcoming them through developing technologies, gaining operational experience and obtaining enabling scientific knowledge. Sustainable exploration of the Moon will itself require that a number of scientific questions are addressed, relating to risks posed by the lunar environment to both human crews and the systems that support them.

The Moon may also prove to be an enabler for exploration through the resources found at its surface (e.g. Anand et al., 2012). These raw materials could be used to support a sustained human presence at the lunar surface and may also be used to fuel and equip missions to more distant locations or human activities closer to home, which utilise the Moon's low escape velocity.

Water and other volatiles found at the surface of the Moon could provide a major potential resource for future exploration (e.g. Anand, 2010, Starukhina 2012)). A vital consumable for human explorers, water can also provide a source of oxygen for life support systems and hydrogen and oxygen as fuel. Other volatiles including C,H, He, N, O, P, S as well as molecular species can be applied as feedstock to various processes in life support and various other exploration supporting systems. These volatiles also have an intrinsic scientific value which is discussed in later sections.

In general volatiles at the lunar surface may be divided into several categories:

- 1) Water ice and other volatiles preserved in high latitude cold traps
- 2) Volatiles bound to the surfaces of minerals.
- 3) Indigenous lunar volatiles
- 4) Cosmogenic volatiles produced in-situ

An additional source of oxygen as a resource can be found in lunar minerals. Rocks found at the lunar surface are chemically more that 40% oxygen. Various processes have been proposed to extract this oxygen in situ from Lunar regolith. Performing such an extraction in-situ would provide a demonstration of the potential application of technologies to future exploration and provide insight into the specific challenges that will need to be considered by future systems.

2.1 Cold trapped (physisorbed) water and volatiles at the lunar poles

It has long been suggested that water might be found in permanently shadowed areas near to the lunar poles (e.g. Arnold, 1979). At these sites the Moon's low obliquity coupled with local topographic lows result in areas which are never illuminated by the Sun. The locations of these sites in the South polar region are shown in Figure 2.1. These regions are of particular interest because temperatures within them are low enough that water ice present could remain stable, on the basis of temperature alone, for periods consistent with geological timescales (Vassavada et al., 1999). Volatiles found in these locations may have been delivered to the lunar surface by impacting comets and meteorites (e.g. Zhang and Paige 2009 and 2010), most of which will have been delivered much earlier in the lunar surface's history. After delivery to the lunar surface these volatiles will tend to migrate to cold traps where, if present today, they will have remained for periods of several billion years. An additional source of these volatiles will be the solar wind, which forms water through the reduction of surface minerals through a process described in Section 2.2.

The cold traps where these volatiles are expected to accumulate are shown in Figure 2.2. Figure 2.2 A-C present the measured surface day, night, and mean surface temperatures in the South polar region as recorded from orbit by the DIVINER instrument on NASA's Lunar Reconnaissance Orbiter (LRO) (Paige et al, 2010). Consistent surface temperatures as low as 25K are recorded in permanently shaded regions, which compare with day time surface temperatures as high as 300K in illuminated regions. An additional and important implication of these measurements is presented in Figure 2.2 D, which shows the depth at which water could be "stable" for sufficiently long time periods that it could conceivably be present today. "Stability" here is defined as a loss rate of less than $1 \text{ kg m}^{-2} \text{ Ga}^{-1}$, which corresponds to a loss of 1mm from a planar sheet of ice in 1 billion years. The implication of this plot is that if water ice were buried beneath a regolith layer, in sufficient quantities and in regions outside of Permanently Shaded Regions (PSRs), but where partial illumination led to sufficiently reduced surface temperatures, then it is not inconceivable that it is still there today. This has practical implications in terms of mission access as solar illumination is present in these locations to provide power and surface temperatures are much greater than those in permanently shaded regions.

The important effect of temperature on "stability" of water ice is illustrated in Figure 2.3, which shows the sublimation rate of water ice in a vacuum as a function of temperature using the sublimation model of Andreas (2007). At the low temperatures associated with PSRs water ice losses through sublimation are low enough to be negligible on timescales relevant for any events which have taken place since the formation of the lunar topography we observe today. In partially shaded regions subsurface temperatures are much warmer and water losses through sublimation are greater by tens of orders of magnitude. "Stability" of water ice in this case is critically dependent on the diffusive barrier of the regolith under which the ice is buried (Schorghofer and Taylor, 2007). Such burial can occur via two processes. The first is burial by ejecta particles following impacts. Such events should be individual large events occurring within a sufficiently short time following water deposition as to preserve it. The second is diffusion into the sub-surface following

heating. In the latter case heated surface volatiles will tend to migrate into the subsurface until they reach a surface of sufficiently cold temperature as to become trapped. This terminal depth is expected to be at a point where the temperature is around 110 K to 120 K (Schorghofer and Taylor, 2007).

In permanently shaded regions, where sublimation rates are negligible, migration into the subsurface by heating does not occur and volatiles will be trapped at the surface. Volatiles at the surface will then be subject to space weathering effects and this will lead to losses, which could be as great as $1000 \text{ kg m}^{-2} \text{ Ga}^{-1}$. Thus it is not a given that water trapped at the surface will persist for sufficiently long as to be observable in the present day, and burial beneath a regolith layer is likely to be a requirement for survival of water deposits in all thermal environments.

The persistence of water ice in PSR's appears unlikely in the present day, however it is worth noting that permanently shaded regions have not always been so. All have at some point in the past been illuminated, or partially illuminated and have later become permanently shaded. Such a scenario may have led to a situation where water has been able to migrate into the subsurface before becoming trapped at very low temperatures. This historical variation in illumination arises because the obliquity of the Moon, and thus the relative angle of incident solar radiation, has changed over time (Siegler et al. 2011). An illustration of the permanently shaded regions as they would have existed at different lunar obliquities are shown in Figure 2.4.

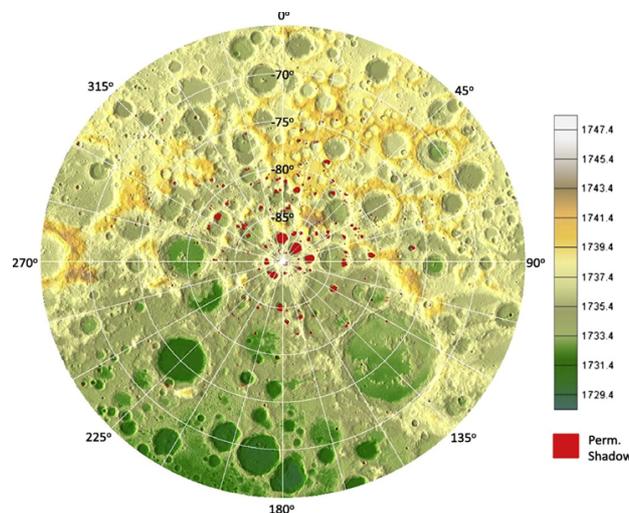


Figure 2.1. Polar stereographic shaded relief rendering of lunar South Pole topography from 65° to 90°S. Permanent shadows are denoted in red and the color scale maps color to surface radius values in kilometers. From (McGovern et al., 2013).

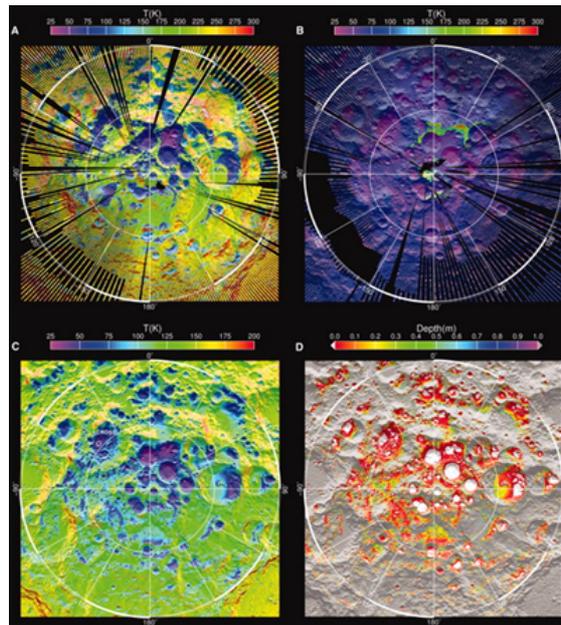


Figure 2.2. Maps of measured and model-calculated surface and subsurface temperatures in the lunar south polar region as measured by the DIVINER instrument on LRO. The outer circle on all maps is 80° south latitude. (A) Diviner-measured daytime bolometric brightness temperatures acquired between 11.4 and 13.6 hours local time (5). (B) Diviner-measured night time bolometric brightness temperatures acquired between 21.41 and 1.66 hours local time (5). (C) Model-calculated annual average near- surface temperatures and the location of the LCROSS impact in Cabeus Crater. (D) Model-calculated depths at which water ice would be lost to sublimation at a rate of less than 1 kg m⁻² per billion years. The white regions define the locations where water ice can currently be cold trapped on the surface, the coloured regions define the upper surface of the lunar ice permafrost boundary, and the grey regions define locations where subsurface temperatures are too warm to permit the cold-trapping of water ice within 1 m of the surface.

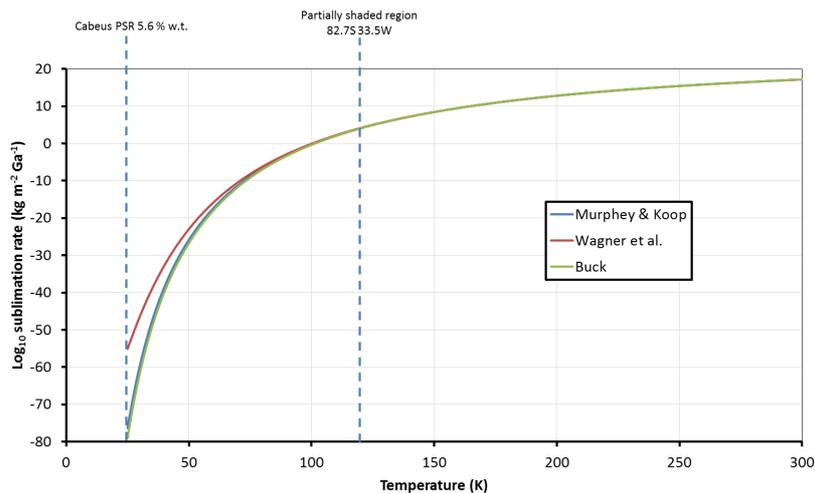


Figure 2.3. Sublimation rate from water ice in a vacuum as a function of temperature. The model used here is that of Andreas (2006) which builds on the data of Murphey and Koop (2005), Wagner et al. (1994) and Buck (1981). Note that data used to generate these curves is only intended for use to 110 K. Andreas (2006) extends on the basis of physical arguments to 40K. Extrapolation here is to 25 K.

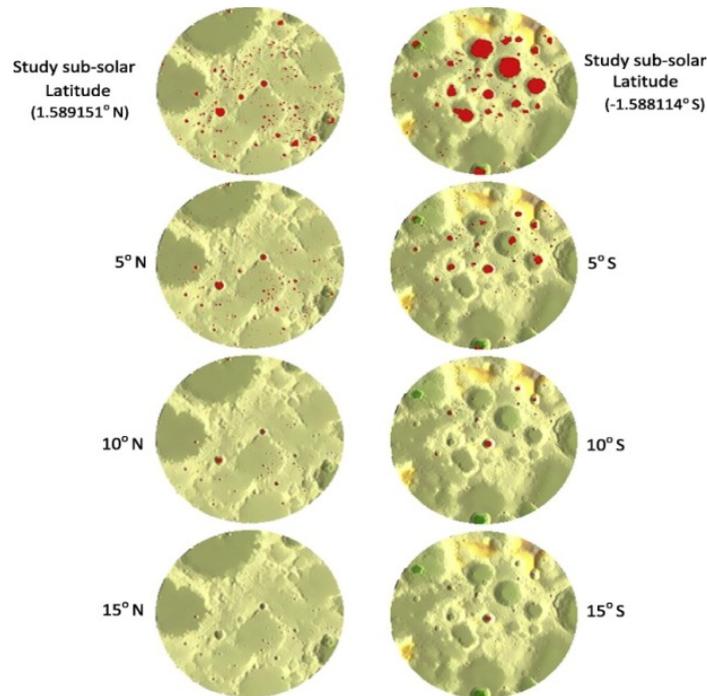


Figure 2.4. Polar stereographic maps of the North Pole from 85°N to 90° (left) and South Pole from 85°S to 90° (right). Each row shows permanent shadows analysis with the sub-solar latitude set to the labelled value.

The stability criteria of 1mm/Ga from a planar sheet of ice, which gives rise to Figure 2.2 D provides a useful indication of the likely hood of water ice persistence but may not however be physical. It may be more likely to find water ice on the external surfaces of regolith grains or in the pore spaces between grains. Figure 2.5 illustrates how water ice deposits might be incorporated into the regolith in both cases. In case water is accommodated in a similar way to that illustrated then ice thicknesses of micrometres to fractions of a millimetre might be expected. In this case a loss rate of 1mm/Ga is very significant and the details of how water might migrate and be lost within such a sample become important. Of similar importance is the present day volatile flux to the surface and the balance between the losses due to sublimation and space weathering and delivery of volatiles to the surface in the present day. In summary the distribution and abundance of water in the lunar polar regions is complex and poorly constrained on the basis of theoretical considerations.

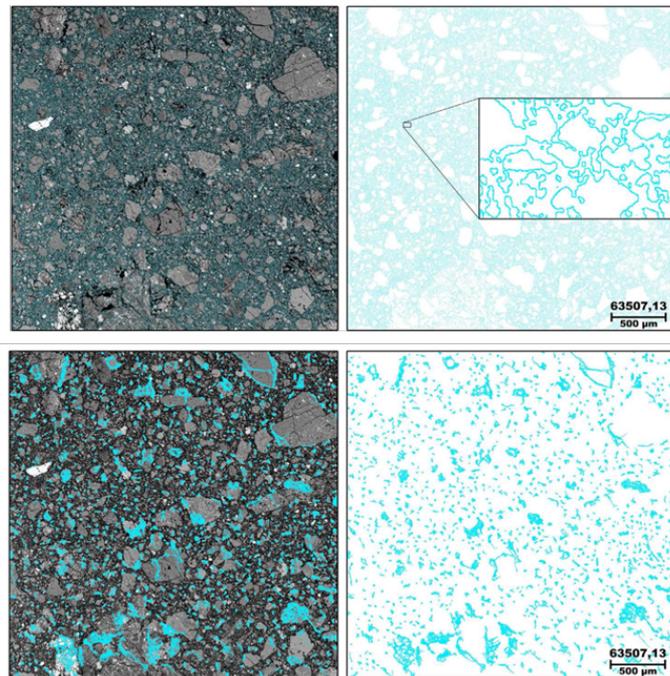


Figure 2.5. Cross section of Apollo breccia sample 63507 illustrating possible states of ice deposits on grain surfaces (top) and in pore spaces between grains (bottom). 5% w.t. water is assumed. Breccia is applied here as it closely resembles the structure of sub-surface regolith in situ on the surface (credit Fagan and Kring 2013).

In an attempt to constrain and quantify water abundance a number of measurements have been made from orbit and from Earth facilities to try and identify the presence or otherwise of water ice in the polar regions of the Moon. These measurements have been made in Radio (e.g. Stacy et al, 1997, Spudis et al., 2010; Thompson et al., 2012) using the LOLA laser altimeter on LRO (Zuber et al., 2012) and through detection of epithermal neutrons on the Lunar Prospector (e.g. Feldman et al., 1998) and LRO (e.g. Mitrofanov et al., 2010) spacecraft. Of these techniques the former two have, to date, largely yielded inconclusive results regarding the presence or otherwise of ice and have at best determined upper limits on the possible abundances of water in some craters and placed constraints on the types of water deposit that may be expected. In the case of epithermal neutrons a definitive detection of increased hydrogen has been confirmed at high lunar latitudes. It is postulated that this hydrogen exists in the form of water ice, deposited in cold traps, though a definitive measurement of water ice is not possible by this technique.

The distribution of this hydrogen remains a topic of some debate. Due to the poor surface resolution available to the Lunar Prospector Neutron Spectrometer instrument it was not possible to resolve individual PSRs or surface features. However it has been demonstrated that the data observed is consistent with a hypothesis that PSRs are the primary contributors to the observations (Elphic et al, 2007). It is also clear from this analysis that if this is the case then the abundance of water must be different in different PSRs. Table 2.1 presents the different values, predicted on the basis of LPNS data, of water equivalent hydrogen in some permanently shaded regions close to the lunar South pole. It is important to note that the absolute values calculated are strongly linked to assumptions on the depth and distribution of water deposition in these cold traps and the abundance of

hydrogen in the regolith outside of the cold traps. As such these values might best be considered as indications of the extent of variability in the hydrogen/water content of different PSRs rather than absolute amounts.

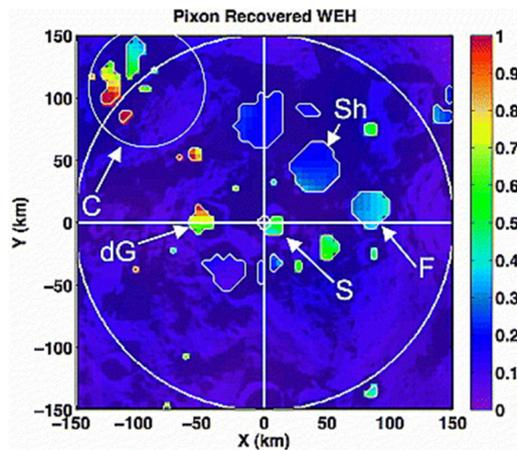


Figure 2.6. Water-equivalent hydrogen (WEH) in wt% in permanently shaded regions at the Lunar South Pole as recovered from LPNS epithermal neutron data through pixion reconstruction. Large circle denotes 85°S (from Elphic et al, 2007).

Crater	Location	Diameter (km)	Shadowed Area (km ²)	Water Equivalent Hydrogen (wt%)
Cabaeus	84.5°S, 322°E	-	900	0.7±0.16
De Gerlache	88.5°S, 273°E	22.6	300	0.72±0.24
Shackleton	89.7°S, 110°E	17.0	200	0.48±0.13
Shoemaker	88.1°S, 45°E	51.0	1175	0.23±0.05
Faustini	87.3°S, 77°E	39.0	700	0.34±0.06
Unnamed	87.5°S, 356°E	32.1	1300	0.19±0.04

Table 2.1. Water equivalent hydrogen content predicted for some permanently shaded cratered in the South polar region based on pixion reconstruction analysis of LPNS neutron data (values from Elphic et al, 2007)

More recent measurements from the Lunar Exploration Neutron Spectrometer (LEND) on LRO have added further uncertainty and complication to the question of where there could be water and how much there is. The primary difference between the LEND instrument and LPNS was the addition of a collimator, whose function was to provide a reduced field of view for the instrument and reduce the surface footprint of neutron measurements. Published analyses of the LEND data set has added complexity to the discussion. Some key findings of the LEND team are summarised as follows:

1. The inferred hydrogen concentration is not correlated with a lack of illumination
2. Hydrogen is observed in the PSRs associated with Cabeus and Shoemaker craters in the Southern hemisphere but does not appear to be related to their illumination conditions.

3. Hydrogen abundance appears to be uncorrelated in general with topography or geology (with one or two notable exceptions)
4. Hydrogen enhancements appear to be uncorrelated with the special distribution of regions where water could exist, as identified in Figure 2.2

The LEND analysis has some important and counter intuitive implications. First of all hydrogen may be concentrated in some but not all PSRs, but its presence is not correlated with illumination or temperature. It may also be concentrated in some partially shaded regions? However it is not clear what physical process could drive the hydrogen distribution that is presented. As such it is perhaps premature to assume that the hydrogen concentration map presented is due to the presence of water ice. A key measurement for future surface missions will be to verify the presence and chemistry of hydrogen at the surface on these locations.

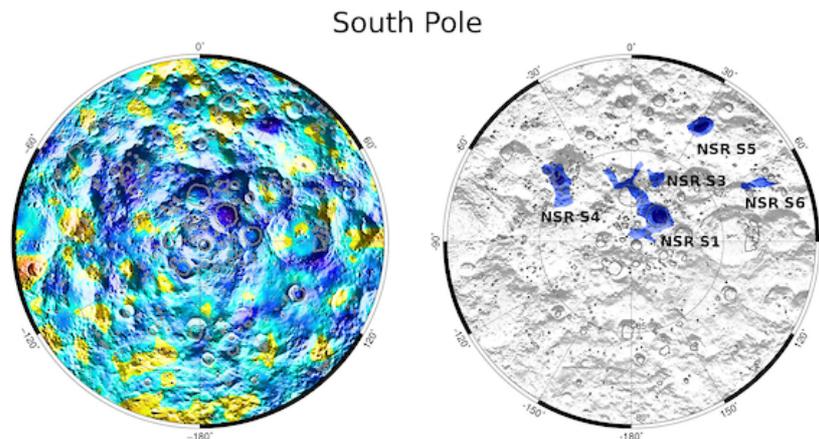


Figure 2.7. (left) Map of the south pole is presented above the latitude of 80°. (right) The map of detected local spots of NSRs is also shown, which could be associated with water-rich lunar permafrost, shown in blue. Bright blue and dark blue regions correspond to detection thresholds of -2.5% and -5.0%, respectively. Black spots and contours of the maps represent the boundaries of PSRs according to LOLA data (Mazarico et al., 2011). Figure from Mitrofanov et al. (2012).

To date only one measurement has been made of water at the lunar surface. This was made by the L-CROSS mission, which recorded infrared spectra of the plume generated as a Centaur upper stage impacted into the surface of the PSR in Cabeus. The abundance reported following this measurements was 5.6+/- 2.9 % w.t. for water. This represents an average abundance in the region affected by the impact, which is likely to have been several meters in diameter and depth. In addition a number of other compounds were reported in the plume. These are shown in Table 2.2. It is important to note that these compounds are observed following the impact and may be impact derived compounds from pre-impact precursors in the surface, whose composition may differ somewhat from that observed.

Compound	Molecules cm ⁻²	% relative to H ₂ O(g)*
H ₂ O	5.1(1.4)E19	100.0
H ₂ S	8.5(0.9)E18	16.75
NH ₃	3.1(1.5)E18	6.03

SO ₂	1.6(0.4)E18	3.19
C ₂ H ₄	1.6(1.7)E18	3.12
CO ₂	1.1(1.0)E18	2.17
CH ₃ OH	7.8(42)E17	1.55
CH ₄	3.3(3.0)E17	0.65
OH	1.7(0.4)E16	0.03

Table 2.2. Abundances (relative to H₂O) of compounds observed in the L-CROSS impact plume. From Colaprete et al. (2010).

2.1.1 Objectives for cold trapped (physisorbed) volatiles

The composition, abundance and distribution of cold trapped volatiles across the polar regions are currently very poorly constrained. These major unknowns currently precludes any assessment of their potential as resources for future exploration activities. Comprehensive measurements of samples from multiple depths at a single landing site can provide ground truth for orbital measurements and models, by indicating the vertical distribution, composition and abundance at that site. It is also important to show that these volatiles, if present, can be extracted and processed in a controlled manner.

One important limitation of measurements made at a static location, without the option of mobility, is that they may not be representative of the situation on regional, or even local scales. If distribution is variable on scales of kilometres or even meters, as is often the case for example in terrestrial sub surface ices. Given the uncertainty on the representatively of measurements made it is essential to ensure that measurements provide the maximum information possible, to allow the identification of the sources and emplacement processes of any volatiles present. This allows some extrapolation of the findings at one site to the broader region. To achieve this it is necessary to accurately measure the isotopic abundances of key volatile elements contained in any cold trapped ices identified, in a way that allows comparison with measurements in terrestrial laboratories.

Objectives for the assessment of cold trapped volatiles as potential resources are given below:

- OB-CV-001 Determine the absolute abundance of volatiles, as a function of depth, at a location where their enhancement, compared with average lunar values, is expected
- OB-CV-002 Determine to what extent hydrogen and water in the lunar polar regions is found in ices or is chemically bound to regolith grains
- OB-CV-003 Determine the volatile inventory at a location where their enhancement is expected
- OB-CV-004 Identify the sources and emplacement processes of cold trapped volatiles at a location where their presence is confirmed
- OB-CV-005 Determine the cold trapped volatile inventory at a location where their presence is expected



- OB-CV-006 Determine the absolute abundance of cold trapped volatiles, as a function of depth, at a location where their presence is expected
- OB-CV-007 Identify the sources and emplacement processes of cold trapped volatiles at a location where their presence is confirmed

2.1.2 Requirements for investigations into cold trapped (physisorbed) volatiles

2.1.2.1 Sample Requirements

- RQ-SA-010. Samples shall be extracted from sites where cold trapped volatiles are expected based on data from previous missions.

Justification: This is needed to ensure that there is a chance to collect ices, which are not expected to occur at the majority of lunar location. Locations of interest are most likely to be those identified as being compatible with water ice stability within 1 m of the surface by Paige et al. 2010 and supported by data from orbit of epithermal neutrons to indicate hydrogen enhancement.

- RQ-SA-020. Samples shall be taken from depths from the top cm of the surface up to a depth of 1m with a goal of 1.2m.

Justification: This is needed to ensure that there is a chance to collect ices. Depths at which ices can be expected might vary from tens of cm depending on the specific properties of the sites accessed. Hydrogen enhancements recorded from orbit through epithermal neutron measurements must be located within approximately 1m from the surface. The model of Paige et al. 2010 indicated water stability criteria are met at many locations within 1m – 2 m. L-CROSS results coupled with those of epithermal neutron measurements indicate a sub-surface concentration within 1m overlaid by a desiccated regolith layer.

The surface will be the most contaminated layer. Extraction of this layer will allow identification and characterisation of the contaminants.

- RQ-SA-030. Losses of ice from the sampled material from its original state to the point of analysis shall be no greater than 5%(TBC) for samples containing more than or equal to 1% (TBD) by weight water ice.

Justification: This is to ensure that the process of sampling and sample handling maintains the original ice content of the sampled material to within an uncertainty that is acceptable for determination of abundance and for determining isotopic fractionation. In the case of fractionation preliminary investigations based on basic physical principles have indicated that a 10% loss of ice through sublimation is likely to lead to a 65‰ bias in the determined δD (Savoia et al., 2014). A 5% loss introduces a bias of around 30‰. Experimental investigations into sublimation of water ice by Mortimer et al. (2016) have indicated that this effect is less pronounced but that fractionation is a complex function of



temperature, fraction sublimed and the properties of the regolith matrix from which sublimation is occurring. The requirement stated later is for an uncertainty of 100%. A minimum abundance for which it applies is provided in order to provide a baseline against which to work. Later requirements address the need to be able to identify what the losses were in order to provide some provision for this in calculated isotope values.

Comment: the loss rate of water ice from a sample is a function of the sample size and geometry, the temperature and the time taken. Expected times for losses from samples of geometry expected to be similar to that for PROSPECT are provided by Formisano et al. (2016).

Verification of this requirement should be performed against the materials specified in (reference document in preparation).

RQ-SA-040. The depths from which delivered samples are extracted shall be determined within an uncertainty of $\pm 10\text{mm}$ (TBC).

Comment: Nominally considered sufficient to allow determination of sub-surface distribution. Paige et al. 2010 and epithermal neutron measurements indicate a distribution over a 1-2 m depth. In this context a positional knowledge as given above is considered meaningful.

RQ-SA-050. It shall be possible to collect samples from depth intervals of 200 mm or less

Comment: Nominally considered sufficient to allow determination of sub-surface depth distribution. Paige et al. 2010 and epithermal neutron measurements indicate a distribution over a 1-2 m depth. In this context the ability to provide samples at intervals as given above (i.e. 200mm spacing between samples) is considered meaningful.

RQ-SA-060. Acquired samples shall be demonstrated, by tests on analogues, to be representative of original sampled material in terms of the relative proportions of fines ($5\mu\text{m} - 0.5\text{mm}$), coarse particles ($>0.5\text{mm}$) and ices.

Justification: If the sample proportions as described above are altered or biased then this may have an effect in the cold trapped volatiles in terms of both content and isotopes, depending on the way in which these volatiles are contained in the regolith.

Verification of this requirement should be performed against the regolith simulant specified in (reference document in preparation)



RQ-SA-070. Data shall be generated that allows the losses of ice and other volatiles during sample handling to be determined.

RQ-SA-071. The temperature of samples should be recorded from acquisition to delivery with an uncertainty of 0.1K (TBC) between 110K and 180K.

Justification: sublimation rate is a very strong function of temperature over the temperature range given above (e.g. Andreas, 2010). It is inevitable that some losses will occur. In order to minimise the errors that these losses introduce to isotopic analysis an estimate of the actual losses must be generated. This estimation will be done on the basis of temperature measurements. A high temperature resolution is requested in this temperature range as this is a critical range for sublimation rate at lunar pressure.

Comment: It is not possible to measure the sample temperature. Temperatures close to the samples may be measured and used to infer the actual sample temperature. This requirement could be updated to better reflect this. The precision requested here is challenging and so is considered a “should” requirement.

RQ-SA-072. The temperature of samples shall be recorded from acquisition to delivery with an uncertainty of 1K (TBC) for temperatures above 180K.

Justification: At temperatures above 180K losses of cold trapped volatiles becomes very rapid and very precise measurements are unlikely to be required. Temperature measurements are still needed for other measurement types. The requirement is included here in order to show the transition in measurement requirements.

RQ-SA-073. The mechanical environment of samples shall be determined from the acquisition to delivery

Justification. Losses may result from mechanical (shock) disturbances to the samples. Such disturbances are expected to be most likely to occur during sampling and during transfer. These disturbances may also increase the surface area available for sublimation by spreading of the sample over a larger area.

Comment: This requirement will need to be defined more specifically in terms of shocks, accelerations, packing etc.. Mechanical disturbances may be more important for chemisorbed volatiles, described later.

RQ-SA-080. The level of terrestrial contamination in measurements shall be sufficiently low as to allow measurements of samples in line with the requirements



Justification: Contamination by materials containing light elements will bias the measurements made in terms of isotopes and may introduce false measurements of some chemistry of interest.

Comment: a list of materials of concern could be added here. Limits need to be applied.

RQ-SA-090. The level of contamination from the lander, its fuel or exhaust products in measurements shall be sufficiently low as to allow measurements of samples in line with the requirements.

Justification: Contamination by chemicals containing light elements will bias the measurements made in terms of isotopes and may introduce false measurements of some chemistry of interest. Note that extraneous implies that lander induced contamination can be introduced to the chain if that is the subject of a measurement.

Comment: a list of materials of concern could be added here. Limits need to be applied. Further elaboration of this requirement and the verification approach is needed.

RQ-SA-100. The level of cross-contamination between samples shall be sufficiently low as to allow measurements which are representative of separate samples in line with the requirements.

Justification: Cross contamination between samples can lead to false results. As an extreme example 5% contamination of a water ice sample to a following sample containing no water ice would lead to an interpreted result in the later sample of 5% water content. The nominal value of 5% (TBC) is based on the established and verified requirement that has been generated for the Exomars SPDS (project internal communication)

Comment: It is expected that detailed contamination requirements and the verification approach shall be derived by the contractor such that measurement quality is assured.

RQ-SA-110. Images should be produced of samples within ovens with resolution of better than or equal to 10 μ m per pixel.

Justification: Images allow the quality and quality of the samples being measured to be accounted for. The resolution here allows inference of the size distribution of the particles in the samples. Mean size for regolith samples is typically around 70 μ m so 10 μ m per pixel is sufficient to infer particle size. Images also provide a means of identifying any non-



optimal situation regarding the samples and their ingress into the oven. Images could be recorded after deposition into the oven.

Comment: This is left as a “should” requirement as feasibility may depend on external factors and boundary conditions related to the lander configuration and PROSPECT accommodation.

2.1.2.2 Volatile extraction and measurement requirements

RQ-EM-010. Volatiles shall be extracted from lunar regolith samples by heating.

Justification: This is a controlled way to extract physisorbed volatiles and also demonstrates heating as an extraction process for ISRU.

Comment: In the case of cold trapped volatiles the temperatures required for extraction are expected to be fairly low. Temperatures above 0°C are probably sufficient. 300°C is probably a good target temperature.

RQ-EM-020. The chemical identity of chemical species with m/z between 2 and 200 shall be determined when in concentrations greater than 1ppb (TBC).

Justification: This ensures that all of the prevalent chemical species in the samples are identified. List of elements compiled from the summary of Lunar Volatile Materials from Berezhnoy et al. (2012) are all included in this mass range. The 1ppb (TBC) value reflects that some of the species are expected to be very rare in the regolith outside of permanently shaded areas and thus significantly rarer than the values presented for Cabeus crater by Berezhnoy et al. (2012).

Comment: It is recognised that to maintain this m/z range there is a possibility that for samples with m/z less than 10 sensitivity may be compromised. This requirement may be revised depending on the results of testing.

Comment: For complex molecules (e.g. organics) it is recognised that identification may not be at the level of individual species, but may be limited to suites of species type.

Comment: Verification is to be performed against a standard to be provided by ESA and derived from CV and CM chondrites (standard and reference document in preparation).

RQ-EM-030. A quantitative measure of the total volatile yield (uncertainty TBD) and the yields for individual volatiles (uncertainty TBD) shall be provided as a function of the sample mass.

Justification: The ultimate goal is to determine the concentration of those identified chemical species in % or ppm etc. Practically this is envisaged as being achieved through



the determination of the total amount extracted from a sample. Abundance is then achieved by knowing the sample mass.

Comment: Sample mass probably needs to be determined through imaging or through measurement of the gas pressure in an oven of known size after the introduction of a sample. Other methods may also be considered.

Comment: Verification for chemicals other than water ice is to be performed against a standard to be provided by ESA and derived from CV and CM chondrites (standard and reference document in preparation).

RQ-EM-040. The abundance of any precursors within the regolith to the liberated volatiles which are produced during the extraction process should be determined with an uncertainty of $\pm 50\%$ (TBD)

Justification: The chemical species which are measured post evolution from samples will have been altered from their original state in the samples. Measurements of the evolved gasses need to be sufficient to allow the inference of the original species. The error target should be derived from uncertainty requirements concerning ISRU viability. A value of $\pm 50\%$ is suggested as appropriate to future ISRU aspirations?

Comment: It is noted that determining the precursors is primarily an analytical problem rather than a system requirement and while important is challenging to assure. For this reason this remains a “should” requirement.

Verification is to be performed against a standard to be provided by ESA and derived from CV and CM chondrites (standard and reference document in preparation).

2.1.2.3 Isotopic analysis requirements

Comments: Requirements linked to the isotopic measurement of a number of species not listed here shall be added to this section.

RQ-IS-010. The isotopic composition of hydrogen in volatile species in lunar regolith samples, δD , shall be determined with an uncertainty of 100‰

Justification: To enable distinguishing primary sources of lunar hydrogen. Solar Wind is -1000 per mil; terrestrial water is -100 per mil; cometary organics +1000 per mil. The given uncertainty should allow identification of the source and allow investigation in to the fractionation and systematics of the processing that has taken place during emplacement and processing. See for example δD values for different solar system objects presented by Saal et al. (2013) and Robert (2006).

Comment: Verification is to be performed against a standard to be provided by ESA and derived from CV and CM chondrites (standard and reference document in preparation).

RQ-IS-020. As a goal the isotopic composition of carbon in volatile species in lunar regolith samples, $\delta^{13}\text{C}$, should be determined with an uncertainty of 1‰.

Justification: As ^{13}C is cosmogenic the $^{13}\text{C}/^{12}\text{C}$ ratio can provide an idea of the exposure age of the carbon in the sample or its origins (ten Kate et al, 2010; Sephton and Botta, 2005) (. Carbon isotope fractionation and measurements in the Solar System are discussed by Woods et al. (2009) and Woods (2009).

Comment: In order to achieve this it is expected that the system will need to enable combustion of samples to extract carbon for analysis and achieve oven temperatures consistent with this. This is not considered a requirement within this document but is highlighted as a likely requirement to be carried at system level to achieve the User Requirement above.

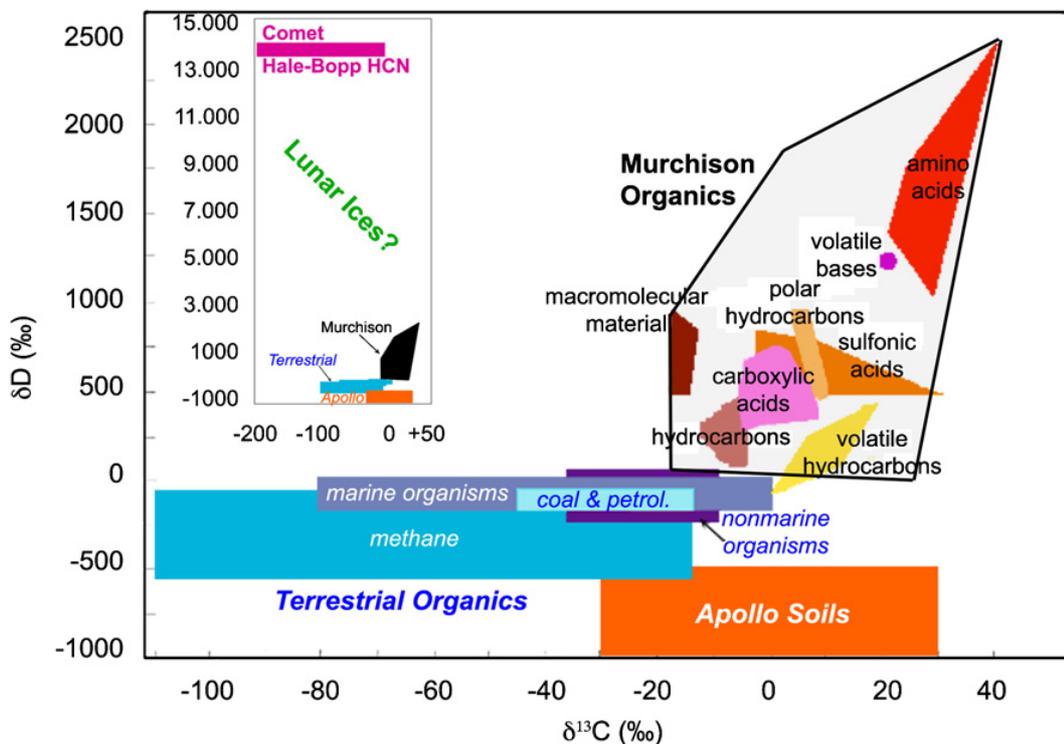


Figure 2.8 hydrogen and carbon isotopes and the relationship with the origins of a wide variety of samples from ten Kate et al. (2010).

Comment: Verification is to be performed against a standard to be provided by ESA and derived from CV and CM chondrites (standard and reference document in preparation).

RQ-IS-030. The isotopic composition of nitrogen in volatile species in lunar regolith samples, $\delta^{15}\text{N}$, shall be determined with an uncertainty of 10‰.

Justification: This level of uncertainty is needed to distinguish nitrogen components. The given uncertainty should allow identification of the source and allow investigation in to



the fractionation and systematics of the processing that has taken place during emplacement and processing. See for example $\delta^{15}\text{N}$ values for Earth, Moon, comets and carbonaceous chondrites presented by Fűri et al. (2015) and Saal et al. (2013).

Comment: Verification is to be performed against as standard to be provided by ESA and derived from CV and CM chondrites (standard and reference document in preparation).

RQ-IS-040. The isotopic composition of oxygen in volatile species in lunar regolith samples, $\delta^{18}\text{O}$, shall be determined with an uncertainty of 1‰.

Justification: Only coupled, (ultra-)high-precision measurements of the three O isotopes can provide detailed source information and this is hard to achieve even in terrestrial laboratories. However $\delta^{18}\text{O}$ alone should be sufficient to determine whether solar wind is or is not the source of oxygen measured.

Comment: Reference is needed here to the $\delta^{18}\text{O}$ of different oxygen sources.

Comment: Verification is to be performed against as standard to be provided by ESA and derived from CV and CM chondrites (standard and reference document in preparation).

RQ-IS-050. As a goal The isotopic composition of oxygen in volatile species in lunar regolith samples, $\delta^{17}\text{O}$, shall be determined with an uncertainty of 0.1‰.

Justification: It is recognised that this measurement is by no means straightforward even in a terrestrial laboratory and it is probably unlikely that the measurement can be achieved in situ. The requirement is therefore expressed as a goal. As described above only coupled, (ultra-)high-precision measurements of the three O isotopes can provide detailed source information.

Comment: Verification is to be performed against as standard to be provided by ESA and derived from CV and CM chondrites (standard and reference document in preparation).

RQ-IS-060. Isotopic measurements described above shall be possible, where relevant, for all chemical species defined in Table 2.3 and Table 2.4 if present above 1 ppm (TBC).

Justification: This ensures that isotopic measurements shall be made for elements associated with all the chemical species of interest. A TBD ppm limit is applied here to allow for the practical limitations for measurements of very rare chemical species.

Comment: Verification is to be performed against as standard to be provided by ESA and derived from CV and CM chondrites (standard and reference document in preparation). Reference document defines a “reference” set of sample gasses from a nominal sample.

species	Design concentration (ppm)	reference
H ₂ O	200	Tartese and Anand (2013)
H ₂	50	Tartese and Anand (2013)
4He	10	Fegley and Swindle (1993)
20Ne	0.5	Wieler (2002) & Wieler and Heber (2003)
22Ne	0.05	Wieler (2002) & Wieler and Heber (2003)
36Ar	0.0075	Wieler (2002) & Wieler and Heber (2003)
38Ar	0.001	Wieler (2002) & Wieler and Heber (2003)
40Ar	0.02	Wieler (2002) & Wieler and Heber (2003)
N ₂	100	Mortimer et al. 2016
O ₂	0.01	assumes scales to solar abundance relative to H ₂
CO	10	Indistinguishable from N ₂ so assume same profile
CO ₂	100	McCubbin et al. (2015)
NH ₃	0.001	Arbitrary value
CH ₄	0.001	Arbitrary value
C ₂ H ₄	0.001	Arbitrary value
C ₄ H ₈	0.001	Arbitrary value
C ₆ H ₆	0.001	Arbitrary value
C ₇ H ₈	0.001	Arbitrary value
C ₈ H ₈	0.001	Arbitrary value
C ₈ H ₁₀	0.001	Arbitrary value
C ₉ H ₈	0.001	Arbitrary value
C ₉ H ₁₀	0.001	Arbitrary value
C ₉ H ₁₂	0.001	Arbitrary value
C ₄ H ₄ S	0.001	Arbitrary value
84Kr	0.00004	TBD
132Xe	0.000006	TBD
F	100	McCubbin et al. (2015)

Cl	50	McCubbin et al. (2015)
SO ₂	100	McCubbin et al. (2015)
H ₂ S	200	McCubbin et al. (2015)

Table 2.3 reference volatile content of a “dry” lunar sample.

Molecule	Abundance normalised to that of water	source
H ₂ O	1	N/a
H ₂ S	1.67E-01	Collaprete et al. 2010
NH ₃	6.08E-02	
SO ₂	3.14E-02	
C ₂ H ₄	3.14E-02	
CO ₂	2.16E-02	
CH ₃ OH	1.53E-02	
CH ₄	6.47E-03	
CO	2.00E-01	
H ₂ O ₂	3.00E-04	
C ₂ H ₂	0.001	
C ₂ H ₆	0.003	
CH ₃ C ₂ H	0.00045	
CH ₃ OH	0.024	
H ₂ CO	0.011	
HCOOH	0.0008	
CH ₃ COOH	0.0006	
HCOOCH ₃	0.0008	
CH ₃ CHO	0.00025	
H ₂ CCO	0.00032	
C ₂ H ₅ OH	0.0005	
CH ₃ OCH ₃	0.0045	
CH ₂ OHCHO	0.0004	
NH ₃	0.007	
HCN	0.0025	

HNCO	0.001	
HNC	0.0004	
CH ₃ CN	0.0002	
HC ₃ N	0.0002	
NH ₂ CHO	0.00011	
NH ₂ CH ₂ COOH	0.0015	
C ₂ H ₅ CN	0.0001	
CH ₂ NH	0.00032	
HC ₅ N	0.00003	
N ₂ O	0.0023	
NH ₂ OH	0.0025	
H ₂ S	0.015	
OCS	0.003	
SO	0.005	
CS ₂	0.002	
SO ₂	0.0023	
H ₂ CS	0.0002	
S ₂	0.00005	
NaCl	0.000008	
NaOH	0.000003	

Table 2.4 reference volatile content within water ice at the lunar poles. A cometary composition is used as a design reference analogue for lunar water.

2.2 Chemisorbed and Solar wind implanted volatiles

Volatiles, which have been implanted into the surface by the solar wind, provide another potential resource, which can be extracted from lunar soil by simple heating. They are almost certainly ubiquitous to all lunar soils and have been recovered from samples obtained during the Apollo and Luna missions. The main major elements present in this population are H, N, C and He (e.g. Fegley and Swindle, 1993). These elements, once extracted, could be applied in support of various aspects of lunar exploration. Potential applications include use as a feed stock for processes for the reduction of metal oxides for the production of O and H₂O (see later sections) as well as chemicals used in life support and other surface systems.

The extraction of solar wind implanted volatiles by heating (Figure 2.9) probably constitutes the simplest conceivable extraction means for any potential resource but for most lunar sites the abundance of volatile elements in the regolith is low (e.g. of the order of 50 ppm by mass in the case of H; Fegley and Swindle, 1993). As a result the practical application of such volatiles as resources, in areas similar to those already sampled requires further investigation and is not a given. However at unexplored high lunar latitudes concentrations may well be higher. In these locations the regolith exists at much lower temperatures than those sampled by Apollo, which should result in a slower diffusion of light atoms out of mineral lattices.

One solar wind implanted volatile that has been the focus of much speculation is ³He. This element has been identified as a potential fuel for future nuclear fusion reactors (e.g. Schmitt, 2006). However, the concentration of ³He in regolith samples returned by Apollo is very low (in the range 2–10 parts per billion by mass; Fegley and Swindle, 1993) and so the economic benefits it may yield remain far from demonstrated. Again there is uncertainty regarding the global abundance of ³He, however, there is an observed correlation between ³He abundance and ilmenite abundance (Fegley and Swindle, 1993). This correlation implies that the highest concentrations will probably occur in high-Ti mare basalt regions, such as those in Mare Tranquillitatis, which were sampled by Apollo 11. In these samples the ³He concentration is 9.5 part per billion by mass (Fegley and Swindle, 1993). Preliminary remote sensing observations by the Chang'e-1 mission (Fa and Jin, 2010) support this hypothesis. For this reason it seems unlikely that enhancements in concentrations of ³He in other areas of the Moon will be significant enough to increase the economic viability of the proposed scheme.

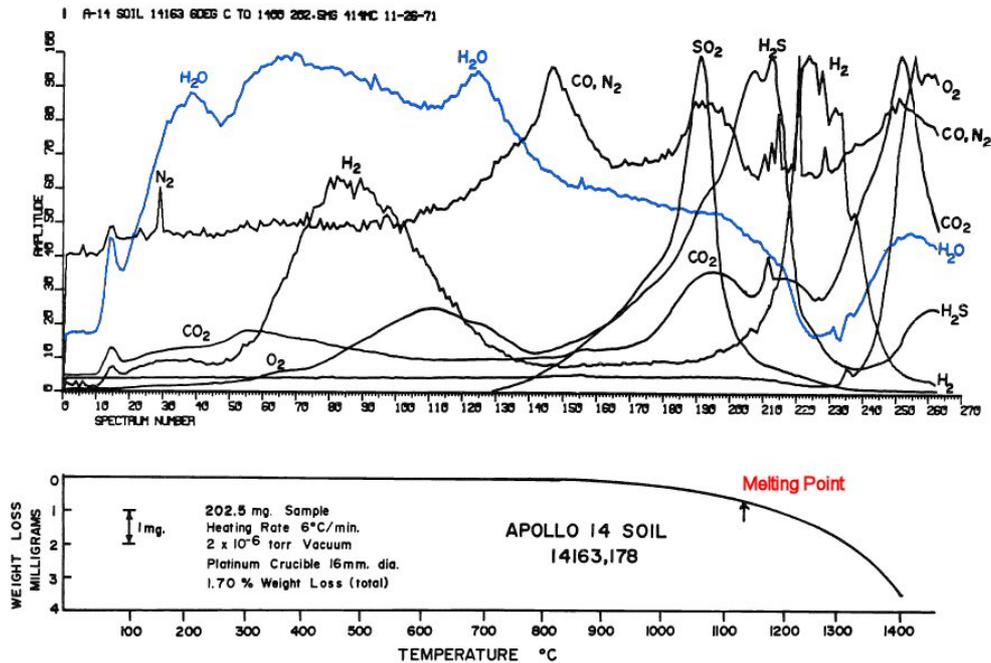


Figure 2.9 Evolved gas release from Apollo 14 lunar soil 14163. Volatile species released during heating lunar soil 14163 at 6°C/minute from room temperature to 1400°C. Gas release profiles are normalized to 100% at the temperatures of greatest abundance. A great many lunar soil samples have been analysed using this technique by Gibson et al.

An additional population of volatiles, most likely resulting from solar wind implantation, have been identified through measurements of infrared spectra from the M3 instrument on Chandrayaan-1 (Pieters et al., 2009). These measurements, along with those from the Deep Impact and Cassini missions (Clark et al., 2009; Sunshine et al., 2009) have revealed an absorption feature at around 3 microns which has been attributed to the fundamental vibration of the OH chemical group and thus is an indicator of the presence of OH and/or H₂O. The feature has been observed across the lunar surface but is seen to increase with latitude such that that the highest prominence close to the poles. Variations in absorption have also been associated with different surface mineralogies, and the feature is particularly associated at lower latitudes with plagioclase feldspar in anorthositic highland regions (Clark, 2009). Time variations have also been inferred in the strength of the absorption feature suggesting that the OH is dynamic and migrating across the lunar surface, and may provide one source of ice in cold traps at the lunar poles.

The observed OH is most likely to exist in the form of chemically bound hydroxyl groups created by implantation of solar wind hydrogen (McCord et al., 2011; Starukhina, 2012). The observations made to date are sensitive to regolith depths of approximately 1 mm. Within this depth of the surface initial indications are that up to a few tenths of a per cent by weight of water equivalent may be present. Another instrument on the Chandrayaan-1 spacecraft reportedly detected water vapour in the tenuous lunar atmosphere (Sridharan, et al., 2010).

The discovery of water/hydroxyl on and near the lunar surface have been complemented by a number of new ground-based findings of water/hydroxyl in lunar samples that originated at depth in the Moon (e.g., Boyce et al., 2010; Greenwood et al., 2011; Hauri et al., 2011; McCubbin et al., 2010; Saal et al., 2008), although the sources of water/hydroxyl are probably quite different in the two cases (e.g. Anand, 2010; McCord et al., 2011).

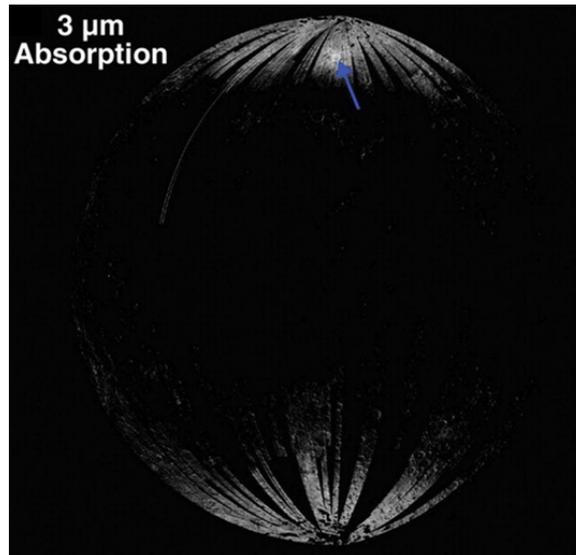


Figure 2.10. 3- μm absorption strength on the lunar surface, indicating OH/H₂O content, as measured by the M3 instrument on Chandrayaan. Brighter areas indicate strong absorption. The large northern crater near 0° longitude with strong 3- μm absorption is Goldschmidt (indicated with arrow). Taken from Pieters et al., 2009.

2.2.1 Objectives for chemisorbed and Solar Wind implanted volatiles

An analysis of adsorbed volatiles from the solar wind and other sources at new and distinct landing sites, and in particular those at high latitudes can provide ground truth for orbital measurements and complement measurements of Apollo and Luna samples from low latitudes and different terrains. This would allow the assertion of the abundance and composition of such volatiles across the lunar surface. Doing so in a manner in which contamination is strictly controlled throughout the sample chain can also address questions on the potential contamination of samples obtained during the Apollo missions and add value to measurements made previously on these samples.

It is important to note that the surface at the location of landing will have been altered by the influence of the landing. As such objectives should be considerate of the fact that surface volatiles are most likely unrepresentative of the surface as a whole and are likely to be heavily contaminated.

Objective for investigations into solar wind implanted volatiles as potential resources are therefore:



- OB-SW-001 Determine the composition of chemisorbed and solar wind implanted volatiles at new and distinct locations
- OB-SW-002 Determine the abundance of chemisorbed and solar wind implanted volatiles at new and distinct locations
- OB-SW-003 Determine the variation in concentration of chemisorbed H₂O/OH with depth below the surface.
- OB-SW-004 Determine the isotopic composition of the elemental components of chemisorbed H₂O/OH found below the surface.

2.2.2 Requirements for investigations into chemisorbed and Solar Wind implanted volatiles

2.2.2.1 Sample Requirements

- RQ-SA-120. Samples shall be extracted from sites which are distinct from those for which data currently exists.

Justification: This provides a new data set which is distinct from anything in the current inventory.

Comment: There is a general priority for high latitude sites as these represent significantly different environments from those explored before and where concentrations are expected to be higher due to reduced surface temperatures.

- RQ-SA-130. Samples shall be taken from depths which are sufficient to ensure that contamination due to a lander are negligible.

Justification: Contaminants from lander engines contain compounds and elements of interest for the scientific investigations.

Comment: models and experiments will be required to establish the contaminants and to characterise their interaction with regolith. An initial study performed in the frame of L-VRAP (Barbar et al., 2012) indicated that penetration of exhaust gasses from the lander plume into the surface would have a penetration of a several cm, although this was a preliminary finding and further work is required.

Comment: While accessing water at the surface is of strong interest it is not pursued here as it is assumed that surface alteration by the lander will prevent any such measurements.

- RQ-SA-140. Losses of chemisorbed and solar wind implanted volatiles from the sampled material from its original state to the point of analysis shall be no greater than 5%(TBC).



Justification: This is to ensure that the process of sampling and sample handling maintains the original volatile content of the sampled material to within an error that is consistent with the abundance requirements and the isotopic measurement requirements.

Comment: Failure to meet this requirement would most likely be due to exposure to high temperatures or extreme mechanical disturbance. These extreme events are expected to be unlikely given the need to address preservation requirements linked to cold trapped volatiles (RQ-SA-030), which are expected to be driving. In terms of verification demonstration that requirement for preservation of cold trapped volatiles are preserved would be sufficient. As such this requirement is assumed not to be included in the System Requirements Document.

The following requirements also apply:

RQ-SA-040 The depths from which delivered samples are extracted shall be determined within an uncertainty of $\pm 10\text{mm}$ (TBC).

Justification: Over a depth of 1 – 2 m a positional knowledge of 10mm is considered sufficient to allow a depth distribution to be established. Chemisorbed OH/H₂O are likely to only survive in the surface few cm.

RQ-SA-050 It shall be possible to collect samples from depth intervals of 200 mm or less

RQ-SA-060 Acquired samples shall be demonstrated, by tests on analogues, to be representative of original sampled material in terms of the relative proportions of fines ($5\mu\text{m} - 0.5\text{mm}$), coarse particles ($>0.5\text{mm}$) and ices.

Justification: It has been observed previously that the extent and content of SWIPs in lunar regolith varies with particle size and type and soil maturity. It is therefore important to ensure that no bias is introduced to measurements by unintended alteration of the relative proportions.

Comment: Verification of this requirement is expected to be performed using the analogue defined in [reference document needed]

RQ-SA-072 The temperature of samples shall be recorded from acquisition to delivery with an uncertainty of 1K (TBC) for temperatures above 180K.

Justification: Temperature needs to be recorded in order to establish the point at which different species are evolved. Chemisorbed species are likely to start evolving at temperatures of around 180K (Hibbets et al. 2011). A reduced uncertainty is required here



than for ices as loss rates are a less strong function of temperature and high uncertainty sampling across the full temperature range expected is very challenging.

Comment: As noted previously it is unlikely that sample temperature can be measured directly but will instead need to be inferred from measurements made in proximity to samples. This requirement may need to be updated to reflect an appropriate measuring scheme.

RQ-SA-073 The mechanical environment of samples shall be determined from the acquisition to delivery

Justification: Anecdotal evidence from working with Apollo samples indicates that some surface bound solar wind volatiles may be sufficiently weakly bound to be lost through physical disturbance (L. Taylor, personal communication). Providing a record of the accelerations and disturbances experienced by the samples up to the point of delivery allow some inference of the likely losses experienced due the transfer process.

RQ-SA-080 The level of terrestrial contamination in measurements shall be sufficiently low as to allow measurements of samples in line with the requirements

Justification: see earlier justification.

RQ-SA-090 The level of contamination from the lander, it's fuel or exhaust products in measurements shall be sufficiently low as to allow measurements of samples in line with the requirements.

Justification: see earlier justification.

RQ-SA-100 The level of cross-contamination between samples shall be sufficiently low as to allow measurements which are representative of separate samples in line with the requirements.

Justification: see earlier justification.

2.2.2.2 Volatile extraction and measurement requirements

The following requirements apply:

RQ-EM-010 Volatiles shall be extracted from lunar regolith samples by heating.

Justification: see earlier justification.



Comment: Solar wind implanted chemicals are typically extracted at temperatures of less than 700°C. temperatures required for chemisorbed volatiles are typically around 1000°C or higher. It is therefore expected that sample temperatures of more than 1000°C will be targeted.

RQ-EM-020 The chemical identity of chemical species with m/z between 2 and 200 shall be determined when in concentrations greater than 1ppb (TBC).

Justification: see earlier justification.

RQ-EM-030 A quantitative measure of the total volatile yield (uncertainty TBD) and the yields for individual volatiles (uncertainty TBD) shall be provided as a function of the sample mass.

Justification: see earlier justification.

RQ-EM-040 The abundance of any precursors within the regolith to the liberated volatiles which are produced during the extraction process should be determined with an uncertainty of $\pm 50\%$ (TBD)

Justification: see earlier justification.

2.2.2.3 Isotopic analysis requirements

The following requirements apply:

RQ-IS-010 The isotopic composition of hydrogen in volatile species in lunar regolith samples, δD , shall be determined with an uncertainty of 100‰

Justification: see earlier justification.

RQ-IS-020 As a goal the isotopic composition of carbon in volatile species in lunar regolith samples, $\delta^{13}C$, should be determined with an uncertainty of 1‰.

Justification: see earlier justification.

RQ-IS-030 The isotopic composition of nitrogen in volatile species in lunar regolith samples, $\delta^{15}N$, shall be determined with an uncertainty of 10‰.

Justification: see earlier justification.

RQ-IS-040 The isotopic composition of oxygen in volatile species in lunar regolith samples, $\delta^{18}O$, shall be determined with an uncertainty of 1‰.



Justification: see earlier justification.

RQ-IS-050 As a goal The isotopic composition of oxygen in volatile species in lunar regolith samples, $\delta^{17}\text{O}$, shall be determined with an uncertainty of 0.1‰.

Justification: see earlier justification.

RQ-IS-060 Isotopic measurements described above shall be possible, where relevant, for all *chemical* species defined in Table 2.3 and Table 2.4 if present above 1 ppm (TBC).

3 OXYGEN EXTRACTION FROM MINERALS IN REGOLITH

The Lunar surface is comprised of a complex collection of minerals and rocks, formed through geological processes associated with a chemically differentiated body like the Earth. As on the Earth, it is conceivable that several ore-forming processes might have operated on the lunar surface and in the interior. Ore refers to a naturally occurring solid material from which a metal or valuable mineral can be profitably, or in the lunar case we might say usefully, extracted. To this end the composition and physical state of the material is important, as are requirements of potential users of the materials. A major potential useful component of lunar materials is oxygen. Schemes for the production of oxygen, along with other materials including metals, from lunar regolith have been discussed extensively (e.g. Schwandt et al., 2012).

The most likely primary feed stock for resource extraction processes is the lunar regolith; a layer of rocks and fine-grained particles at the lunar surface, with a thickness which varies between approximately 3 m and 20 m (McKay et al., 1991), and which has been produced over billions of years by a continuous flux of impacts coupled with space weathering processes. These processes lead to the formation of a material unlike anything found in terrestrial environments (e.g., Lucey et al., 2006) with particle morphologies which can vary from highly irregular and angular vesicular agglutinates to spherical glass beads generated during impacts and explosive volcanic (pyroclastic) activities (Liu and Taylor, 2011; McKay et al., 1991; Papike et al., 1982). Lunar soils can generally be described by log-normal size distributions with mean diameters of between 45 μ m and 100 μ m, and which can be at least as small as 10nm. (Greenberg et al., 2007; Liu et al., 2008). In order to realise utilisation of resources in lunar regolith in the future it is important to first:

- Identify the composition regolith at new locations where future mission may seek to extract resources.
- Determine the in-situ physical of the regolith at these locations.
- Demonstrate in-situ extraction of useful resources (e.g. oxygen) from that regolith.

The most abundant minerals in lunar regolith are plagioclase, pyroxene, olivine, ilmenite and spinel. Other, less abundant minerals include cristobalite, apatite, sulphides, and native metals such as Fe and Ni. In general the basaltic terrains of lunar mare tend to be much richer in ilmenite, olivine and pyroxene whilst the more primitive lunar highlands are dominated by Ca-rich plagioclase (e.g. Haskin et al., 1993). The actual composition of lunar soils is however observed to be very localised, even on the scale of a few kilometres, indicating a limited extent of lateral mixing (Papike et al., 1982) and a strong correlation between the resource potential of a given location and the specific geology and geochemistry associated with that site.



The vast majority of our understanding and knowledge of Lunar regolith properties and composition has been gained from the analysis of samples returned by the Apollo and three Luna missions. Laboratory analysis of these returned samples provides ground truth, against which remote sensing datasets are calibrated and interpreted. Limitations of our understanding occur primarily because the majority of samples were collected from Lunar Mare in near-side equatorial regions. As a result our knowledge of the composition and properties of mare regolith is disproportionately mature compared with non-mare regions. As a result we know that mare regions are composed of basaltic lava flows with varying proportions of plagioclase, pyroxene and olivine as well as ilmenite (FeTiO_3). Following a classification scheme proposed by Neal and Taylor (1992) these can be further subdivided into 'high-Ti' and 'low-Ti' basalts depending on whether their TiO_2 content is above or below 6% by mass. While information about these regions is comparatively mature it is important to note that the majority of mare basalts on both the near and far side have not been sampled, and data obtained from lunar orbit indicates that some of these have compositions differ from those present in the returned samples (e.g. Hiesinger et al., 2000).

The diversity of highland regolith is less well constrained from sample studies, and most knowledge comes from analyses of remote sensing data, lunar meteorites, and a limited number of Apollo samples. Although generally anorthositic (i.e. plagioclase-rich), the large diversity of lunar crustal materials continues to be demonstrated by results from orbital remote sensing instruments on Kaguya, Chang'e-1, Chandrayaan-1 and Lunar Reconnaissance Orbiter (LRO) spacecraft. As summarised by Crawford et al. (2012), these include outcrops of pure anorthosites which may represent pristine magma ocean flotation cumulates (e.g., Ohtake et al., 2009), olivine-rich outcrops which may sample mantle material (Yamamoto et al., 2010), and spinel-rich (Sunshine et al., 2010) and silica-rich (Glotch et al., 2010; Greenhagen et al., 2010; Jolliff et al., 2011) lithologies not represented in the existing sample collection.

The Apollo and Luna sample locations are unrepresentative of the lunar surface as a whole and as a result our understanding of the materials available for utilisation and the properties of those materials is poorly constrained globally. Identifying and establishing the resource potential of lunar materials requires a comprehensive catalogue of lunar minerals alongside an understanding how they were formed. It is this combination that allows the identification and prospection of ore. Relevant processes include those involved in the origin and differentiation of the Moon to those primarily acting on the lunar surface (e.g., space weathering). All of these have the potential to re-mobilize and concentrate elements into useful mineral deposits (Haskin et al., 1993). As one example crustal evolution processes in the north-western nearside Procellarum KREEP Terrain (Jolliff et al., 2000) have led to a material which is particularly enriched in incompatible trace elements. Other localised areas of highly evolved magmatism (e.g. the Compton–Belkovich region on the farside; Jolliff et al., 2011) may also have concentrated incompatible trace-elements and other potentially useful materials.

An additional and important issue for potential resource extraction and utilisation is the physical properties of the input material. At new and unexplored locations, in particular at



high latitudes, where temperatures are reduced and the volatile content of the regolith may be greater, it is possible that the physical properties may deviate significantly from those at lower latitudes.

A number of processes have been proposed for the extraction of oxygen from lunar regolith. An overview of these processes is described by Schwandt et al. (2012). In summary these are:

- Reduction with hydrogen
- Oxidation using fluorine (Seboldt et al., 1993)
- Reduction with methane
- Vapour phase pyrolysis
- Sulphuric acid reduction
- Electrolysis of molten lunar regolith
- Electrolysis of solid lunar regolith

Each of these processes has its strengths and weaknesses and it is far from clear at the present time which if any will become a standard process for future application. It is likely that processes applied will vary depending on location and individual mission or programme requirements.

3.1 Objectives for oxygen extraction of minerals in regolith

A major step forwards for the establishment of the feasibility of extracting resources in-situ would be the in situ demonstration of one or more of the candidate oxygen extraction processes. Such a demonstration would bring confidence that such systems could be incorporated in the future and provide valuable insight into the specific challenges of performing such reactions at the lunar surface. A package providing in situ chemical processing of regolith samples can be used to demonstrate of in-situ oxygen extraction from regolith. Objectives on this regard are as follows:

- OB-OM-001 Demonstrate in-situ extraction of oxygen from minerals in lunar regolith.
- OB-OM-002 Record key metrics to allow the determination of the feasibility of candidate oxygen extraction processes
- OB-OM-003 Determine the composition of regolith at a new and unexplored location
- OB-OM-004 Determine physical properties of lunar regolith at a new location

The requirements on the following sections, which derive from these objectives have temperature and sealing implications for the ovens/reaction vessels used by PROSPECT. These requirements and the objectives from which they are derived will need to be reassessed on the basis of feasibility demonstrated during Phase B.

3.2 Requirements for oxygen extraction of minerals in regolith

3.2.1 Sample Requirements

RQ-SA-150. Samples of regolith shall be extracted for processing and analysis.

3.2.2 Oxygen extraction and measurement requirements

RQ-OM-010 The bulk mineralogy of samples should be determined

Justification: The efficiency of any candidate process for oxygen extraction depends on the mineralogical content of the regolith (e.g. hydrogen reduction is only an efficient process when applied to ilmenite and so the ilmenite content of the soils as a % is an important value to know). It is therefore important to establish the broad mineralogical content of the samples which are being tested.

Comment: Given practical limitations on the instrumentation available to PROSPECT the only means to generate this information are likely to be through colour imaging of the surface (including cuttings), imaging of samples in ovens or through information obtained through the heating of samples and the power Vs temperature profile during heating. Because of present uncertainties in the feasibility of achieving this with PROSPECT this requirement is presented as should rather than shall.

RQ-OM-020 Where suitable mineralogy is present, oxygen shall be extracted from minerals in regolith by reduction in hydrogen.

Justification: Hydrogen reduction is arguably the simplest oxygen extraction process conceivable. However it is only an efficient process when applied to ilmenite, which is not expected in significant quantities at high latitudes, so yield is low and needs to be considered in the context of the bulk mineralogy. Thus oxygen can only be extracted where appropriate mineralogy is present.

Comment: Verification should be performed against a terrestrial analogue containing ilmenite.

RQ-OM-030 Oxygen should be extracted from minerals using methane as a reductant.

Justification. Carbothermal reduction using methane is a candidate process that can be applied to a broad mix of mineral types and is thus appropriate as a process at the polar regions. However the required temperatures required and the expected production of complex organic contaminants as bi-products of the reactions make its inclusion a challenge. For this reason this is included as a goal.

RQ-OM-040 The yield of oxygen shall be determined as a function of the sample mass.

Justification: The yield of oxygen is the key metric for establishing the efficiency of the process (i.e. how much oxygen was produced from a given mass of regolith)



Comment: Sample mass probably needs to be determined through imaging or through measurement of the gas pressure in an oven of known size after the introduction of a sample. Other methods may also be considered.

RQ-OM-050 The presence of oxygen and any other products of the reactions shall be identified.

Justification: This defines the products of the reaction allowing determination of the chemistry that has taken place.

RQ-OM-060 The temperatures at which the reaction takes place shall be measured to $\pm 1^{\circ}\text{C}$.

Justification: This defines the energy balance of the reaction, allowing the determination of the process efficiency.

3.2.3 Isotopic analysis requirements

RQ-IS-040 The isotopic composition of oxygen in volatile species in lunar regolith samples, $\delta^{18}\text{O}$, shall be determined with an uncertainty of 1‰.

Justification: see earlier justification.

RQ-IS-050 As a goal The isotopic composition of oxygen in volatile species in lunar regolith samples, $\delta^{17}\text{O}$, shall be determined with an uncertainty of 0.1‰.

Justification: see earlier justification.

4 THE ORIGINS OF TERRESTRIAL VOLATILES

A number of volatile elements (e.g., C, H, O, N) play vital role in sustaining life on Earth. (e.g., Dehant et al. 2012). Early Earth was most likely depleted in these volatile elements and a later additions through impacts is thought to be necessary to account for the Earth's present volatile budget and for the volatiles needed to make Earth habitable (e.g. Albarède et al, 2009). It is proposed that the quantity of water delivered to the Earth by impacts may have been 10 – 25 times the total mass of the present day oceans (Albarède et al, 2013).

It is probable that the water ice in permanently shadowed regions is ultimately derived from comet and/or meteorite impacts. Even though the original volatiles will have been considerably reworked, it remains probable that some information concerning the composition of the original sources will remain (Zhang and Paige, 2009). However, in reality, the geochemical signature of volatiles present in PSRs today will reflect time-averaged composition of cometary, meteoritic, solar and cosmogenic sources for these volatiles unless volatiles emplaced during discrete events were immediately isolated from their surroundings and preserved thereafter (e.g., via burial under an impact ejecta). Among other valuable scientific insights, access and analysis of volatiles from PSRs may yield critical information of astrobiological importance and the role of comets and meteorites in delivering volatiles and pre-biotic organic materials to the terrestrial planets (Chyba and Sagan, 1992; Pierazzo and Chyba, 1999; Zhang and Paige, 2009).

The lunar regolith in general is known to contain much that is of interest for studies of Solar System history. For example, studies of Apollo samples have revealed that solar wind particles are efficiently implanted in the lunar regolith (McKay et al., 1991; Lucey et al., 2006), which therefore contains a record of the composition and evolution of the Sun throughout the Solar System history (e.g., Wieler et al., 1996; Chaussidon and Robert, 1999; Hashizume et al., 2000). Recently, samples of the Earth's early atmosphere may have been retrieved from lunar regolith samples (Ozima et al., 2005; 2008), and it has been suggested that samples of Earth's early crust may also be preserved on the Moon in the form of terrestrial meteorites (Gutiérrez, 2002; Armstrong et al., 2002; Crawford et al., 2008; Armstrong, 2010).



A giant leap in our understanding of lunar volatiles occurred when Saal et al. (2008) reported new data on volatile contents of volcanic glasses collected during Apollo missions, constituting the first direct measurement of water contents in lunar samples. These measurements were made possible through considerable recent advances in the field of Secondary Ion Mass Spectrometry (SIMS), which have provided improved detection limits for volatiles (e.g., H₂O, CO₂, F, S and Cl) up to 2 orders of magnitude better than previously used techniques used in the study of lunar samples such as electron microprobe and Fourier Transform Infrared Spectroscopy (FTIR). A separate study by Hauri et al. (2011) measured the volatile content of melt inclusions trapped in these lunar volcanic glasses and reported similar abundances of water as in melt inclusions in basalts formed at mid-ocean ridges on Earth. Most recently, Saal et al. (2013) reported hydrogen isotopic composition of lunar volcanic glasses. Their results indicate that carbonaceous chondrites are the main source of water in the Earth-Moon system.

Besides volcanic glasses, several studies of lunar volatiles have focused on mineral apatite, that occurs ubiquitously in a variety of lunar rock types. Apatite, with an idealised formula of Ca₅(PO₄)₃(F,Cl,OH), can indeed contain water, structurally bounded into the crystal structure as hydroxyl (OH) and is commonly associated with other volatiles such as F and Cl. A number of recent studies have targeted apatite in lunar samples to investigate the volatile inventory of the lunar interior (e.g., Barnes et al., 2013a,b; Boyce et al., 2010; Greenwood et al., 2011; McCubbin et al., 2010; Tartèse et al., 2013). These recent studies have provided significant new insights into the lunar volatile inventory and have highlighted the need for understanding effects of complex petrological processes before ascribing measured geochemical signatures to that of the source materials (e.g., Tartèse and Anand, 2013). Perhaps the most striking finding from recent sample-based research on lunar samples has been the revelation that the water in the Earth-Moon system shares a common origin and the most likely source of this water was chondritic (i.e., asteroidal) and not cometary, as previously thought (e.g., Barnes et al., 2013b; Saal et al., 2013; Tartèse and Anand, 2013). However, the exact timing of the delivery of water (and associated volatiles) to the Earth-Moon system remains poorly constrained. It is possible that the Earth retained some of its primordial water after the giant-impact origin of the Moon (Section 6.1) and additional water was delivered to the Earth-Moon system by late accretion of chondritic material (e.g., Bottke et al., 2010; Tartèse and Anand, 2013).



Other volatile elements such as C, N and noble gases have also been measured in returned lunar samples over the past 4 decades. Although earlier studies mainly focussed on measurements of these volatiles in lunar soils, a few studies also analysed basalt fragments that were returned by the Apollo missions. In contrast to the volatile inventory of lunar soils, which is dominated by solar-wind-derived components, the basaltic rock samples carry indigenous signatures of these volatiles in the lunar interior, apart from noble gases which are formed through cosmogenic processes. However, the abundances of some volatiles, especially C and N are extremely low in lunar samples and until recently such measurements to sufficient accuracy and precision were technically challenging. Recent analysis for C and N in lunar basalts using a high resolution stepped combustion technique is permitting an in-depth analysis of various volatile components present in lunar basalts. In addition, cosmogenic isotopes present in the samples document the exposure history of basalts on the lunar surface. The cosmogenic isotope abundances in lunar samples are well-correlated with calculated exposure ages found in the literature, and they detail the changing flux of extra-lunar volatile additions to the lunar surface through time.

4.1 Objectives for the origins of terrestrial volatiles

Analysis of samples of polar cold trapped ices and adsorbed volatiles can inform notions of the fractions of terrestrial volatiles that are derived from cometary or asteroidal sources. Nominal volatile molecules targeted are H₂O, CO₂, H₂, CO, SO₂, H₂S, COS, CS₂, Hydrocarbons from C₁-C₆, HCN, CH₃CHO, C₁₀H₈(+PAH), NO_x, N₂, O₂, Kr, Xe, Ar, Ne, He. For most of these volatiles temperatures for ices are too low to be considered. As a result water ice is the driver for requirements, with the possibility that other volatiles will be trapped in the ice.

Objectives relating to the origins of terrestrial volatiles are:

- OB-TV-001. Constrain values for the fraction of volatiles which have been delivered to the Earth-Moon system by asteroids, comets and solar wind.
- OB-TV-002. Assess the time averaged volatile inventory to the Earth-Moon system.
- OB-TV-003. Infer any relationship between molecules associated with the building blocks of life and those occurring in lunar ices and their sources.

4.2 Requirements for investigations into the origins of terrestrial volatiles

4.2.1 Sample requirements

The following requirements apply (*previously provided justifications apply*):

- RQ-SA-010 Samples shall be extracted from sites where cold trapped volatiles are expected based on data from previous missions.
- RQ-SA-020 Samples shall be taken from depths from the top cm of the surface up to a depth of 1m with a goal of 1.2m.



- RQ-SA-030** Losses of ice from the sampled material from its original state to the point of analysis shall be no greater than 5%(TBC) for samples containing more than or equal to 1% (TBD) by weight water ice.
- RQ-SA-040** The depths from which delivered samples are extracted shall be determined within an uncertainty of ± 10 mm (TBC).
- RQ-SA-050** It shall be possible to collect samples from depth intervals of 200 mm or less
- RQ-SA-060** Acquired samples shall be demonstrated, by tests on analogues, to be representative of original sampled material in terms of the relative proportions of fines ($5\mu\text{m} - 0.5\text{mm}$), coarse particles ($>0.5\text{mm}$) and ices.
- RQ-SA-070** Data shall be generated that allows the losses of ice and other volatiles during sample handling to be determined.
- RQ-SA-072** The temperature of samples shall be recorded from acquisition to delivery with an uncertainty of 1K (TBC) for temperatures above 180K.
- RQ-SA-073** The mechanical environment of samples shall be determined from the acquisition to delivery
- RQ-SA-080** The level of terrestrial contamination in measurements shall be sufficiently low as to allow measurements of samples in line with the requirements
- RQ-SA-090** The level of contamination from the lander, it's fuel or exhaust products in measurements shall be sufficiently low as to allow measurements of samples in line with the requirements.
- RQ-SA-100** The level of cross-contamination between samples shall be sufficiently low as to allow measurements which are representative of separate samples in line with the requirements.
- RQ-SA-120** Samples shall be extracted from sites which are distinct from those for which data currently exists.
- RQ-SA-130** Samples shall be taken from depths which are sufficient to ensure that contamination due to a lander are negligible.
- RQ-SA-140** Losses of chemisorbed and solar wind implanted volatiles from the sampled material from its original state to the point of analysis shall be no greater than 5%(TBC).

4.2.2 Volatile extraction and measurement requirements

Justification: List of elements compiled from the summary of Lunar Volatile Materials from Berezhnoy et al. (2012) combined with consultation with expert panel on Topical Team on Exploitation of Local Planetary Materials. The 1ppm value reflects that some of the species are expected to be very rare in the regolith outside of permanently shaded areas and thus significantly rarer than the values presented for Cabeus crater by Berezhnoy et al. (2012).

The following requirements apply:

- RQ-EM-010 Volatiles shall be extracted from lunar regolith samples
- RQ-EM-020 The chemical identity of chemical species with m/z between 2 and 200 shall be determined when in concentrations greater than 1ppb (TBC).

4.2.3 Isotopic analysis requirements

- RQ-IS-070. Isotopic measurements of elements should be associated with their precursor compounds.

The following requirements also apply:

- RQ-IS-010 The isotopic composition of hydrogen in volatile species in lunar regolith samples, δD , shall be determined with an uncertainty of 100‰
- RQ-IS-020 As a goal the isotopic composition of carbon in volatile species in lunar regolith samples, $\delta^{13}C$, should be determined with an uncertainty of 1‰.
- RQ-IS-030 The isotopic composition of nitrogen in volatile species in lunar regolith samples, $\delta^{15}N$, shall be determined with an uncertainty of 10‰.
- RQ-IS-040 The isotopic composition of oxygen in volatile species in lunar regolith samples, $\delta^{18}O$, shall be determined with an uncertainty of 1‰.
- RQ-IS-050 As a goal The isotopic composition of oxygen in volatile species in lunar regolith samples, $\delta^{17}O$, shall be determined with an uncertainty of 0.1‰.

Earlier justifications apply

5 PREBIOTIC CHEMISTRY

Obtaining improved knowledge of the presence, composition, and abundance of volatiles at the lunar poles will be of considerable astrobiological interest. It is probable that the ice in permanently shadowed regions is ultimately derived from comet and/or asteroid impacts. Comets, asteroids and interplanetary dust particles are all known to contain organic molecules, while the organic contents varies between bodies (e.g. Martins and Sephton, 2009) and even though the original volatiles will have been considerably reworked by impact, it is likely that some information concerning the composition of the original sources will remain. As an example Table 5.1 and Table 5.2 present values for the abundance of various compounds in three comets and the Murchison meteorite. This may yield astrobiologically important knowledge on the role of comets and meteorites in delivering volatiles and pre-biotic organic materials such as amino acids to the terrestrial planets (Chyba and Sagan, 1992; Pierazzo and Chyba, 1999). It is also possible that organic molecules may be synthesised in comet collisions with planetary surfaces (Chyba and Sagan, 1992; Martins et al., 2013) and that records of such processes may be preserved in lunar polar ices.

Lunar polar ice deposits are likely to be of interest from a pre-biotic chemistry point of view even if they do not retain vestigial information concerning their ultimate sources. This is because any such ices will have been subject to irradiation by galactic cosmic rays and, as such, may be expected to undergo organic synthesis reactions (e.g. Lucey, 2000; Crites, et al., 2011). Analogous reactions may be important for producing organic molecules in the icy mantles of interstellar dust grains, and on the surfaces of outer Solar System satellites and comets (e.g. Bernstein et al., 2002; Muñoz Caro et al., 2002; Elsila et al., 2007; Meinert et al., 2012), but the lunar poles are much more accessible than any of these other locations.

The analysis of samples returned from polar volatile deposits would therefore reveal valuable information concerning the delivery and/or synthesis of organic molecules to the terrestrial planets. Analyses of the required sensitivity will almost certainly require samples to be returned to Earth for study in terrestrial laboratories. In order to minimise the risk of chemical reactions occurring between organic molecules present in the sample during the transport of the samples to Earth it will be desirable to keep the samples as close as possible to the very low temperatures at which they were collected (<100 K), and this may pose significant engineering challenges for the sample collection, handling, and curation activities. Another challenge will be to prevent any terrestrial contamination of samples.

Molecule	Halley	Hyakutake	Hale-Bopp
H ₂ O	100	100	100
1. H ₂ O ₂	2.	<0.04	<0.03
CO	15	6-30 ^a	20 ^a
CO ₂	3	<7 ^b	6 ^b
CH ₄	0.2-1.2	0.7	0.6
C ₂ H ₂	~0.3	0.5	0.1
C ₂ H ₆	~0.4	0.4	0.3
CH ₃ C ₂ H			<0.045
CH ₃ OH	1.7-1.7	2	2.4
H ₂ CO	0.-5	0.2-1 ^a	1.1 ^a
HCOOH			0.08
CH ₃ COOH			<0.06
HCOOCH ₃			0.08
CH ₃ CHO			0.025
H ₂ CCO			<0.032
C ₂ H ₅ OH			<0.05
CH ₃ OCH ₃			<0.45
CH ₂ OHCHO			<0.04
NH ₃	0.1-2	0.5	0.7
HCN	~0.2	0.1	0.25
HNCO		0.07	0.10
HNC		0.01 ^a	0.04 ^a
CH ₃ CN		0.01	0.02
HC ₃ N			0.02
NH ₂ CHO			0.011
NH ₂ CH ₂ COOH			<0.15
C ₂ H ₅ CN			<0.01
CH ₂ NH			<0.032
HC ₅ N			<0.003
N ₂ O			<0.23
NH ₂ OH			<0.25
H ₂ S	0.04	0.8	1.5
OCS		0.1 ^a	0.3 ^a
SO			0.2-0.8 ^a
CS ₂		0.1 ^c	0.2 ^c
SO ₂			0.23
H ₂ CS			0.02
S ₂		0.005	
NaCl			<0.0008
NaOH			<0.0003

Table 5.1. Molecular abundances of ices for comets Halley, Hyakutake, and Hale-Bopp (after Martins and Sephton, 2009) Abundances are normalized to H₂O and were measured at around 1 AU from the Sun. Values are adapted from Ehrenfreund et al., (2002), Ehrenfreund and Chamley (2000), Crovisier et al. (2004), Bockelée-Morvan et al. (2000), Mumma et al., (2005). ^aExtended sources (the abundance is model dependent). ^bMeasured at 2.9 AU from the Sun. ^cAbundance deduced from CS.

Compounds	Concentration (ppm)
Carboxylic acids (monocarboxylic)	332
Sulfonic acids	67
Amino acids	60
Dicarboximides	>50
Dicarboxylic acids	>30
Polyols	24
Ketones	17
Hydrocarbons (aromatic)	15-28
Hydroxycarboxylic acids	15
Hydrocarbons (aliphatic)	12-35
Alcohols	11
Aldehydes	11
Amines	8
Pyridine carboxylic acid	>7
Phosphonic acid	1.5
Purines	1.2
Diamino acids	0.4
Benzothiophenes	0.3
Pyrimidines	0.06
Basic N-heterocycles	0.05-0.5

Table 5.2. Abundances (in ppm) of the soluble organic matter found in the Murchison meteorite (after Martins and Sephton, 2009). Adapted from Botta and Bada (2002), Sephton (2002), Sephton and Botta (2005), Pizzarello et al. (2001).

5.1 Objectives for prebiotic chemistry

Analysis of lunar samples of cold trapped ices can provide access to the products of Urey-Miller type organic synthesis reactions, which may occur in ices exposed to galactic cosmic rays. Measurement of the presence, abundance composition and isotopic nature of these chemicals (e.g. amino acids) can indicate the extent to which amino acids and their building blocks were delivered to the Early Earth by impacts. Objectives relating to prebiotic chemistry are given below:

- OB-PC-001. Establish whether the products of organic synthesis reactions occur in lunar ices
- OB-PC-002. Establish the composition, chemistry and isotopic nature of any prebiotic organic molecules which are present and compare them with their terrestrial counterparts.

5.2 Requirements for investigations into prebiotic chemistry

5.2.1 Sample Requirements

The following requirements apply:

- RQ-SA-010* Samples shall be extracted from sites where cold trapped volatiles are expected based on data from previous missions.
- RQ-SA-020* Samples shall be taken from depths from the top cm of the surface up to a depth of 1m with a goal of 1.2m.
- RQ-SA-030* Losses of ice from the sampled material from its original state to the point of analysis shall be no greater than 5%(TBC) for samples containing more than or equal to 1% (TBD) by weight water ice.
- RQ-SA-040* The depths from which delivered samples are extracted shall be determined within an uncertainty of $\pm 10\text{mm}$ (TBC).
- RQ-SA-050* It shall be possible to collect samples from depth intervals of 200 mm or less
- RQ-SA-060* Acquired samples shall be demonstrated, by tests on analogues, to be representative of original sampled material in terms of the relative proportions of fines ($5\mu\text{m} - 0.5\text{mm}$), coarse particles ($>0.5\text{mm}$) and ices.
- RQ-SA-070* Data shall be generated that allows the losses of ice and other volatiles during sample handling to be determined.
- RQ-SA-073* The mechanical environment of samples shall be determined from the acquisition to delivery
- RQ-SA-080* The level of terrestrial contamination in measurements shall be sufficiently low as to allow measurements of samples in line with the requirements



- RQ-SA-090** The level of contamination from the lander, its fuel or exhaust products in measurements shall be sufficiently low as to allow measurements of samples in line with the requirements.
- RQ-SA-100** The level of cross-contamination between samples shall be sufficiently low as to allow measurements which are representative of separate samples in line with the requirements.
- RQ-SA-120** Samples shall be extracted from sites which are distinct from those for which data currently exists.
- RQ-SA-130** Samples shall be taken from depths which are sufficient to ensure that contamination due to a lander are negligible.
- RQ-SA-140** Losses of chemisorbed and solar wind implanted volatiles from the sampled material from its original state to the point of analysis shall be no greater than 5%(TBC).
- RQ-SA-150** Samples of regolith shall be extracted for processing and analysis.

5.2.2 Organic Compound extraction and measurement requirements

- RQ-PB-010.** Organic compounds shall be extracted from lunar regolith samples.

Comment: extraction of organic compounds may be via heating or combustion for less volatile species. In the latter case it is accepted that chemical information will be lost.

- RQ-PB-020.** Organic molecules, which have been evolved from samples and which were present in those samples in concentrations greater than 1ppm (TBC) should be identified.

Justification: It is necessary to provide a sensitivity requirement for the organics but also to specify that only those which can be evolved through heating should be measured.

Comment: It should be noted that determining the species of organics may not be possible without addition of a GC, which is not assumed. As such identifying the presence of organics is a requirement. Identifying the specific species present should be considered a goal.

- RQ-PB-030.** The precursors of those evolved organic compounds should be determined

Justification: the process of evolving compounds results in the alteration of the chemical species. What is of interest is the species as present in the regolith. Thus sufficient data needs to be generated to allow the original species to be identified.

Comment: This requirement is more a requirement for the analysis than the system, but relies on the heating data from the system, which must be available. It is kept as a should as it is something that should be targeted but cannot be assured in its entirety. It may not be possible to determine based on the data available from the mass spec.



RQ-PB-040. Measured organic molecules shall be associated with elemental isotopic measurements.

Justification: This allows the origins of those organic compounds to be established.

RQ-PB-050. The presence of organic molecules shall confirmed when in concentrations greater than 1pbb (TBC)

Justification: Individual organic molecules are unlikely to be discernible or identifiable, especially in low concentrations. However the presence of complex organic molecules, or not, needs to be discerned.

5.2.3 Isotopic analysis requirements

- RQ-IS-010 The isotopic composition of hydrogen in volatile species in lunar regolith samples, δD , shall be determined with an uncertainty of 100‰
- RQ-IS-020 As a goal the isotopic composition of carbon in volatile species in lunar regolith samples, $\delta^{13}C$, should be determined with an uncertainty of 1‰.
- RQ-IS-030 The isotopic composition of nitrogen in volatile species in lunar regolith samples, $\delta^{15}N$, shall be determined with an uncertainty of 10‰.
- RQ-IS-040 The isotopic composition of oxygen in volatile species in lunar regolith samples, $\delta^{18}O$, shall be determined with an uncertainty of 1‰.
- RQ-IS-050 As a goal The isotopic composition of oxygen in volatile species in lunar regolith samples, $\delta^{17}O$, shall be determined with an uncertainty of 0.1‰.
- RQ-IS-070 Isotopic measurements of elements should be associated with their precursor compounds.

6 MEASUREMENT CONTEXT REQUIRMENTS

Measurements of samples taken from beneath the surface must be interpreted with respect to the broader context within which they were taken. This context is both geological (i.e. the geological characteristics of the sampled material and the local geology) and operational (i.e. what happened during the sample extraction and delivery, was a sample delivered to the oven and if so how much). This information can be obtained by various means but the primary means of doing so it by imaging. This section presents requirements for imaging during the drilling and extraction of samples that will provide contextual information in support of the analysis of PROSPECT measurement data samples. The requirements represent a set of expectations which are considered to be consistent with the technical boundary conditions for PROSPECT.

RQ-CX-010. Images shall be recorded during drilling.

RQ-CX-020. Images obtained during drilling should be recorded at frequencies of up to 10Hz (TBC), subject to mission data handling and downlink limitations.

Comment: This frame rate could be achieved using a sub-frame and need not be achieved using the whole pixel array. It is understood that the ability to generate and to download these images will be limited by the communications link to the lander. No requirement is placed at this time on the time for a given image sequence. A guideline is 5 – 10 second movies should be possible as a minimum with a goal of 1 minute as a driver for memory provision.

RQ-CX-030. Images shall be obtained of the robotic operations involved in the transfer of samples.

Comment: The intention is to generate images of the robotic operations as they occur. There is not a requirement to image the actual samples themselves as they are transferred

RQ-CX-040. Images obtained during the transfer of samples drilling should be recorded at frequencies of up to 10Hz (TBC), subject to mission data handling and downlink limitations.

Comment: This frame rate could be achieved using a sub-frame and need not be achieved using the whole pixel array.

RQ-CX-050. Images shall be obtained which verify the presence of a sample within a sample oven.

RQ-CX-060. Colour static images shall be recorded.

Comment: This can be achieved using different illumination wavelengths with a monochrome device.



RQ-CX-070. The spectral response of any cameras at the illumination wavelengths bands shall be characterised.

Justification: In order to use images at different illumination wavelengths to determine the mineralogy it is important to characterise the effective area of the cameras at those wavelengths, combining the spectral response of the optics and detectors. The final products would be on axis effective area and any off-axis vignetting function.

RQ-CX-080. Images recorded without sunlight (i.e. in shadow) shall be performed with artificial illumination.

RQ-CX-090. Artificial illumination shall be uniform across the image field of view.

Justification: light from any illumination source will be scattered from the regolith, with an angular dependency on the extent of scattering. Such scattering has a spectral response and will affect the interpretation of images. As such it is important that illumination is uniform across the sample, without angular bias (Schmitz et al. (2016)).

Comment: Ideally illumination in all colours / wavelengths shall be performed from the same position. This can only be achieved with a multi-wavelength LED. Individual wavelength LEDs are more easily sourced but will result in different illumination angles (Schmitz et al. (2016)).

RQ-CX-100. Artificial illumination shall be provided at the following (TBC) wavelengths in Table 6.1.

Justification: reflectivity of light at well selected wavelengths can allow the determination of mineralogy of the regolith which provides an important contextual measurement for measurements of volatiles.

The possibility to perform spectral investigations using these illumination wavelengths and with a camera needs to be verified and tested in advance of finalisation of this requirement. The precise wavelengths to be used may be updated based on the availability of suitable LEDs.

Central Wavelength (nm)	Bandwidth (FWHM nm)
440	25
600	20
750	20
930	25
980	30
1000	30

Table 6.1 Illumination wavelengths of interest for the camera (TBC). Schmitz et al (2016).

RQ-CX-101. Images taken in different wavelengths should be taken using a monochromatic imager



Justification: Interpretation of images recorded in different wavelengths is best performed when a monochromatic detector is used (reference document in preparation). Colour sensitive detectors using Bayer filters are difficult, and may be impossible, interpret geologically (reference document in preparation).

RQ-CX-110. Field of view shall be sufficient to image the full diameter of a cuttings pile uplifted by the drill for a drill hole of 1m depth.

RQ-CX-120. The full height of a cuttings pile uplifted by the drill for a drill hole of 1m depth shall be imaged.

RQ-CX-130. Image spatial resolution shall be sufficient to resolve features as small as 0.5mm at the surface, including during drilling.

Justification: 0.5 mm resolution is sufficient to resolve individual larger fragments of the regolith (mean particle diameter is typically around 70µm) as well as (qualitatively) general geomechanical properties of the regolith as it is uplifted.

7 OPERATIONAL EXPERIENCE REQUIREMENTS

PROSPECT offers opportunities to gain important experience on the in-situ operation of such a sampling and sample analysis suite on the Lunar surface. There are many uncertainties on the characteristics and nature of the lunar regolith which the sampling tool must interact with, especially at the poles and in the subsurface. These uncertainties are addressed, at least partially, through ground based experiments, field testing activities, and design assumptions. To understand the actual behaviour and performance of the system in-situ, it is vital to understand what the actual characteristics of the lunar regolith encountered were during operations.

7.1 Objectives associated with Operational Experience

OB-OE-010 Determine the in-situ mechanical properties of the lunar regolith being sampled.

Justification: The mechanical properties of regolith are required to inform the design of future systems. The detailed mechanical properties to be determined is TBD as this the link to the metrics being measured.

OB-OE-020 Understand the in-situ operational behaviour and performance of the PROSPECT package.

Justification: This is needed in order to allow an understanding of the system in the environment to be developed and applied to future projects. The detailed metrics to be recorded is TBD.

OB-OE-030 Make static imagery of all key PROSPECT operations available on ground to support operations and for post-operations analysis.

Justification: This allows lessons to be learned and applied in real time and post mission.

7.2 Requirements associated with Operational Experience

RQ-OE-010 Data shall be obtained which allows determination of the following regolith mechanical properties: unconfined compressive strength, density, cohesion, adhesion

Comment: this requirement needs to be further developed. The link between these properties and the measurements made during drilling, by imaging and through electrical permittivity needs to be established.



RQ-OE-020 Static imagery of the drill site shall be obtained before, during and after drilling operations.

Justification: This provides an important means of assessing the performance of the system and how it is operating. In real time and post mission.

Comment: Details of what shall be image and with what qualities need to be defined.

RQ-OE-030 Imaging of drilling operations shall be possible at intervals of less than 0.2 seconds (TBC).

Justification: This provides an immediate means of assessing the performance of the system and how it is operating.

Comment: Details of the qualities of the video footage need to be defined. Comment applies to the below video related requirements too.

RQ-OE-040 Imagery shall be obtained of the Point of Sample Transfer to the Russian sample handling device, at the time of sample transfer.

RQ-OE-050 Imagery shall be obtained of the Point of Sample Transfer to the ProSPA instrument interface, at the time of sample transfer.

RQ-OE-060 All images of PROSPECT operations received on ground shall have a minimum resolution of 1mm/pixel (TBC).

RQ-OE-070 All images received on ground shall have a minimum size of 1024 x 1024 pixels.

RQ-OE-080 All imagery shall be available for use in supporting operations a maximum of TBD minutes after the operations observed.

Comment: This requirement should be included in the requirements provided to the platform / partner and may not need to be reflected in the SRD.

RQ-OE-090 Localisation aids shall be provided to give reference to imagery.

Comment: Better to give a required position knowledge.

RQ-OE-100 Colour calibration aids shall be provided to give reference to imagery.



Comment: Better to provide requirements on the image product qualities that might require calibration targets.

The following requirement defined in Section 6 applies:

RQ-CX-080 Images recorded without sunlight (i.e. in shadow) shall be performed with artificial illumination.

~~RQ-OE-110 Artificial illumination shall be provided to support imaging operations in low light or dark conditions.~~

Comment: Better to provide the imaging requirement that is likely to lead to the need for a light source or perhaps accept that the requirement to image will in of itself result in the introduction of a light source.

RQ-OE-120 Temperatures at all critical locations, including as a minimum the drill tip, sample chamber, drill rod and all actuators, shall be recorded with an uncertainty of 1K (TBC), during all drilling operations.

8 OUTREACH & COMMUNICATIONS USER REQUIREMENTS

8.1 Objectives associated with Outreach & Communications

OB-OC-001 Ensure that a broad section of the general public are aware of PROSPECT and its objectives and are engaged prior to, during and post flight.

8.2 Requirements associated with Outreach & Communications

RQ-OC-010 Static imagery shall be obtained of the drill site before, during and after drilling operations.

Justification: Static images may be available on a shorter timescale and can provide rapid and broad access to the public (via web, TV, print).

Comment: Image qualities need to be defined.

RQ-OC-020 Video footage shall be obtained of all (TBC) drilling operations.

Justification: Video footage can effectively convey the reality of the operations performed and make them easily understood by the public.

Comment: video qualities need to be defined – perhaps superseded by 10Hz requirement introduced in context requirements.

The following requirements defined in Section 7.2 apply:



RQ-OE-020 Static imagery of the drill site shall be obtained before, during and after drilling operations.

RQ-OE-040 Imagery shall be obtained of the Point of Sample Transfer to the Russian sample handling device, at the time of sample transfer.

RQ-OE-050 Imagery shall be obtained of the Point of Sample Transfer to the ProSPA instrument interface, at the time of sample transfer.

~~RQ-OC-030 Static imagery shall be obtained of the Point of Sample Transfer to the Russian sample handling device, at the time of sample transfer.~~

~~RQ-OC-040 Static imagery shall be obtained of the Point of Sample transfer to the ProSPA instrument interface, at the time of sample transfer.~~

RQ-OC-050 Video footage shall be obtained of the Point of Sample Transfer to the Russian sample handling device, at the time of sample transfer.

RQ-OC-060 Video footage shall be obtained of the Point of Sample Transfer to the ProSPA instrument interface, at the time of sample transfer.

~~RQ-OC-070 Ensure all static images received on ground are of a minimum resolution of 1mm/pixel (TBC).~~

RQ-OC-080 Static images shall be produced with a minimum size of 1M pixels with a goal of 4M pixels.

Comment: 4Mpixels is considered a minimum size for public engagement related images.

~~RQ-OC-090 Ensure all video footage received on ground is of a minimum resolution of TBD mm/pixel.~~

RQ-OC-100 Video footage shall be generated with a size of 1Mpixels with a goal of 4M pixels.

Comment: Lower resolution video is also possible but 4Mpixel video should be achieved.

RQ-OC-101. Video footage shall be generated with a frame rate of up to 10Hz with a goal of 50Hz.

Justification: Human brain can identify up to 10 separate images per second. Typically 50Hz is the frame rate required to provide a sense of image stability.



Comment: This frame rate could be achieved using a sub-frame and need not be achieved using the whole pixel array.

RQ-OC-102. Static images in colour shall be generated

RQ-OC-110 All static and video imagery shall be available for outreach and communications use a maximum of 12 hours after the operations observed.

Comment: This requirement should be included in the requirements provided to the platform / partner and may not need to be reflected in the SRD.

The following requirement defined in Section 6 applies:

RQ-CX-080 Images recorded without sunlight (i.e. in shadow) shall be performed with artificial illumination.

~~RQ-OC-120 Artificial illumination shall be provided to support imaging operations in low light or dark conditions.~~

9 SUMMARY OF REQUIREMENTS

9.1 Sample Requirements

- RQ-SA-010* Samples shall be extracted from sites where cold trapped volatiles are expected based on data from previous missions.
- RQ-SA-020* Samples shall be taken from depths from the top cm of the surface up to a depth of 1m with a goal of 1.2m.
- RQ-SA-030* Losses of ice from the sampled material from its original state to the point of analysis shall be no greater than 5%(TBC) for samples containing more than or equal to 1% (TBD) by weight water ice.
- RQ-SA-040* The depths from which delivered samples are extracted shall be determined within an uncertainty of $\pm 10\text{mm}$ (TBC).
- RQ-SA-050* It shall be possible to collect samples from depth intervals of 200 mm or less
- RQ-SA-060* Acquired samples shall be demonstrated, by tests on analogues, to be representative of original sampled material in terms of the relative proportions of fines ($5\mu\text{m} - 0.5\text{mm}$), coarse particles ($>0.5\text{mm}$) and ices.
- RQ-SA-070* Data shall be generated that allows the losses of ice and other volatiles during sample handling to be determined.
- RQ-SA-071* The temperature of samples should be recorded from acquisition to delivery with an uncertainty of 0.1K (TBC) between 110K and 180K.
- RQ-SA-072* The temperature of samples shall be recorded from acquisition to delivery with an uncertainty of 1K (TBC) for temperatures above 180K.
- RQ-SA-073* The mechanical environment of samples shall be determined from the acquisition to delivery
- RQ-SA-080* The level of terrestrial contamination in measurements shall be sufficiently low as to allow measurements of samples in line with the requirements
- RQ-SA-090* The level of contamination from the lander, it's fuel or exhaust products in measurements shall be sufficiently low as to allow measurements of samples in line with the requirements.
- RQ-SA-100* The level of cross-contamination between samples shall be sufficiently low as to allow measurements which are representative of separate samples in line with the requirements.
- RQ-SA-110* Images should be produced of samples within ovens with resolution of better than or equal to $10\mu\text{m}$ per pixel.
- RQ-SA-120* Samples shall be extracted from sites which are distinct from those for which data currently exists.
- RQ-SA-130* Samples shall be taken from depths which are sufficient to ensure that contamination due to a lander are negligible.



RQ-SA-140 Losses of chemisorbed and solar wind implanted volatiles from the sampled material from its original state to the point of analysis shall be no greater than 5%(TBC).

RQ-SA-150 Samples of regolith shall be extracted for processing and analysis.

9.1.1.1 Oxygen from minerals; extraction and measurement requirements

RQ-OM-010 The bulk mineralogy of samples should be determined

RQ-OM-020 Where suitable mineralogy is present, oxygen shall be extracted from minerals in regolith by reduction in hydrogen.

RQ-OM-030 Oxygen should be extracted from minerals using methane as a reductant.

RQ-OM-040 The yield of oxygen shall be determined

RQ-OM-050 The presence of oxygen and any other products of the reactions shall be identified.

RQ-OM-060 The temperatures at which the reaction takes place shall be measured to $\pm 1^{\circ}\text{C}$.

9.1.1.2 Volatile extraction and measurement requirements

RQ-EM-010 Volatiles shall be extracted from lunar regolith samples by heating.

RQ-EM-020 The chemical identity of chemical species with m/z between 2 and 200 shall be determined when in concentrations greater than 1ppb (TBC).

RQ-EM-030 A quantitative measure of the total volatile yield (uncertainty TBD) and the yields for individual volatiles (uncertainty TBD) shall be provided as a function of the sample mass.

RQ-EM-040 The abundance of any precursors within the regolith to the liberated volatiles which are produced during the extraction process should be determined with an uncertainty of $\pm 50\%$ (TBD)

9.1.1.3 Organic Compound extraction and measurement requirements

RQ-PB-010 Organic compounds shall be extracted from lunar regolith samples.

RQ-PB-020 Organic molecules, which have been evolved from samples and which were present in those samples in concentrations greater than 1ppm (TBC) should be identified.

RQ-PB-030 The precursors of those evolved organic compounds should be determined

RQ-PB-040 Measured organic molecules shall be associated with elemental isotopic measurements.

RQ-PB-050 The presence of organic molecules shall confirmed when in concentrations greater than 1pbb (TBC)

9.1.1.4 Isotopic analysis requirements

- RQ-IS-010 The isotopic composition of hydrogen in volatile species in lunar regolith samples, δD , shall be determined with an uncertainty of 100‰
- RQ-IS-020 As a goal the isotopic composition of carbon in volatile species in lunar regolith samples, $\delta^{13}C$, should be determined with an uncertainty of 1‰. As a goal the isotopic composition of carbon in volatile species in lunar regolith samples, $\delta^{13}C$, should be determined with an uncertainty of 1‰.
- RQ-IS-030 The isotopic composition of nitrogen in volatile species in lunar regolith samples, $\delta^{15}N$, shall be determined with an uncertainty of 10‰.
- The isotopic composition of nitrogen in volatile species in lunar regolith samples, $\delta^{15}N$, shall be determined with an uncertainty of 10‰. RQ-IS-040 The isotopic composition of oxygen in volatile species in lunar regolith samples, $\delta^{18}O$, shall be determined with an uncertainty of 1‰.
- RQ-IS-050 As a goal The isotopic composition of oxygen in volatile species in lunar regolith samples, $\delta^{17}O$, shall be determined with an uncertainty of 0.1‰.
- RQ-IS-060 Isotopic measurements described above shall be possible, where relevant, for all chemical species defined in Table 2.3 and Table 2.4 if present above 1 ppm (TBC).
- RQ-IS-070 Isotopic measurements of elements should be associated with their precursor compounds.

9.1.1.5 Measurement Context Requirements

- RQ-CX-010 Images shall be recorded during drilling
- RQ-CX-020 Images obtained during drilling should be recorded at frequencies of up to 10Hz (TBC), subject to mission data handling and downlink limitations
- RQ-CX-030 Images shall be obtained of the robotic operations involved in the transfer of samples
- RQ-CX-040 Images obtained during the transfer of samples drilling should be recorded at frequencies of up to 10Hz (TBC), subject to mission data handling and downlink limitations
- RQ-CX-050 Images shall be obtained which verify the presence of a sample within a sample oven
- RQ-CX-060 Colour static images shall be recorded.
- RQ-CX-070 The spectral response of any cameras at the illumination wavelengths bands shall be characterised
- RQ-CX-080 Images recorded without sunlight (i.e. in shadow) shall be performed with artificial illumination
- RQ-CX-090 Artificial illumination shall be uniform across the image field of view



- RQ-CX-100 Artificial illumination shall be provided at the following (TBC) wavelengths in Table 6.1.
- RQ-CX-101 Images taken in different wavelengths should be taken using a monochromatic imager
- RQ-CX-110 Field of view shall be sufficient to image the full diameter of a cuttings pile uplifted by the drill for a drill hole of 1m depth
- RQ-CX-120 The full height of a cuttings pile uplifted by the drill for a drill hole of 1m depth shall be imaged.
- RQ-CX-130 Image spatial resolution shall be sufficient to resolve features as small as 0.5mm at the surface, including during drilling.

9.1.1.6 Requirements associated with Operational Experience

- RQ-OE-010 Data shall be obtained which allows determination of the following regolith mechanical properties: unconfined compressive strength, density, cohesion, adhesion
- RQ-OE-020 Static imagery of the drill site shall be obtained before, during and after drilling operations.
- RQ-OE-030 Imaging of drilling operations shall be possible at intervals of less than 0.2 seconds (TBC).
- RQ-OE-040 Imagery shall be obtained of the Point of Sample Transfer to the Russian sample handling device, at the time of sample transfer.
- RQ-OE-050 Imagery shall be obtained of the Point of Sample Transfer to the ProSPA instrument interface, at the time of sample transfer.
- RQ-OE-060 All images of PROSPECT operations received on ground shall have a minimum resolution of 1mm/pixel (TBC).
- RQ-OE-070 All images received on ground shall have a minimum size of 1024 x 1024 pixels.
- RQ-OE-080 All imagery shall be available for use in supporting operations a maximum of TBD minutes after the operations observed.
- RQ-OE-090 Localisation aids shall be provided to give reference to imagery.
- RQ-OE-100 Colour calibration aids shall be provided to give reference to imagery.
- RQ-OE-110 ~~Artificial illumination shall be provided to support imaging operations in low light or dark conditions.~~
- RQ-OE-120 Temperatures at all critical locations, including as a minimum the drill tip, sample chamber, drill rod and all actuators, shall be recorded with an uncertainty of 1K (TBC), during all drilling operations.



9.1.1.7 Requirements Associated with Outreach & Communications

- RQ-OC-010 Static imagery shall be obtained of the drill site before, during and after drilling operations.
- RQ-OC-020 Video footage shall be obtained of all (TBC) drilling operations.
- RQ-OC-030 ~~Static imagery shall be obtained of the Point of Sample Transfer to the Russian sample handling device, at the time of sample transfer.~~
- RQ-OC-040 ~~Static imagery shall be obtained of the Point of Sample transfer to the ProSPA instrument interface, at the time of sample transfer.~~
- RQ-OC-050 Video footage shall be obtained of the Point of Sample Transfer to the Russian sample handling device, at the time of sample transfer.
- RQ-OC-060 Video footage shall be obtained of the Point of Sample Transfer to the ProSPA instrument interface, at the time of sample transfer:
- RQ-OC-070 ~~Ensure all static images received on ground are of a minimum resolution of 1mm/pixel (TBC).~~
- RQ-OC-080 Static images shall be produced with a minimum size of 1M pixels with a goal of 4M pixels.
- RQ-OC-090 ~~Ensure all video footage received on ground is of a minimum resolution of TBD mm/pixel.~~
- RQ-OC-100 Video footage shall be generated with a size of 1Mpixels with a goal of 4M pixels.
- RQ-OC-101 Video footage shall be generated with a frame rate of up to 10Hz
- RQ-OC-102 Static images in colour shall be generated
- RQ-OC-110 All static and video imagery shall be available for outreach and communications use a maximum of 12 hours after the operations observed.
- RQ-OC-120 ~~Artificial illumination shall be provided to support imaging operations in low light or dark conditions.~~

10 REFERENCES

- Albarède, F., 2009. Volatile accretion history of the terrestrial planets and dynamic implications, *Nature*, 461, 1227-1233.
- Albarede, F.; Ballhaus, C.; Blichert-Toft, J.; Lee, C.; Marty, B.; Moynier, F.; Yin, Q., 2013. Asteroidal impacts and the origin of terrestrial and lunar volatiles, 2013, *Icarus*, 222, 1, 44-52.
- Anand et al., A standard material for PROSPECT measurement performance verification, TBW September 2016, expected delivery date Q2 2017.
- Anand, M., 2010. Lunar water: A brief review. *Earth, Moon and Planets* 107, 65–73.
- Anand, M.; Crawford, I. A.; Balat-Pichelin, M.; Abanades, S.; van Westrenen, W.; Péraudeau, G.; Jaumann, R.; Seboldt, W., 2012. A brief review of chemical and mineralogical resources on the Moon and likely initial in situ resource utilization (ISRU) applications, *Planetary and Space Science*, 74, 1, 42-48.
- Andreas, E.L., 2007. New estimates for the sublimation rate for ice on the Moon, *Icarus*, 186, 24–30.
- Armstrong J. C., Wells L. E., and Gonzalez G., 2002. Rummaging through Earth's attic for remains of ancient life. *Icarus*. 160, 183-196.
- Armstrong J. C., 2010. Distribution of impact locations and velocities of Earth meteorites on the Moon. *Earth Moon Planets*. 107, 43-54.
- Arnold, J.R., 1979. Ice at the lunar poles, *J.Geophys.Res.*, 84, 5659–5668.
- Barbar et al., 2012, L-VRAP final report, ESA GSP study.
- Barnes J. J., Franchi I. A., Anand M., Tartèse R., Starkey N. A., Koike M., Sano Y. and Russell S. S., 2013a. Accurate and precise measurements of the D/H ratio and hydroxyl content in lunar apatites using NanoSIMS. *Chem. Geol.* 337-338, 48-55.
- Barnes, J. J., Tartèse, R., Anand, M., Starkey, N. A., Franchi, I. A. & Russell, S. S., 2013b. Investigating the H₂O content and H isotopic composition of the primitive lunar magma ocean (LMO) cumulates. *Earth Planet. Sci. Conf.*, Abstract EPSC2013-105.
- Berezhnoy A. A., Kozlova E.A., Sinitsyn, M.P., Shangaraev, A.A. and Shevchenko V.V., 2012, Origin and stability of lunar polar volatiles, *Advances in Space Research*, 50, 1638-1646.
- Bernstein, M.P., Dworkin, J.P., Sandford, S.A., Cooper, G.W., and Allamandola, L.J. 2002. The formation of racemic amino acids by ultraviolet photolysis of interstellar ice analogs. *Nature*, 416:401-403.
- Bockelée-Morvan, D., Lis, D.C., Wink, J.E., Despois, D., Crovisier, J., Bachiller, R., Benford, D.J., Biver, N., Colom, P., Davies, J.K., Gerard, E., Germain, B., Houde, M., Mehringer, D., Moreno, R., Paubert, G., Phillips, T.G., and Rauer, H., 2000. New molecules

found in comet C/1995 O1 (Hale–Bopp). Investigating the link between cometary and interstellar material. *Astronomy and Astrophysics*, 353, 1101–1114.

Botta, O. and Bada, J.L., 2002. Extraterrestrial organic compounds in meteorites. *Surveys in Geophysics*, 23, 411–467.

Bottke, W. F.; Walker, R. J.; Day, J. M. D.; Nesvorný, D.; Elkins-Tanton, L., 2010. Stochastic Late Accretion to Earth, the Moon, and Mars, *Science*, 330, 6010, 1527.

Boyce, J.W., Liu, Y., Rossman, G.R., Guan, Y., Eiler, J.M., Stolper, E.M., Taylor, L.A., 2010. Lunar apatite with terrestrial volatile abundances. *Nature*, 466, 466–469.

Buck, A.L., 1981. New equations for computing vapor pressure and enhancement factor. *J. Appl. Meteor.* 20, 1527–1532.

Carpenter, J. and the PROSPECT User Group, 2016, reference volatile content for polar lunar samples. PROSPECT User Group technical note, in preparation September 2016 expected delivery October 2016.

Chaussidon, M. and Robert, F., 1999, Lithium nucleosynthesis in the Sun inferred from the solar-wind $^7\text{Li}/^6\text{Li}$ ratio, *Nature*, 402, 6759, 270–273.

Chyba, C. and Sagan, C., 1992. Endogenous production, exogenous delivery and impact-shock synthesis of organic molecules: an inventory for the origins of life. *Nature*, 355, 125–132.

Colaprete, A., Schultz, P., Heldmann, J., Wooden, D., Shirley, M., Ennico, K, et al., 2010. Detection of water in the LCROSS ejecta plume. *Science*, 330, 6003, 463–468.

Crawford, I.A., Anand, M., Cockell, C.S., Falcke, H., Green, D.A., Jaumann, R., Wicczorek, M.A., 2012. Back to the Moon: the scientific rationale for resuming lunar surface exploration. *Planetary and Space Science* <http://dx.doi.org/10.1016/j.pss.2012.06.002>.

Crites, S. T.; Lucey, P. G.; Lawrence, D. J., 2011. In-situ production of organic molecules at the poles of the Moon, AGUFM.P13D1730C.

Crovisier, J., Bockelee-Morvan, D., Colom, P., Biver, N., Despois, D., and Lis, D.C., 2004. The composition of ices in comet C/1995 O1 (Hale–Bopp) from radio spectroscopy. Further results and upper limits on undetected species, *Astronomy and Astrophysics*, 418, 1141–1157.

Dehant, V.; Breuer, D.; Claeys, P.; Debaille, V.; De Keyser, J.; Javaux, E.; Goderis, S.; Karatekin, Ö.; Spohn, Y.; Vandaele, A.C.; Vanhaecke, F.; Van Hoolst, T.; Wilquet, V., 2012. From meteorites to evolution and habitability of planets, *Planetary and Space Science*, 72, 1, 3–17.

Ehrenfreund, P. and Charnley, S.B., 2000, Organic molecules in the interstellar medium, comets, and meteorites: a voyage from dark clouds to the early Earth. *Annual Review of Astronomy and Astrophysics*, 38, 427–483.

Elphic, R. C.; Eke, V. R.; Teodoro, L. F. A.; Lawrence, D. J.; Bussey, D. B. J., 2007, Models of the distribution and abundance of hydrogen at the lunar south pole, *Geophysical Research Letters*, 34, 13, CiteID L13204.



- Elsila, J.E., Dworkin, J.P., Bernstein, M.P., Martin, M.P., Sandford, S.A., 2007. Mechanisms of Amino Acid Formation in Interstellar Ice Analogs. *Astrophys. J.*, 660, 911-918.
- Fa, W.Z., Jin, Y.Q., 2010. Global inventory of helium-3 in lunar regoliths estimated by a multi-channel microwave radiometer on the Chang-E 1 lunar satellite. *Chinese Science Bulletin* 55, 35, 4005–4009.
- Fagan, A.L. and Kring, D. A., 2013. Personal communication.
- Fegley, B., Jr.; Swindle, T. D., 1993. Lunar volatiles: implications for lunar resource utilization, *Resources of near-Earth space*, University of Arizona Press, 367 – 426.
- Feldman, W. C.; Maurice, S.; Binder, A. B.; Barraclough, B. L.; Elphic, R. C.; Lawrence, D. J., 1998. Fluxes of Fast and Epithermal Neutrons from Lunar Prospector: Evidence for Water Ice at the Lunar Poles, *Science*, 281, 5382, 1496.
- Feldman, W. C.; Maurice, S.; Binder, A. B.; Barraclough, B. L.; Elphic, R. C.; Lawrence, D. J., 1998,. Fluxes of Fast and Epithermal Neutrons from Lunar Prospector: Evidence for Water Ice at the Lunar Poles, *Science*, 281, 5382, 1496
- Formisano, M.; De Sanctis, M.C.; De Angelis, S., 2016, Modelling of water ice sublimation from PROSPECT regolith samples, PROSPECT User Group technical report, in preparation Septemehr 2016 expected delivery October 2016.
- Füri, E., Marty, B., 2015. Nitrogen isotope variations in the solar system. *Nature Geoscience* 8, 515-522.
- Glotch, T.D., Lucey, P.G., Bandfield, J.L., Greenhagen, B.T., Thomas, I.R., Elphic, R.C., Bowles, N., Wyatt, M.B., Allen, C.C., Hanna, K.D., Paige, D.A., 2010. Highly silicic compositions on the Moon. *Science*, 329, 1510–1513.
- Greenberg, P.S., Chen, D.-R. and Smith, S.A., 2007. Aerosol Measurements of the Fine and Ultrafine Particle Content of Lunar Regolith, NASA TM/2007-214956.
- Greenhagen, B.T., et al., 2010. Global silicate mineralogy of the Moon from the Diviner lunar radiometer. *Science* 329, 1507–1509.
- Greenwood, J.P., Itoh, S., Sakamoto, N., Warren, P., Taylor, L., Yurimoto, H., 2011. Hydrogen isotope ratios in lunar rocks indicate delivery of cometary water to the Moon. *Nature Geoscience* 4, 79–82.
- Gutiérrez J. L. ,2002. Terrene meteorites in the moon: its relevance for the study of the origin of life in the Earth In: *Proceedings of the First European Workshop on Exo-Astrobiology*. 16 - 19 September 2002, Graz, Austria. Ed.: Huguette Lacoste. ESA SP-518, Noordwijk, Netherlands: ESA Publications Division, ISBN 92-9092-828-X, pp. 187-191
- Hashizume, K.; Chaussidon, M.; Marty, B.; Robert, F., Solar Wind Record on the Moon: Deciphering Presolar from Planetary Nitrogen, *Science*, 290, 5494, 1142-1145.
- Haskin, L.A., Colson, R.O., Vaniman, D.T., Gillett, S.L., 1993. A geochemical assessment of possible lunar ore formation. In: Lewis, John S., Matthews, Mildred Shapely, Guerrieri, Mary L. (Eds.), *resources of Near-Earth Space*. The University of Arizona Press, Tucson, Arizona, 977.

- Hauri, E.H., Weinreich, T., Saal, A.E., Rutherford, M.C., Van Orman, J.A., 2011. High pre-eruptive water contents preserved in Lunar melt inclusions. *Science*, 333, 213–215.
- Hibbits, C.A., Grieves, G.A., Poston, M.J., Dyar, M.D., Alexandrov, A.B., Johnson, M.A., Orlando, T.M., 2011. Thermal stability of water and hydroxyl on the surface of the Moon from temperature-programmed desorption measurements of lunar analogue materials, *Icarus*, 213, 64-72.
- Hiesinger, H., Jaumann, R., Neukum, G., Head III, J.W., 2000. Ages of mare basalts on the lunar nearside. *Journal of Geophysical Research* 105 (E12), 29239–29275.
- Jolliff, B.L., Gillis, J.J., Haskin, L.A., Korotev, R.L., Wiczorek, M.A., 2000. Major lunar crustal terranes: surface expressions and crust-mantle origins. *Journal of Geophysical Research* 105, 4197–4216.
- Jolliff, B.L., et al., 2011. Non-mare silicic volcanism on the lunar farside at Compton–Belkovich. *Nature Geoscience* 4, 566–571.
- Liu, Y., Schnare, D.W., Eimer, B.C., Taylor, L.A., 2008. Dry separation of respirable lunar dust: providing samples for the lunar airborne dust toxicity advisory group. *Planetary and Space Science*, 56, 1517–1523.
- Liu, Y. and Taylor, L.A., 2011. Characterization of lunar dust and a synopsis of available lunar simulants. *Planetary and Space Science* 59, 1769–1783.
- Loftus, D.J., Rask, J.C., McCrossin, C.G., Tranfield, E.M., 2010. The chemical reactivity of lunar dust: from toxicity to astrobiology. *Earth Moon and Planets* 107, 95–105.
- Lucey, P.G., 2000. Potential for prebiotic chemistry at the poles of the Moon. *Proc. SPIE*, 4137, 84-88.
- Lucey, P., Korotev, R.L., Gillis, J.J., Taylor, L.A., Lawrence, D., Campbell, B.A., Elphic, R., Feldman, B., Hood, L.L., Hunten, D., Mendillo, M., Noble, S., Papike, J.J., Reedy, S., Lawson, S., Prettyman, T., Gasnault, O., Maurice, S., 2006. Understanding the lunar surface and Space–Moon interactions. *Reviews in Mineralogy and Geochemistry* 60, 83–219.
- Martins, Z. and Sephton, S.A., 2009, Extra terrestrial amino acids, in *Amino Acids, Peptides and Proteins in Organic Chemistry*. Vol.1 – Origins and Synthesis of Amino Acids., Ed. A. B. Hughes, Wiley, Germany, ISBN: 978-3-527-32096-7.
- Martins, Z., et al., 2013. Shock synthesis of amino acids from impacting cometary and icy planet surface analogues, *Nature Geoscience*, 6, 1045-1049.
- Mazarico, E., G. A. Neumann, D. E. Smith, M. T. Zuber, and M. H. Torrence, 2011, Illumination conditions of the lunar polar regions using LOLA topography, *Icarus*, 211, 1066–1081, doi:10.1016/j.icarus.2010.10.030.
- McCubbin, F.M., Kaaden, K.E.V., Tartese, R., Klima, R.L., Liu, Y., Mortimer, J., Barnes, J.J., Shearer, C.K., Treiman, A.H., Lawrence, D.J. and Elardo, S.M., 2015. Magmatic volatiles (H, C, N, F, S, Cl) in the lunar mantle, crust, and regolith: Abundances, distributions, processes, and reservoirs. *American Mineralogist*, 100(8-9), pp.1668-1707.

- McCubbin, F.M., Steele, A., Hauri, E.H., Nekvasil, H., Yamashita, S., Hemley, R.J., 2010. Nominally hydrous magmatism on the Moon. *Proceedings of the National Academy of Sciences USA* 27, 11223–11228.
- McGovern, J. Andrew; Bussey, D. Benjamin; Greenhagen, Benjamin T.; Paige, David A.; Cahill, Joshua T. S.; Spudis, Paul D., 2013. Mapping and characterization of non-polar permanent shadows on the lunar surface, *Icarus*, 223, 1, 566-581.
- McKay, D.S., Heiken, G.H., Basu, A., Blanford, G., Simon, S., Reedy, R., French, B.M., Papike, J., 1991. The lunar regolith. In: Heiken, G.H., Vaniman, D., French, B.M. (Eds.), *The Lunar Sourcebook: A User's Guide to the Moon*. Cambridge University Press, 285–356.
- McSween H. Y., Jr., 1976. A new type of chondritic meteorite found in lunar soil. *Earth and Planet. Sci. Lett.* 31, 193-199.
- Meinert, C., Filippi, J. J., de Marcellus, P., Le Sergeant d'Hendecourt, L., Meierhenrich, U. J., 2012. N-(2-Aminoethyl) glycine and amino acids from interstellar ice analogues. *ChemPlusChem.*, 77, 186 – 191.
- Mitrofanov, I.; Litvak, M.; Sanin, A.; Malakhov, A.; Golovin, D.; Boynton, W.; Droege, G.; Chin, G.; Evans, L.; Harshman, K.; Fedosov, F.; Garvin, J.; Kozyrev, A.; McClanahan, T.; Milikh, G.; Mokrousov, M.; Starr, R.; Sagdeev, R.; Shevchenko, V.; Shvetsov, V.; Tret'yakov, V.; Trombka, J.; Varenikov, A.; Vostrukhin, A., 2012, Testing polar spots of water-rich permafrost on the Moon: LEND observations onboard LRO, *Journal of Geophysical Research*, 117, CiteID E00H27.
- Mortimer, J. et al., 2016, Experimental investigations into ice sublimation, PROSPECT technical report, in preparation September 2016. Expected delivery November 2016.
- Mortimer, J., Verchovsky, A.B. and Anand, M., 2016. Predominantly non-solar origin of nitrogen in lunar soils. *Geochimica et Cosmochimica Acta*, 193, 36-53.
- Mortimer, J., Verchovsky, A. B., Anand, M., Gilmour, I., Pillinger, C. T., 2014. Simultaneous Analysis of Abundance and Isotopic Composition of Helium, Neon, and Argon in Lunar Basalts, In *Lunar and Planetary Institute Science Conference Abstracts* 45, 2503.
- Mumma, M.J., DiSanti, M.A., Magee-Sauer, K., Bonev, B.P., Villanueva, G.L., Kawakita, H., Dello Russo, N., Gibb, E.L., Blake, G.A., Lyke, J.E., Campbell, R.D., Aycock, J., Conrad, A., and Hill, G.M., 2005. Parent volatiles in comet 9P/ Tempel 1: before and after impact. *Science*, 310, 270–274.
- Muñoz Caro, G. M., Meierhenrich, U. J., Schutte, W. A., Barbier, B., Arcones Segovia, A., Rosenbauer, H., Thiemann, W. H.-P., Brack, A., Greenberg, J. M., 2002. Amino acids from ultraviolet irradiation of interstellar ice analogues, *Nature*, 416, 6879, 403-406.
- Murphy, D.M. and Koop, T., 2005. Review of the vapour pressures of ice and supercooled water for atmospheric applications. *Quart. J. R. Meteor. Soc.* 131, 1539–1565.
- Neal, C.R., Taylor, L.A., 1992. Petrogenesis of mare basalts: a record of lunar volcanism. *Geochimica et Cosmochimica Acta*, 56, 2177–2211.
- Ohtake, M., et al., 2009. The global distribution of pure anorthosite on the Moon. *Nature*, 461, 236–240.

- Ozima, M.; Seki, K.; Terada, N.; Miura, Y. N.; Podosek, F. A.; Shinagawa, H., 2005. Terrestrial nitrogen and noble gases in lunar soils, *Nature*, 436, 7051, 655-659.
- Ozima, M.; Yin, Q.-Z.; Podosek, F. A.; Miura, Y. N., 2008. Toward understanding early Earth evolution: Prescription for approach from terrestrial noble gas and light element records in lunar soils, *Proceedings of the National Academy of Sciences*, 105, 46, 17654-17658.
- Paige, D.A.; Siegler, M.A.; Zhang, J. A.; Hayne, P.O.; Foote, E.J.; Bennett, K.A.; Vasavada, A.R.; Greenhagen, B.T.; Schofield, J.T.; McCleese, D.J.; Foote, M.C.; DeJong, E.; Bills, B.G.; Hartford, W.; Murray, B. C.; Allen, C. C.; Snook, K.; Soderblom, L. A.; Calcutt, S.; Taylor, F. W.; Bowles, N. E.; Bandfield, J. L.; Elphic, R.; Ghent, R.; Glotch, T. D.; Wyatt, M. B.; Lucey, P. G., 2010. Diviner Lunar Radiometer Observations of Cold Traps in the Moon's South Polar Region, *Science*, 330, 6003, 479.
- Papike, J.J., Simon, S.B., Laul, J.C., 1982. The lunar regolith: chemistry, mineralogy, and petrology. *Reviews of Geophysics and Space Physics* 20, 4, 761-826.
- Pierazzo, E., Chyba, C.F., 1999. Amino acid survival in large cometary impacts. *Meteorit. Planet. Sci.*, 34, 909-918.
- Pizzarello, S., Huang, Y., Becker, L., Poreda, R.J., Nieman, R.A., Cooper, G., and Williams, M., 2001. The organic content of the Tagish Lake meteorite. *Science*, 293, 2236-2239.
- Robert, F., 2006. Solar System Deuterium/Hydrogen Ratio. *Meteorites and the Early Solar System II*, 943.
- Saal, A.E., Hauri, E.H., Cascio, M.L., van Orman, J.A., Rutherford, M.C., Cooper, R.F., 2008. Volatile content of lunar volcanic glasses and the presence of water in the Moon's interior. *Nature*, 454, 7201, 192-195.
- Saal A. E., Hauri E. H., Van Orman J. A. and Rutherford M. J., 2013. Hydrogen isotopes in lunar volcanic glasses and melt inclusions reveal a carbonaceous chondrite heritage. *Science* 340, 1317-1320.
- Savoia et al., 2014, Handling planetary ices sample chain requirements, ESA GSP study "handling planetary ices", HPI-REQ-SES-001.
- Schmitt, H.H., 2006. *Return to the Moon*. Praxis Publishing Ltd.
- Schmitz, N. et al. (2016), PROSPECT User Group Report, in preparation September 2016 expected delivery October 2016.
- Schorghofer and Taylor, 2007. Subsurface migration of H₂O at lunar cold traps, *JGR*.
- Schwandt, C.; Hamilton, J. A.; Fray, D. J.; Crawford, I A., 2012. The production of oxygen and metal from lunar regolith, *Planetary and Space Science*, 74, 1, 49-56.
- Seboldt, W.; Lingner, S.; Hoernes, S.; Grimmeisen, W.; Lekies, R.; Herkelmann, R.; Burt, D. M., 1993. *Lunar Oxygen Extraction Using Fluorine, Resources of near-earth space*. Edited by John S. Lewis, Mildred S. Matthews, and Mary L. Guerrieri. Space Science Series. Tucson, London: The University of Arizona Press, 129.

Sephton, M.A., 2002. Organic compounds in carbonaceous meteorites. *Natural Product Reports*, 19, 292–311.

Sephton, M.A. and Botta, O., 2005. Recognizing life in the Solar System: guidance from meteoritic organic matter. *International Journal of Astrobiology*, 4, 269–276.

Siegler, M.A.; Bills, B.G.; Paige, D.A., 2011. Effects of orbital evolution on lunar ice stability, *Journal of Geophysical Research*, Volume 116, Issue E3, CiteID E03010.

Spudis, P. D.; Bussey, D. B. J.; Baloga, S. M.; Butler, B. J.; Carl, D.; Carter, L. M.; Chakraborty, M.; Elphic, R. C.; Gillis-Davis, J. J.; Goswami, J. N.; Heggy, E.; Hillyard, M.; Jensen, R.; Kirk, R. L.; LaVallee, D.; McKerracher, P.; Neish, C. D.; Nozette, S.; Nylund, S.; Palsetia, M.; Patterson, W.; Robinson, M. S.; Raney, R. K.; Schulze, R. C.; Sequeira, H.; Skura, J.; Thompson, T. W.; Thomson, B. J.; Ustinov, E. A.; Winters, H. L., 2010. Initial results for the north pole of the Moon from Mini-SAR, Chandrayaan-1 mission, *Geophysical Research Letters*, Volume 37, Issue 6, CiteID L06204.

Sephton, M.A., Botta, O., 2005. Recognising life in the solar system: guidance from meteoritic organic matter. *International Journal of Astrobiology* 4, 269–276. Stacy, N. J. S.; Campbell, D. B.; Ford, P. G., 1997. Arecibo radar mapping of the lunar poles: A search for ice deposits, *Science*, vol. 276, p. 1527-1530.

Starukhina, L., 2012. Water on the Moon: What is derived from the observations?. In: Badescu, V. (Ed.), *Moon: Prospective Energy and Material Resources*. Springer, Heidelberg, 57–85.

Strasdeit, H., 2010. Chemical evolution and early Earth's and Mars' environmental conditions, *Paleodiversity*, 107-116, Supplement, 3.

Sunshine, J.M., Besse, S., Petro, N.E., Pieters, C.M., Head, J.W., Taylor, L.A., Klima, R.L., Isaacson, P.J., Boardman, J.W., Clark, R.C. and the M3 Team, 2010. Hidden in plain sight: spinel-rich deposits on the nearside of the Moon as revealed by Moon Mineralogy Mapper (M3). *Lunar and Planetary Science Conference (abstract#1508)*. Tartèse, R. & Anand, M., 2013. Late delivery of chondritic hydrogen into the lunar mantle: Insights from mare basalts. *Earth Planet Sci. Lett.* 361, 480-486.

Tartèse, R. and Anand, M., 2013, Late delivery of chondritic hydrogen into the lunar mantle: Insights from mare basalts, *Earth and Planetary Science Letters*, 361, 480-486.

Tartèse, R., Anand, M., Barnes, J.J., Starkey, N.A., Franchi, I.A., Sano, Y., 2013. The abundance, distribution, and isotopic composition of Hydrogen in the Moon as revealed by basaltic lunar samples: Implications for the volatile inventory of the Moon. *Geochimica et Cosmochimica Acta* 122, 58-74.

Ten Kate, I. L., Cardiff, E.H., Dworkin, J.P., Feng, S.H., Holmes, V., Malespin, C., Stern J.G., Swindle T.D., Glavin D.P., 2010, VAPoR – Volatile Analysis by Pyrolysis of Regolith – an instrument for in situ detection of water, noble gases, and organics on the Moon, *Planetary and Space Science*, 58, 1007–1017.

Thomson, B. J.; Bussey, D. B. J.; Neish, C. D.; Cahill, J. T. S.; Heggy, E.; Kirk, R. L.; Patterson, G. W.; Raney, R. K.; Spudis, P. D.; Thompson, T. W.; Ustinov, E. A., 2012. An



upper limit for ice in Shackleton crater as revealed by LRO Mini-RF orbital radar, *Geophysical Research Letters*, 39, 14, CiteID L14201.

Vasavada, Ashwin R.; Paige, David A.; Wood, Stephen E., 1999. Near-Surface Temperatures on Mercury and the Moon and the Stability of Polar Ice Deposits, *Icarus*, 141, 2, 179-193.

Wagner, W.; Saul, A.; Pruss, A., 1994. International equations for the pressure along the melting and along the sublimation curve of ordinary water substance. *J. Phys. Chem. Ref. Data* 23, 515-527.

Wieler R. and Heber V. S., 2003. Noble gas isotopes on the Moon. *Space Sci. Rev.* 106, 197-210,.

Wieler R. Noble gases in the solar system, 2002. *Rev, Mineral. and Geochemistry*, 2-70.

Wieler, R., Kehm, K., Meshik, A.P., and Hohenberg, C.M., 1996. Secular changes in the xenon and krypton abundances in the solar wind recorded in single lunar grains. *Nature*, 384, 46-49.

Wilde, S.A., Valley, J.W., Peck, W.H., Graham, C.M., 2001. Evidence from detrital zircons for the existence of continental crust and oceans on the Earth 4.4 Gyr ago, *Nature*, 409, 175-178.

Woods, P.M. and Willacy, K., 2009. Carbon isotope fractionation in protoplanetary disks. *Astrophys. J.* 693, 1360-1378.

Woods, P.M., 2009. Carbon isotope measurements in the Solar System. arXiv:0901.4513

Yamamoto, S., Nakamura, R., Matsunaga, T., Ogawa, Y., Ishihara, Y., Morota, T., Hirata, N., Ohtake, M., Hiroi, T., Yokota, Y., Haruyama, J., 2010. Possible mantle origin of olivine around lunar impact basins detected by SELENE, *Nature Geoscience* 3, 533-536.

Zhang, J.A.; Paige, D. A., 2009, Cold-trapped organic compounds at the poles of the Moon and Mercury: Implications for origins, *Geophysical Research Letters*, 36, 16, CiteID L16203.

Zhang, J. A.; Paige, D.A., 2010, Correction to "Cold-trapped organic compounds at the poles of the Moon and Mercury: Implications for origins", *Geophysical Research Letters*, 37, 3, CiteID L03203.

Zuber, M.T.; Head, J.W.; Smith, D.E.; Neumann, G.A.; Mazarico, E.; Torrence, M.H.; Aharonson, O.; Tye, Al.R.; Fassett, C.I.; Rosenburg, M.A.; Melosh, H. J., 2012. Constraints on the volatile distribution within Shackleton crater at the lunar south pole, *Nature*, 486, 7403, 378-381.