Welcome to Münster! We are hoping the ELS program will find your interest and that you will have a great meeting and an enjoyable stay. We are pleased to welcome all participants to the Fifth European Lunar Symposium (ELS), which is taking place at the Westfälische Wilhelms-Universität Münster, Germany in partnership with NASA’s Solar System Exploration Research Virtual Institute (SSERVI). This pan-European lunar meeting builds upon the highly successful previous ELS meetings. The range of lunar topics covered by the abstracts submitted to this meeting demonstrates the diversity of lunar research currently being pursued in Europe and elsewhere. We are especially delighted to see a strong participation from PhD students and early-career researchers at this meeting. We also hope that the ELS continues to provide a platform to the European lunar researchers for networking as well as exchanging new ideas and latest results.

We thank the NASA SSERVI for hosting the meeting website. Our special thanks to our SSERVI colleague, Kristina Gibbs for implementing numerous updates to the website at a short notice and often at unsocial hours!

Members of the Science Organizing Committee are thanked for their input in putting together an exciting program and for volunteering to chair various sessions at the ELS!

Ana Cernok acted as editor of the abstract booklet and looked after various aspects of ELS organization.

Finally, we owe a huge debt of gratitude to Iris Weber and the local organizing committee who helped tremendously with making this conference happen.

We couldn’t have done without them!

Harald Hiesinger and Mahesh Anand
(On behalf of the ELS organizers)

MEETING VENUE
The ELS meeting will take place in the main building of the university, labeled “Schloss” in the map below. The street address is: Schlossplatz 2, 48149 Münster. After entering the building through the main entrance, you will immediately find the registration/help desk on the ground floor. The meeting room seats about 390 people and is equipped with a beamer (HDMI, VGA). There is also a second room (53 seats) available for break-out meetings upon request. Oral sessions will be held in the “Aula” on the first floor of this building; the posters will be located in the foyer on the ground floor.

REGISTRATION
All participants should register at the registration/help desk on Tuesday (2nd May) and Wednesday (3rd May), preferentially between 8 am and 8:30 am. Name badges, and conference materials will be available at the registration/help desk in the foyer.

MEALS
We will provide coffee, tea, water, juice, and cookies during coffee breaks and will serve sandwiches and soup for lunch. All refreshments and lunches will be served in the foyer.
The meeting venue is shown in the black circle; the planetarium is shown in the blue circle; the Mühlenhof (location of the group dinner) is shown in the red circle.

Downtown area with the promenade and the cathedral (Dom). The Aa lake (Aasee) is at the left margin, central station (Bahnhof) is to the lower right.
PRESENTATIONS
All presentations will take place in the “Schloss”, the main building of the university. Those presenting talks are encouraged to upload their oral presentation to the provided computers in the lecture hall as early as possible to ease organization and to avoid any delays in the schedule. Those presenting on Tuesday morning, please come to the lecture hall no later than 8:15 am. Those presenting in the afternoon session, please upload your presentation during lunch break. Those presenting on Wednesday, please upload your presentation on Tuesday. At the very latest, all presenters should upload their presentations during the preceding refreshment/lunch break prior to their session.

Presentations should be saved in Microsoft PowerPoint or PDF format.

Those wishing to use their own PC and/or Mac laptops must obtain prior approval from ELS organizers and bring appropriate cables and connectors. Any delays caused by technical problems will be taken out from your presentation time.

Speakers have a 10 minutes slot allocated in the timetable. There will be a dedicated Q&A time slot after several talks, so please feel free to take up the entire 10 minutes for your presentation.

The posters will be on display in the foyer area for the entire time of the meeting. Posters can be put up for display from Tuesday, 8:00 am until Wednesday, 6:15 pm. We encourage presenters to put up their posters as early as possible to guarantee maximum visibility. Posters can be a maximum size of 140 x 90 cm. Mounting material will be available at the registration/help desk. Any uncollected poster will be disposed at the end of the meeting.

WIFI ACCESS
The meeting hall is equipped with Wifi access. Your personal login information will be included in your conference materials package.

SOCIAL EVENT
On Wednesday night (6:00 pm), there will be a special show at the local planetarium, followed by a group dinner. The planetarium is located at the Sентрuper Straße 285 and can be reached by public transportation (bus line 14, final stop Zoo/Naturkundemuseum). There is also a large parking lot, which costs €3,00. For further information, please see:

http://www.lwl.org/LWL/Kultur/lwl-naturkunde/planetarium/

The group dinner will take place at the Mühlenhof Museum, located at Theo-Breider-Weg 1. Dinner is scheduled for 8:00 pm. The museum is within walking distance from the planetarium. Should you take the public bus (line 14), please exit the bus at the stop „Mühlenhof“. There is also a parking lot available free of charge. For further information, please see:

https://www.muehlenhof-muenster.org/

LODGING
Starting July 1st, 2016, the City of Münster raises an accommodation tax of 4.5% on overnight stays in hotels, holiday flats, on camping sites or comparable facilities. Accommodations necessitated by business travel, educational, or training purposes are exempt from the tax, if you provide the hotel with the Tax Exemption Form attached to the end of this information. We will be more than happy to sign your tax exemption form at the registration desk.
TRANSPORTATION
Together with your conference materials, you will receive a free pass for the local public transportation system. This pass allows you to use any public transportation bus free of charge, as many times as you want. Please be aware that you need to have your pass at hand when riding the buses otherwise you might be charged a penalty fee of €60,00.

In Münster, Germany’s bicycle capital, a bicycle is the most common way of transportation and is used by more than 100,000 people daily. No wonder, because the city has a well-developed system of dedicated bicycle lanes. Bicycle lanes are often marked in red - as a pedestrian, please be extra careful not to walk on bicycle lanes!

If you are interested, several options are available to rent bicycles, for example from:

Radstation Münster Hundt KG
Berliner Platz 27a
48143 Münster
Tel. + 49 (0)2 51.4 84 01 70; Fax + 49 (0)2 51.4 84 01 77
www.radstation-muenster.de

- 230 bicycles – €8,00
- 15 E-Bikes – €22,50 (€50 deposit)

Prices are per bike and day; prices and availability may vary. Prices were carefully researched, but are not guaranteed.

WEATHER
“It either rains or the church bells ring. And if both occur at the same time, it’s Sunday.” Sounds worse than it is. In May, we have typical spring weather with some fairly warm days and some chilly days. Please be prepared for some rain and dress appropriately.

<table>
<thead>
<tr>
<th></th>
<th>Jan</th>
<th>Feb</th>
<th>Mär</th>
<th>Apr</th>
<th>Mai</th>
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<td>3,9</td>
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<td>17,5</td>
<td>20,4</td>
<td>21,9</td>
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<td>Regentage (d)</td>
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<td>Luftfeuchtigkeit (%)</td>
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<td>74</td>
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<td>83</td>
<td>85</td>
<td>88</td>
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</tbody>
</table>
SIGHTSEEING
In 797 AD, missionary Ludger founds a Cathedral School in the location of Münster. Münster is a member of the Hanseatic League and is probably most famous for the Westphalian peace treaty, which ended the 30-year war in 1648. Today, 300,000 people (500,000 bicycles) live in Münster, which is home to the Westfälische Wilhelms-Universität (43,000 students) and the Institut für Planetologie.

Münster offers numerous attractions and tourist highlights, including several art museums, historic buildings, and the farmers market on Wednesday. As a planetologist, you might want to take the opportunity seeing the medieval astronomical clock in the cathedral, i.e., the “Dom”, specifically at noon. For detailed information on sightseeing, please contact the local tourist office at:

Klemensstraße 10
48143 Münster
Tel. +49(0)2 51/4 92-27 10
Fax +49(0)2 51/4 92-77 43

SAFETY
In case of an emergency or fire alarm, please follow the green emergency exit signs and gather at the meeting points. There will be a head count at the meeting points, so please do not leave the meeting points before you are instructed to do so. Please familiarize yourself with the locations of the meeting points.

LIABILITY
We will do our best to provide a safe meeting venue. However, we cannot accept any liability relating to loss/damage of personal property, injuries or loss of life. By participating in the European Lunar Symposium you agree to hold the Westfälische Wilhelms Universität Münster, the Institut für Planetologie, and all their representatives entirely free from any liability, including financial responsibility for injuries or damage incurred, regardless of whether injuries or damage are caused by negligence.

CONTACT INFORMATION
We hope this information is useful for ensuring a great conference experience and an enjoyable stay in Münster. Should you have any questions, please do not hesitate to contact us at:

the registration desk
Hiesinger@uni-muenster.de, +49 251 8339057
ifpsek@uni-muenster.de, +49 251 8333424.

Additional information about the Institut für Planetologie can be found at
http://www.uni-muenster.de/Planetology/ifp/institut.html

Harald Hiesinger, Mahesh Anand, and the local organizing committee
Confirmation of Exemption from the Accommodation Tax in the Territory of the City of Münster

Please note the instructions below!

Accommodation business (stamp, if applicable):

Name of accommodated guest, organiser, or employer

Address (explanations no. 1 and 2)

Overnight stay(s) in Münster (explanation no. 3)

from ____________________________ to ____________________________

Declaration

I declare that the accommodation was needed only for gaining income, for educational-, or for training purposes. (Income = income from agriculture and forestry, business, self-employed/freelance work, letting and leasing, capital assets or employment, cf. § 2, Rules on Accommodation Tax [BehSt], in connection with § 2 of the German Income Tax Act [EStG])

Please tick the relevant box:

[ ] for income from employment (employee)

 Confirmation of the employer, business trip approval or comparable evidence is attached (no. 3)

 VAT-ID number (or tax ID number, if applicable)

[ ] Educational or training purposes

 Confirmation of the training/ further training institution or school is attached (no. 2)

 or

 Company or business address

 Reason for generating income

Herewith, I assure that the information provided above is true and given in good faith. I have read and understood the information and explanations overleaf.

Place, date, signature (of the guest, organiser, or employer)

Central contact points to the City of Münster:
Tel. 02 51/4 92-22 03, Fax: 02 51/4 92-77 15, E-Mail: BehSt@stadt-muenster.de

Official form regarding § 8 of the Rules on the Charging of Accommodation Tax in the territory of the City of Münster
Explanations

1. In the event of business trips consisting of several employees (e.g., fitters, meetings), the employer’s form must be completed, signed, and a list of participants with the letterhead of the employer with the information required under para. 2 must be attached (collective certificate).

2. Collective certificates are allowed for organisers who make reservations in a hotel for the participants of seminars, trainings, meetings, and further training sessions. The form must be completed and signed by the organiser, and a list of participants with the employer’s letterhead containing the names and addresses of the travellers’ participants as well as the dates of arrival and departure. If persons arrive individually, the invitation to the training, further training, meeting etc. can also be attached to the form completed by the guest as evidence.

3. The form can also be completed on a quarterly basis etc. for regularly recurring accommodation in an accommodation facility. Business trips require a corresponding certificate of the employer for the same period or the same period to be specified in an invoice addressed to the employer. The calendar quarter is deemed as a quarter (I. Q. = 01.01. - 31.03., II. Q. = 01.04. - 30.06., III. Q =01.07. - 30.09., IV. Q. = 01.10. - 31.12.).

4. In section C, it is basically sufficient if a VAT-ID number (or tax ID number) is stated. Otherwise, an invoice address stating that this is a company address or the address of the seat of the corporation or company, or the location of the freelance activity (e.g., practice, agency) must be stated. It is also sufficient to write ‘see Annex’ in the free-form text and to attach the hotel invoice or business card stating the company or business address to the form.

Furthermore, the address must be stated for the further professional activities for gaining income (rental and agricultural activity, individual entrepreneur, professors etc.). As regards the professional occasion, a short description of the business-related occasion with a key word is required. Keywords such as customer care, customer acquisition, owners’ meeting, planning services, object inspection, lecture etc. are sufficient. The City of Münster reserves the right to check the information provided.

Data Protection

The information regarding the accommodation facility required in the form is provided on a voluntary basis and only serves the purpose of determining the tax liability. In individual cases, for example, when the guest refuses to fill in the form etc., the accommodation facility will inform the City of Münster. The City of Münster reserves the right to check the information at all times. Cases in which the guest, employer or organiser provided incorrect information or forged evidence and the tax was not paid can result in a fine of up to five thousand euros.

Please note:

If the guest/organiser/employer refuses to carry out the proper completion of the form or if the relevant evidence is not provided, the accommodation facility must collect the accommodation tax from the guest. If the documents or evidence are filed with the accommodation facility subsequently, the tax paid can be reimbursed by the accommodation facility. The reimbursement will only be effectuated if the evidence/documents are submitted within one month following the expiry of the tax payable by the accommodation facility, which is to be registered on a quarterly basis.

The evidence/documents must be presented to the accommodation facility

- Until May 15th of each year for overnight during the I. quarter
- Until August 15th of each year for overnight during the II. quarter
- Until November 15th of each year for overnight during the III. quarter
- Until February 15th of the following year for overnight during the IV. quarter.

Small amounts of less than 10.00 € will not be reimbursed.
Program for ELS 2017, the Fifth European Lunar Symposium

https://els2017.arc.nasa.gov/

Venue
Westfälische Wilhelms-Universität Münster (WWU)
Schlossplatz 2
48149 Münster, Germany

Science Organizing Committee
• Harald Hiesinger – Institut für Planetologie, WWU (Chair)
  • Mahesh Anand - Open University, UK (Co-Chair)
    • James Carpenter – ESA
  • Ana Cernok - Open University, UK
  • Doris Daou – NASA (PSD)
  • Simone Dell’Agnello - INFN, Italy
  • Kristina Gibbs (SSERVI, USA)
  • Ralf Jaumann - DLR, Germany
• Clive Neal (University of Notre Dame, USA)
  • Patrick Pinet - IRAP, France
  • Greg Schmidt - SSERVI, USA
• Wim van Westrenen - VU Univ. Amsterdam, NL

Local Host

Institut für Planetologie
TUESDAY, 2ND MAY 2017

08:00  Registration (Tea/Coffee/Refreshments)

08:30  Welcome/Housekeeping (H. Hiesinger/M. Anand)
       Prof. Dr. Johannes Wessels, Rector of the WWU
       Mayor of the city of Münster (TBC)

All talks: 10 mins (Q&A at the end of each session for all speakers in that session)

**Session 1: Exploration and Future Missions; Chair: James Carpenter**

<table>
<thead>
<tr>
<th>Time</th>
<th>Author</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>09:00</td>
<td>Bussey et al.</td>
<td>The ISECG Science White Paper – A Scientific Perspective on the Global Exploration Roadmap</td>
</tr>
<tr>
<td>09:10</td>
<td>Houdou et al.</td>
<td>LUNAR EXPLORATION IN ESA’S NEW EUROPEAN EXPLORATION ENVELOPE PROGRAMME (E3P)</td>
</tr>
<tr>
<td>09:20</td>
<td>Neal and</td>
<td>A MULTI-DEcadAL SAMPLE RETURN CAMPAIGN WILL ADVANCE LUNAR AND SOLAR SYSTEM SCIENCE AND EXPLORATION</td>
</tr>
<tr>
<td></td>
<td>Lawrence</td>
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<tr>
<td>09:30</td>
<td>Jolliff et al.</td>
<td>WHAT CAN WE EXPECT FROM A MOONRISE SAMPLE RETURN FROM SOUTH POLE-AITKEN BASIN?</td>
</tr>
<tr>
<td>09:40</td>
<td>Barabash and</td>
<td>SELMA: A MISSION TO STUDY LUNAR ENVIRONMENT AND SURFACE INTERACTION</td>
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<tr>
<td></td>
<td>Futaana</td>
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<tr>
<td>09:50</td>
<td>Anderson et al.</td>
<td>REVEALING LUNAR HISTORY WITH CODEX: MINIATURE MASS SPECTROMETER Rb-Sr RESULTS</td>
</tr>
<tr>
<td>10:05</td>
<td>Barber et al.</td>
<td>PROSPECTING FOR LUNAR POLAR VOLATILES: THE PROSPA MINIATURE IN-SITU SCIENCE LABORATORY</td>
</tr>
<tr>
<td>10:25</td>
<td>Reiss</td>
<td>SIMULATION AND DEMONSTRATION OF THE EXTRACTION OF WATER FROM LUNAR REGOLITH ANALOGUES FOR THE PROSPA SAMPLE ANALYSIS INSTRUMENT</td>
</tr>
<tr>
<td>10:35</td>
<td>Keller and Petro</td>
<td>THE LUNAR RECONNAISSANCE ORBITER AND ITS CONTINUED EXPLORATION OF THE MOON</td>
</tr>
</tbody>
</table>

09:50 – 10:05  Q&As

10:05  Anderson et al.

10:15  Barber et al.

10:25  Reiss

10:35  Keller and Petro

10:45 – 10:55  Q&As

Lunch (12:10-13:40)  **Poster Session**
### Session 3: Evolution and Environment; Chair: Simone Dell’Agnello

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker(s)</th>
<th>Title</th>
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<tbody>
<tr>
<td>13:45</td>
<td>Zhao et al.</td>
<td>THE AMOUNT OF ILMENITE-BEARING CUMULATES PARTICIPATING IN LUNAR MANTLE OVERTURN: A PARAMETER STUDY</td>
</tr>
<tr>
<td>13:55</td>
<td>Schwinger et al.</td>
<td>MODELING OF LUNAR MAGMA OCEAN CRYSTALLIZATION AND IMPLICATIONS FOR THE PROPERTIES OF PRIMORDIAL LUNAR CRUST.</td>
</tr>
<tr>
<td>14:05</td>
<td>Berezhnoy</td>
<td>BEHAVIOR OF VOLATILE ELEMENTS DURING IMPACT EVENTS ON THE MOON</td>
</tr>
<tr>
<td>14:15</td>
<td>Wöhler et al.</td>
<td>NUMERICAL MODELLING OF THE DAYTIME DEPENDENT LUNAR SURFICIAL HYDROGEN AND HYDROXYL COLUMN DENSITIES</td>
</tr>
<tr>
<td>14:25</td>
<td>Patterson et al.</td>
<td>MINI-RF S- AND X-BAND BISTATIC OBSERVATIONS OF THE FLOOR OF CÂBEUS CRATER AND THEIR IMPLICATIONS FOR THE PRESENCE OF WATER ICE</td>
</tr>
<tr>
<td>14:35 – 14:45</td>
<td>Q&amp;As</td>
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### Session 4: Experimental Petrology; Chair: Wim van Westrenen

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<thead>
<tr>
<th>Time</th>
<th>Speaker(s)</th>
<th>Title</th>
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<tbody>
<tr>
<td>14:45</td>
<td>Lin et al.</td>
<td>A LUNAR HYGROMETER BASED ON PLAGIOCLASE-MELT PARTITIONING OF WATER</td>
</tr>
<tr>
<td>14:55</td>
<td>Steenstra et al.</td>
<td>METAL-SILICATE PARTITIONING OF VOLATILE SIDEROPHILE ELEMENTS: CONSTRAINING VOLATILES IN THE EARLY EARTH-MOON SYSTEM</td>
</tr>
<tr>
<td>15:05</td>
<td>Van der Waal et al.</td>
<td>THE EFFECT OF WATER ON THE METAL-SILICATE PARTITIONING BEHAVIOUR OF MODERATELY SIDEROPHILE ELEMENTS</td>
</tr>
<tr>
<td>15:15</td>
<td>Leitzke et al.</td>
<td>REDOX TRANSITION AND COMPATIBILITY OF MO DURING PARTIAL MELTING IN THE LUNAR MANTLE</td>
</tr>
<tr>
<td>15:25 – 15:35</td>
<td>Q&amp;As</td>
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Tea/coffee break (15:35 – 15:50)

### Session 5: Lunar Samples; Chair: Mahesh Anand

<table>
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<tr>
<th>Time</th>
<th>Speaker(s)</th>
<th>Title</th>
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<tbody>
<tr>
<td>15:55</td>
<td>Furi et al.</td>
<td>REEVALUATING THE SOURCE(S) OF 'WATER' IN LUNAR VOLCANIC GLASSES USING A NEW ESTIMATE OF THE COSMOGENIC DEUTERIUM PRODUCTION RATE</td>
</tr>
<tr>
<td>16:05</td>
<td>Barnes et al.</td>
<td>VOLATILES IN HIGH TITANIUM BASALT FROM THE MOON</td>
</tr>
<tr>
<td>16:15</td>
<td>Cernok et al.</td>
<td>SHOCK-INDUCED TEXTURE IN LUNAR MG-SUITE APATITE AND ITS EFFECT ON VOLATILE DISTRIBUTION</td>
</tr>
<tr>
<td>16:25</td>
<td>Burney and Neal</td>
<td>MODERATELY VOLATILE ELEMENTS IN LUNAR BASALTS</td>
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<tr>
<td>16:35 – 16:45</td>
<td>Q&amp;As</td>
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<thead>
<tr>
<th>Time</th>
<th>Presenter(s)</th>
<th>Title</th>
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<tbody>
<tr>
<td>16:45</td>
<td>Wurz et al.</td>
<td>LASER-ABLATION MASS SPECTROMETRY FOR IN SITU ANALYSIS OF MATERIAL ON PLANETARY SURFACES</td>
</tr>
<tr>
<td>16:55</td>
<td>Thiessen et al.</td>
<td>APOLLO 12 BRECCIA 12013: A STUDY OF PARTIAL PB LOSS IN ZIRCON</td>
</tr>
<tr>
<td>17:05</td>
<td>Alexander et al.</td>
<td>⁴⁰Ar-³⁹Ar AGE DETERMINATION OF BASALTIC FINES FROM APOLLO 12 REGOLITH SAMPLE 12070,889</td>
</tr>
<tr>
<td>17:15</td>
<td>Ashcroft et al.</td>
<td>NWA 10989 – A NEW LUNAR METEORITE CONTAINING VLT AND FELDSPATHIC MATERIAL</td>
</tr>
<tr>
<td>17:25 – 17:35</td>
<td></td>
<td>Q&amp;As</td>
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**Visit of the planetarium/Social Event**

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
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<tbody>
<tr>
<td>18:00</td>
<td>Visit of the planetarium (Sentruper Str. 285, 48161 Münster)</td>
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<tr>
<td>20:00</td>
<td>Conference Dinner (Mühlenhof, Theo-Breider-Weg 1, 48149 Münster)</td>
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</tbody>
</table>
**WEDNESDAY, 3RD MAY 2017**

**All talks: 10 mins (Q&A at the end of each session for all speakers in that session)**

**Session 6: Remote sensing I: Impact Cratering; Chair: Harald Hiesinger**

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker(s)</th>
<th>Title</th>
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<tbody>
<tr>
<td>08:30</td>
<td>Rommel et al.</td>
<td>ANORTHOSITE-RICH MATERIAL INSIDE OF THE SOUTH POLE-AITKEN BASIN</td>
</tr>
<tr>
<td>08:40</td>
<td>Plescia</td>
<td>LUNAR IMPACT MELT RHEOLOGY</td>
</tr>
<tr>
<td>08:50</td>
<td>Stickle et al.</td>
<td>MINI-RF BISTATIC OBSERVATIONS OF COPERNICAN CRATER EJECTA</td>
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<tr>
<td>09:00</td>
<td>Neumann and Mazarico</td>
<td>COPERNICAN-AGE CRATER TOPOGRAPHIC ROUGHNESS AND AGE CORRELATIONS</td>
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**Lunch (13:05-15:00) Poster Session**

**Special talk by Matthias Maurer, ESA astronaut (15:00-15:20)**

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Closing remarks (18:10 – 18:25)
2018 ELS
Finish
**POSTERS** (sorted by last name)

*Presenters note that posters can be displayed from registration on Tuesday, 2nd May, 8:00 am.
Posters should preferably be A0 size but no larger than 140 cm x 90 cm in Portrait form.
Scotch tape will be provided.*

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**Introduction:** This presentation will introduce ispace, a lunar exploration company headquartered in Tokyo, Japan, and Team Hakuto, a front-running team participating in the Google Lunar XPRIZE (GLXP) competition. The presentation will begin by introducing the technology that ispace is developing for lunar exploration. Next, the presentation will outline Team Hakuto’s 2017 mission plans and rover capabilities. The presentation will conclude by explaining ispace’s three-step plan to utilize resources on the lunar surface, while discussing opportunities for the scientific community.

**ispac e & Water on the Moon:** ispace technologies is the commercial arm that manages Team Hakuto in the GLXP Mission. Founded in 2013, its mission is to find the resources necessary to extend human life into outer space. ispace’s primary goal is to locate and utilize water on the lunar surface. Observations from the Moon Mineralogy Mapper aboard India’s Chandrayaan-1, and measurements from NASA’s Lunar Reconnaissance Orbiter, each provide strong evidence for the presence of water ice on the Moon [1]. The water may originate from endogenous sources, delivery by comets or asteroids, or implantation by solar wind [2]. While extracting hydrogen and oxygen from lunar regolith will require significant amounts of energy and infrastructure, the higher concentrations of lunar ice recently discovered at the Southern Lunar Pole could offer an energy-efficient alternative. In 2009, LCROSS impacted the permanently shadowed crater Cabeus and measured a water ice concentration of 5.6-2.9 wt% [3]. Ground truthing missions are needed in order to further verify the distribution of lunar ice in permanently shadowed and other regions.

ispace has a three-step plan that will demonstrate its technology, locate, map and measure resources, and finally utilize those resources on the lunar surface. ispace will have its first attempt to demonstrate its rover technology during the GLXP mission. Once proven successful, ispace will develop a tethered dual rover crater exploration vehicle, as well as rover with a drilling mechanism, which will give the company access to the permanently shadowed lunar surface and the resources that lay beneath it. In this phase ispace plans to partner with space agencies and the scientific community for sensor and technology development to better detect and understand water ice deposits. Finally, depending on the location, distribution, quality and quantity of the lunar ice, ispace will develop extraction, processing, and utilization techniques with interested industrial partners. An ultimate goal is to convert the ice to fuel and deliver it to private companies such as the United Launch Alliance, who recently offered to purchase fuel on the lunar surface for $500/kg [4].

**Team Hakuto:** ispace owns and operates Team Hakuto, the only Japanese Team competing for the $30M GLXP competition. During this first mission to Mare Imbrium, the 4kg rover will attempt to survive one lunar day. The rover has a hybrid communication system, with both 900 MHz and 2.4 GHz capabilities, enabling both long distance and high speed communication. The rover will travel at least 500m and downlink high-definition video at 100 kbits/sec to Earth via the lander to achieve the required objectives of the GLXP. In order to further test and demonstrate new technologies, the rover will attempt a total traverse distance of up to 10 km. The traverse will be executed in a flower petal pattern, repeatedly circling back toward the host lander to be photographed. The mission will provide a low cost opportunity to obtain ground truth data for the numerous remote sensing missions. In the future this technology can be further used to investigate promising regions for potential resource deposits. This mission is the first of many missions planned by ispace technologies.

**Supporting Science:** 2017 is the beginning of a new era of exploration with cost-efficient opportunities for scientists on commercial missions. Japan Aerospace Exploration Agency is partnering with ispace and Team Hakuto to send a dosimeter to measure cosmic rays and solar wind for future human missions. Another GLXP team, Astrobotic, is carrying a university payload funded by the Mexican Space Agency [4]. By decreasing the overall mass of the rover, ispace is able to accommodate future opportunities for scientific payloads and offer the scientific and space technology community unprecedented economical opportunities to gather data and test instruments, algorithms, and equipment during our missions.

**References:**

\textbf{Introduction:} Mare basalt samples provide us with information on the composition and melting history of the Moon’s upper mantle [1,2]. By dating mare basalt samples we can learn about the evolution of lunar volcanism over time.

We present age data for 12 basaltic fines (allocated samples 2-4 mm) from the Apollo 12 regolith sample 12070.889, part of the contingency sample collected in front of the lunar module by the Apollo 12 astronauts [3]. The petrology and geochemistry of these fines has previously been presented by Alexander et al. [4]. Fines from this sample are varied in texture (Figure 1).

**Figure 1.** False colour element maps of four of the regolith basalt particles analysed. Colours on the element maps represent concentrations of different element maps as follows: Si = blue, Fe = red, Mg = green, Ca = yellow, Al = white, Ti = pink, Cr = gold and S = light blue. Abbreviations on BSE images correspond to the following: Pyroxene (Px), Olivine (Ol), Plagioclase (Pl), ilmenite (Ilm), silica (Si), spinel (Sp) and troilite (Tr).

**Temporal history of lava flows at Apollo 12:** Basaltic samples at the Apollo 12 site are divided into lithological groups of olivine, ilmenite, pigeonite and feldspathic basalts. Previously dated Apollo 12 basalts have crystallisation ages between 3.1 and 3.3 Ga [5-7]. A site stratigraphy constructed by [8] indicates that olivine basalts are overlain by ilmenite basalts, with the pigeonite basalts occurring between them. The potential feldspathic basalt group is older than the other units. In addition to these groups, material has also been transported to the Apollo 12 site by impacts [9,10].

**Methods:** Each allocated basalt chip was divided in two and one half used to determine the petrography and mineral chemistry (Figure 1, [4]). The other portion was used for \(^{40}\text{Ar}^{39}\text{Ar}\) age determination. We undertook step heating on neutron irradiated samples with masses ranging from 0.3–3.16 mg using a Photon Machines Fusions IR 10.6 \(\mu\)m wavelength \(\text{CO}_2\) laser coupled to an Argus VI multicollector mass spectrometer at the University of Manchester. Isotopes of \(^{40}\text{Ar},^{39}\text{Ar},^{37}\text{Ar}\) and \(^{39}\text{Ar}\) were measured on Faraday cups. Repeat measurements of two of the samples are in good agreement with each other, demonstrating that the dating approach is reproducible on small mg mass samples.

**Relationship between regolith fines and the Apollo 12 lava flows:** From the textures and chemistries of the 12 fines presented here, 3 are believed to belong to the ilmenite basalt group (samples 889_1, 889_4 and 889_7), 2 to the pigeonite basalt group (samples 889_2 and 889_9) and 2 to the olivine basalt group (samples 889_8 and 889_12). Samples 889_3, 889_6, 889_10 and 889_11 could not be characterised due to their coarse-grained nature, and sample 5 was polished away during processing [4].

**Initial age dating results:** \(^{39}\text{Ar}\) step release profiles of the samples data indicate that many of the chips have had some partial resetting of their argon isotopes at lower temperature release steps. This is typical of mare basalt samples that have had residence close to the lunar surface and may either reflect degassing during impact shock events or diurnal temperature fluctuations in the near-surface environment [e.g. 10,11,12,13]. All low temperature releases are dominated by solar wind implantation \((^{38}\text{Ar}^{36}\text{Ar})\) ratios \(~0.189\), consistent with their regolith history.

High temperature ‘apparent release’ ages in all but two of the samples range between 2.96 and 3.16 Ga, slightly lower than Apollo 12 crystallisation ages previously reported from other isotopic chronometers systems [5-7]. Most high temperature releases are dominated by cosmogenic contribution \((^{38}\text{Ar}^{36}\text{Ar})\) ratios \(~1.54\).

There are two samples displaying notable \(^{39}\text{Ar}\) release patterns. Releases for sample 889_5 show a complex argon loss history with lower high temperature released apparent ages \(~2.1\) Ga) with little or no cosmogenic input indicating Ar loss from the sample. Sample 889_6 has a younger high temp age portion compared to most of the other samples \(~2.89\) Ga). This sample is an equilibrated olivine basalt cumulate [4] and the younger measured age may indicate that a secondary metamorphic equilibration and argon loss event occurred after lava flow emplacement.
Initial exposure ages results: $^{38}\text{Ar}/^{37}\text{Ar}$ ratios are used to provide the apparent cosmic ray exposure (CRE) ages using the P38 $2\pi$ cosmogenic production rates of Eugster (1988) [11]. Exposure ages of the basalt chips are highly variable between 30 and 591 Ma.

Conclusions: Full results and the final age dataset will be presented at the ELS meeting. This will bring together petrological, geochemical and age data for a group of small, 1-2 mm basalt chips, demonstrating that information about the parent lava flows and source regions together with the age relationships can be determined but with specified limitations. This has important implications for future lunar sample return missions that are likely to return small sample masses which will present analytical challenges. Future work on refining the methods presented here will provide a basis for the way in which samples collected by such missions can be selected and categorized.

Acknowledgments: Thanks to Dr Lydia Fawcett for laboratory assistance, to the Leverhulme Trust, STFC and the Royal Society for funding. Thanks to NASA for Apollo 12 sample allocation.

REVEALING LUNAR HISTORY WITH CODEX: MINIATURE MASS SPECTrometer Rb-Sr RESULTS. F. S. Anderson¹, T. J. Whitaker¹, R. Wiesendanger², P. Wurz³, S. Beck³, J. Levine³, ¹Southwest Research Institute, 1050 Walnut St, Suite 300, Boulder, CO (anderson@boulder.swri.edu), ²Physikalisches Institut, University of Bern, Bern, Switzerland, ³The Aerospace Corporation, Los Angeles, CA, ³Department of Physics and Astronomy, Colgate University, New York, USA.

Introduction: We have developed a mission concept [1-4] to address one billion year uncertainties in the history of the Moon [5] by landing on a large, homogeneous lava flow of 2.5–3.5 Ga, obtaining 20 or more Rb-Sr and Pb-Pb radiometric dates, ultimately constraining the age of the surface to well within ±200 Ma (2-σ) [1, 6, 7]. In this abstract, we describe progress on the miniaturization of the in-situ radiometric dating instrument, called the Chemistry, Organics, and Dating EXperiment (CODEX). Specifically, the CODEX instrument is comprised of two main components: a flight-like mass spectrometer developed during five years of international partnership with the University of Bern, and a proto-flight, low-power multi-laser ionization system, which together are used to produce measurements of elements, isotopes, and organics from solid samples. These measurements, in conjunction with heritage rastering sample-handling, imager, near-infrared, and infrared spectrometer systems, allow us make high-resolution context images of elemental and mineralogical composition, and test concordance using isotopes of Rb-Sr, and Pb.

Background: The history of the lunar surface is defined by relating crater density to age through crater flux models constrained by radiometric dates of samples returned by the Apollo and Luna missions [e.g., 5, 8, 9]. However, the 382 kg of returned samples best constrains only about 20% of the history of Moon, from ~3.5 to 4 Ga. As a result, the period from 2.5–3.5 Ga may have up to ±1 Ga of uncertainties, depending on which cratering flux model is used [5]. The modeled relationship between crater density and the age of the Moon is extrapolated to surfaces of planetary bodies throughout the inner solar system, hence uncertainties are propagated to Mars, Venus, Mercury, and throughout the solar system [10-15]. Consequences of this uncertainty include the potential for the duration of peak lunar volcanism to extend for much longer than previously thought, requiring new geochemical models of lunar mantle evolution [16], and revision of our understanding of the development of one-plate planets. Furthermore, for Mars, the era of peak volcanism, volatiles, aqueous mineralogy, fluvial geomorphology, and most importantly habitability, could potentially be one billion years longer than previously recognized [17-23].

Addressing the uncertainty in cratering flux, and hence inner solar system history, will require new radiometric dates from multiple locations on the Moon, and would benefit from similar measurements on Mars, to reduce the unknown uncertainties introduced by extrapolating impact rates.

To address this problem, we have developed mission concepts for in-situ dating on the Moon and Mars, featuring the CODEX instrument. The current instrument design is focused on lunar dating, but could be used for Mars with the addition of a vacuum system [4].

A Lunar In-Situ Dating Mission: To best constrain the 2.5–3.5 Ga time period requires landing on terrain with N(1) crater densities of ~0.0015 km⁻² to 0.0025 km⁻², such as previously unsampled Eratosthenian near-side basalts found near Schiaparelli crater [2]. Our lander would use an arm with a gripper and rake to reveal and acquire a sample [4]. This rock would be imaged with both the camera and NIR/IR spectrometer, before having a flat surface ground onto it’s face. It would then be re-imaged, and assessed for dating suitability. If the rock was an appropriate basalt, the sample would be presented to CODEX for analysis. CODEX rasters over hundreds of points to create an elemental and isotopic abundance image. These data points are used to produce isochrons, and place every point in context [6, 7, 24].

Examples of CODEX Rb-Sr and Pb-Pb Dates: We have previously published Rb-Sr results for the Mars meteorite Zagami, and the Duluth Gabbro, a lunar analog [6, 7], and demonstrated that we can obtain Rb-Sr dates with accuracy better than ±200 Ma (1-σ). We have recently expanded our approach to include Pb-Pb [1], enabling tests of concordance, and with accuracy as good as ±50 Ma on zircons, up to ±90 Ma for difficult, low Pb abundance samples like lunar meteorite MIL. 05035 (1-σ; Fig. 1). We assume we will

Figure 1: CODEX Pb-Pb date for the MIL.05035 (loaned for analysis by JSC), a lunar meteorite with Pb abundance < 400 ppb, with accuracy of ±90 Ma. Previous Pb measurements found only four zirconolites for dating purposes [25].
be able to make at least three, likely 10, and potentially up to 20 measurements of the lava flow, enabling us to obtain dates well-within an uncertainty of ±200 Ma at 2-σ.

**CODEX Laser Miniaturization:** All seven lasers slated for the CODEX instrument consist of high pulse energy fiber-based Master Oscillator Power Amplifier (MOPA) designs, under development through NASA MatISSE. As a backup to this approach, we have previously developed a solid-state free-space set of miniature lasers for ablation and resonance ionization of Rb and Sr under NASA PIDDPA funding. The current effort focuses on building, co-packaging and environmentally testing the 1064 nm ionization laser, 266 nm ablation laser, and two resonant Sr ionization lasers (Fig. 2).

**CODEX Mass Spectrometer Miniaturization:** With internal SwRI support, the University of Bern reflectron time-of-flight (RTOF) miniature mass spectrometer, a pre-flight engineering model, was integrated and tested with the CODEX bench-top laser system (Fig. 3). Initial elemental and isotopic data for Rb and Sr have been obtained on NIST SRM-610 (Fig. 4). After one week of initial testing, preliminary \(^{87}\text{Sr}/^{86}\text{Sr}\) isotope ratios were obtained (0.71±0.04), which consistent with previous measurements. Upon completing commissioning and optimization of the system we anticipate considerable improvement in the accuracy of the isotope measurements. Compared to our previous instruments sensitivity has increased by several orders of magnitude because the miniature RTOF was optimized for maximal ion-optical transmission (=100%), which naturally eliminates isotope fractionation effects in the ion-optical system.

**References:**

5. S. J. Robbins.
**Introduction:** As the youngest and best-preserved large multi-ring basin on the Moon, the Orientale basin is the archetype for multi-ring basins throughout the Solar System [1]. The central basin cavity is surrounded by three major ring scarp: the Inner Rook (IRR, R=230 km), Outer Rook (ORR, R=460 km) and Cordillera (CR, R=310 km) rings. The ORR and CR rings are clearly expressed in topography data as inward facing scarps suggesting formation through normal faulting during the modification stage of the basin [2]. The subsurface structure of the basin and its rings are best revealed by high-resolution gravity data from NASA’s Gravity Recovery and Interior Laboratory (GRAIL) mission [3, 4]. Gravity gradients reveal the presence of ring dikes and ring faults encircling the basin. The crustal structure reveals discrete inflections where the ORR and CR faults cross the crust-mantle interface.

**Methods.** Gravity data from GRAIL provide an incredibly high-resolution view of Orientale [3, 4]. However, models of the subsurface structure of the basin are limited not by the quality of the data, but by the effects of widespread small-scale gravity anomalies arising from density variations at shallow depths within the crust [5]. These background anomalies overprint the basin-related gravity anomalies, and frustrate high-resolution studies of the basin and its rings. To circumvent this difficulty, we use new techniques that take advantage of the symmetry of the basin to average out unrelated anomalies.

Gravity gradients [6] are used to investigate the shallow structure associated with the rings in the upper crust. Radial gravity gradient profiles are stretched and aligned, and the average gravity gradients are used to invert for the subsurface structure. Ring faults offsetting shallow density interfaces should generate nearly symmetric pairs of positive and negative gravity gradients. Ring dikes should be expressed as strong negative gravity gradients, with an asymmetric signature for non-vertical dike dips.

Crustal thickness models are used to represent the deep structure of the basin at the crust-mantle interface. Previous approaches suffered from the amplification of shallow-sourced small-scale gravity anomalies when they are downward-continued to the crust-mantle interface [7, 8], limiting global crustal thickness models to a resolution of spherical harmonic degree 80 (or a full-wavelength resolution of ~140 km) [9]. This wavelength is comparable to the spacing between the rings, and thus this approach cannot adequately resolve the structure of the rings. In the approach employed here, Orientale is first rotated to the pole, and then a degree- and order-dependent spherical harmonic filter is applied so as to smooth the basin more in the azimuthal direction than in the radial direction, minimizing anomalies unrelated to the ring structure while attaining the highest resolution possible in the radial direction (full-wavelength resolution of ~70 km).

**Results.** **Gravity gradients.** GRAIL Bouguer gravity gradients show strong anomalies over the rings, arising from density anomalies in the shallow subsurface. The Outer Rook ring is characterized by a strong negative gravity gradient anomaly, indicating a mass excess at depth. The symmetric signature of the ORR gravity gradients between azimuths of 90° and 360° (measured clockwise from north) is indicative of a nearly vertical ring dike, and is best matched by a dike with a width of 1.4 km (1.0-2.1 km, 1-σ range) and a dip of 96° (74-117°), extending between a top depth of 3.8 km (1.9-6.9 km) and the assumed bottom depth at the base of the crust of 50 km (Fig. 2c). The asymmetric signature of the ORR gravity gradients in the northeastern quadrant is consistent with an inward dipping ring dike (Fig. 2d) with a width of 5.7 km (4.8-16.5 km, 1-σ range) and a dip of 47° (33-77°), extending between a top depth of 13 km (9-24 km) and the assumed bottom depth at the base of the crust of 50 km.

A negative gravity gradient signature similar to that in the Outer Rook is found in the Cordillera between azimuths of 83° and 125°, supporting the presence of a similar ring dike there. The majority of the Cordillera ring is instead characterized by a symmetric pair of positive and negative gravity gradient anomalies. This signature indicates a tectonic offset across an interface separating a lower density upper layer from the underlying higher density crust. We inverted the gravity gradients assuming a 4-km step across a subsurface density interface. The most probable model has a density interface at a depth of 11 km (7-20 km, 1-σ range) with a density contrast of 300 kg/m³ (230-510 kg/m³). These results are consistent with the subsurface density interface representing the contact between the low density Orientale ejecta [9] and the underlying crust [10].
Crustal thickness. Both one-layer and two-layer crustal thickness models were tested, the latter representing a lower density upper crust overlying a higher density lower crust. The crustal thickness models favor a two-layered solution in which a mid-crustal density interface parallels the crust-mantle interface. These models predict similar amplitude undulations along the crust-mantle interface as at the surface, supporting the interpretation that ring faults from the surface propagate down to and offset the crust-mantle interface (Fig. 3). In the western half of the basin, the inflection along the crust-mantle interface at the ORR is aligned with the surface expression of the ring, indicating a vertical fault. In the northeastern quadrant, the expression of the ORR fault at the crust-mantle interface merges with the uplifted mantle plug in the basin center, supporting a lower fault dip consistent with the gravity gradient signature. For the Cordillera ring, the subsurface expression of the ring is shifted toward the basin center relative to its surface expression, leading to fault dips ranging from 60-71° in the northwestern quadrant, to 13-22° in the northeastern quadrant.

Discussion. GRAIL gravity data reveal the subsurface structure at an unprecedented level of detail. Gravity gradients show the presence of a ring dike intruded into the Outer Rook ring fault. The dimensions of this ring dike lead to a total intrusive volume of $2.4 \times 10^5 \text{ km}^3$, which is ~5× greater than the estimated volume of Mare Orientale within the basin center. Similar ring dikes are found around many other basins, and constitute an important component of the magmatic history of the Moon. Crustal thickness models demonstrate that ring faults extend down to and offset the crust-mantle interface at both the Outer Rook and Cordillera Rings, consistent with recent predictions of hydrocode models [11]. These new constraints reveal the subsurface nature of multi-ring basins, and the tectonic and magmatic processes involved in their formation and modification.

INTER- AND INTRA-CRYSTALLINE GEOCHEMICAL AND TEXTURAL VARIATIONS OF APATITES IN TWO APOLLO 12 BASALTS. H. A. Ashcroft¹, M. Anand¹², I. A. Franchi¹, D. Johnson¹ and A. Černok¹ ¹School of Physical Sciences, The Open University, Milton Keynes, UK. ²Department of Earth Sciences, Natural History Museum, London, UK. (mahesh.anand@open.ac.uk).

Introduction: Apatite (Ca₅(PO₄)₃[F,Cl,OH]) crystals in lunar samples exhibit a range in Cl abundances and isotope fractionations [1-3]. Variations in the chlorine inventory of different suites of lunar rocks are attributed to the presence of multiple geochemical reservoirs and/or either magma ocean or volcanic volatile degassing. A major source of uncertainty when interpreting these values is understanding which magmatic and secondary processes the apatite crystals are recording. Often, due to the paucity of apatite grains, and small crystal size, only a few measurements are possible within a polished section, which introduces further uncertainties regarding the representativeness of any single grain in a sample. Cathodoluminescence (CL) is an imaging technique, commonly used in the geosciences (e.g. [4] and [5]) and can complement backscattered electron (BSE), secondary electron (SE) and optical methods. Luminescence, caused by the presence of lattice defects and trace elements, allows geochemical and textural variations in certain minerals to be observed, including apatite. This study is a detailed petrographic and microstructural investigation of apatite in two Apollo 12 basalts, and intra- and inter-crystalline variations in Cl isotopes and abundances.

Samples: The samples were first investigated using a FEI Quanta 200 3D FIB-SEM, with a Deben Centaurus Cathodoluminescence detector. Whole thin section X-ray maps were collected using energy dispersive spectroscopy (EDS). The elemental and BSE maps were then used to identify phosphates and characterise their petrographic context. High resolution CL images of apatite were used to assess microscale structural and compositional variations and select crystals for isotopic analysis. The Open University NanoSIMS 50L was used for isotopic analyses of apatite, using a protocol based on that of [3]. Negative secondary ions including 35Cl, 37Cl, 18OH and 19F were measured simultaneously in multicollection mode. A 50 pA beam was used to measure ~ 5 x 5 μm areas. Apatite standards with a range of OH, Cl and F contents were used as primary reference standards for the calibration of volatile abundances and isotope ratios.

Results: 12016 is an equigranular ilmenite basalt. Apatite occurs within mesostasis regions with other phases including merrillite, Fe metal, FeS, fayalite, K-glass and in one instance a Zr-phase (thought to be baddeleyite). These mesostasis regions are surrounded by pyroxene and feldspar. Apatites occur as euhedral crystals, up to 20 μm in size, as elongate/anhedral crystals up to 100 μm in their longest dimension, or as small (<10 μm) acicular needles.

Figure 1. a) a Secondary Electron (SE) image of mesostasis region 8 in 12016. The main mineral phases are labelled, and the NanoSIMS spots are visible. b) a Cathodoluminescence (CL) image of the same region. In both images, apatite crystals are outlined in thick white lines, and in a) merrillite is outlined by a thin dashed white line.
CL imaging of the apatite grains in 12016 and 12021 shows two types of zoning: gradational zoning which is often observed from core to rim in euhedral crystals, or discrete regions of a different brightness within apatite crystals. CL imaging is particularly sensitive to surface defects including non-planar surfaces, cracks, crystal edges, and variations in carbon coat thickness. CL imaging identified features in apatite crystals not seen in BSE and SE. In 12016 and 12021 crystal fractures could be seen under CL, and in 12021 some irregularly shaped apatite crystals were observed to either comprise multiple smaller more euhedral apatite crystals, or a more complex apatite crystal habit. CL imaging was performed pre- and post-NanoSIMS measurements and the SIMS analyses are not observed to alter the CL sensitive zoning in apatite crystals.

26 analyses of $\delta^{37}$Cl and Cl content were measured in 19 crystals across 11 regions in samples 12021 and 12016 in order to gain maximum coverage, and the results are plotted in Figure 2. In 12016, $\delta^{37}$Cl ranged between +4.3 to +14.9 ‰ with an average of +11.3 ± 6.9 ‰, and Cl contents varied between 360 – 3103 ppm with an average of 1364 ± 879 ppm. In 12021, $\delta^{37}$Cl ranged between +8.9 and +20.8 ‰ with an average of +14.7 ± 6.3 ‰, and Cl content varied between 750 - 2767 ppm with an average of 1543 ± 534 ppm. Both of these results are in keeping with previous measurements of Apollo 12 basalts (+15.0 ± 4.4 ‰ [1], [2]), however the range of values for individual samples is larger than previously observed in any other sample.

Discussion: Intracrystalline measurements of $\delta^{37}$Cl and Cl content in the basal sections of euhedral apatite are within analytical error of each other. However, variations are seen in more irregularly shaped or elongate crystals. For example in region 7 of 12021, three measurements were taken in a single irregularly shaped crystal. Although the $\delta^{37}$Cl values were identical at +12.1 ± 0.08 ‰ the Cl content ranged from 0.13-0.28 wt. % across the crystal over ~ 50 µm. In SE and CL imaging no zoning or defects were observed. In region 5 of 12021, variations in an elongate growth of apatite, in which CL imaging identified either multiple crystals or a more irregular, but euhedral, apatite growth; two spots taken roughly 100 µm apart exhibited differences in Cl content (but not $\delta^{37}$Cl) of 0.05 wt. %. Intracrystalline variations in $\delta^{37}$Cl and Cl content are observed, generally with each mesostasis pocket exhibiting a unique signature. No dependence of $\delta^{37}$Cl, Cl content and location in the thin section with respect to the edges of the sample, or proximity to cracks within the sample are observed.

In 12016, the lowest measurement ($\delta^{37}$Cl = +4 ‰, Cl content = 0.04 wt. ‰) occurs in apatite 8b which shows evidence for disturbance in CL but no surface flaws are observed in SE or BSE images (Fig. 2), possibly suggesting Cl loss. Within an individual region of either 12021, or 12016 no variation in Cl isotope fractionation or abundance is seen with surrounding mineralogy. For example in Region 4 of 12021 a large euhedral apatite crystal has an identical $\delta^{37}$Cl and Cl content to a small apatite which occurs within a symplectite region. The variations in Cl content and $\delta^{37}$Cl observed here between regions in a sample are likely to reflect small-scale heterogeneities in volatile distribution across a magma which are trapped in melt pockets during crystallization and reflect minor variations in extent of crystallization.

Conclusions: This study demonstrates the importance of numerous apatite measurements per sample, to gain a representative range of Cl isotopes and abundances. CL imaging is a useful tool to assess apatite crystals for primary and secondary processes. CL information can guide volatile measurements, to measure zoning or avoid features which may not be observed in SE and BSE alone. The CL imaging can also be used to assess geochemical and textural zoning in other minerals of interest in lunar rocks including feldspars, SiO2 and glass phases.


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**Introduction:** Northwest Africa 10989 (NWA 10989) is a new lunar meteorite found near the Morocco/Algeria border and acquired in 2015. NWA 10989 is a single stone, weighing 14.41 g with a dark brown fusion crust and is classified as a mixed lunar breccia [1]. Terrestrial weathering is limited and is mainly apparent as some carbonate veins. Here we present a preliminary report on the mineralogy and geochemistry of NWA 10989, discuss the potential sources of individual components, and compare it with other, similar meteorites.

**Methods:** A petrographic study was performed on a polished thin section of the sample using an optical microscope and a SEM. Mineral chemistry was determined using an EPMA. Bulk rock analysis was determined using INAA [2], and oxygen isotope analysis was performed using infrared laser-assisted fluorination [3].

**Confirmation of Lunar Origin:** Pyroxene and olivine grains display ranges in Fe/Mn of 63±11 and 105±11 respectively, which are consistent with known lunar trend lines [4], [5]. Oxygen isotopes are also consistent with a lunar origin with Δ17O 3.42 ‰, Δ18O 6.51 ‰, Δ13C 0.03 ‰.

**Petrology and Mineralogy:** NWA 10989 (Fig. 1) is a polymict breccia containing mm-sized minerals, lithic and impact-melt clasts in a dark brown glassy matrix, in which vesicles can be seen in addition to smaller mineral fragments and lithic clasts. Mineral fragments show a diverse range of composition (Fig. 2) and are predominantly feldspar (An80-89), pyroxene (Wo38-42En29.5Fs60.5), and olivine (Fo64-69). Accessory minerals include spinel, ilmenite, apatite, merrillite, silica, troilite, kamacite and schreibersite. Generally, minerals do not exhibit compositional zoning, and many pyroxenes exhibit exsolution lamellae which are ~1 μm thick. Evidence for shock is seen in some feldspar grains through recrystallization and partial maskelynitisation, and offset lamellae are observed in pyroxene. NWA 10989 can be subdivided into three main areas based on texture and composition (Fig. 1a).

**Area 1** is dominated by a partially devitrified impact glass which contains few mineral fragments. Average composition for this area (from multiple EPMA spot analysis) is 49 wt. % SiO2, 1.15 % TiO2, 11.8 % Al2O3, 6.58 % MgO, 12.0 % CaO, 18.0 % FeO, 0.38 % Na2O and 0.05 % K2O.

![Figure 1. a) a full Mosaic image of the NWA 10989 thin section taken for the Virtual Microscope highlighting the different petrographic domains, and a variety of clasts. b) a pyroxene-olivine-spinel clast, c) symplectite of Fayalite-Quartz-Hedenbergite with an apatite crystal in the centre.](image-url)
spar with minor pyroxene, olivine and spinel (labelled as Impact Melt Clast 1 (IMC 1) on Fig. 2). Others contain intergrown feldspar and pyroxene in equal proportions (IMC 2 on Fig. 2). Other textures vary from cryptocrystalline, to glassy, to breccia-in-breccia textures. There is a variation in matrix and impact-melt composition from basaltic to feldspathic.

**Discussion:** Compositionally NWA 10989 appears to share some features with a few other lunar meteorites, in particular the NWA 7834 clan. Similarities to other subgroups include the NWA 7611 clan and also the well characterized YQN group which includes NWA 4884, YAM 981031, YAM 793274 and QUE 94281 (plotted on Fig. 3 for comparison). The Ti contents of the VLT trend pyroxenes were used to calculate parental bulk magma TiO$_2$ of ~ 1 wt. % (method in [8]). At least two distinct compositional sources have contributed material to NWA 10989—a highlands source for mafic and feldspathic lithic clasts and plagioclase with high An content, and a VLT-like basaltic melt. From bulk, mineral and clast compositions a possible source regions for NWA 10989 include an area on the highlands-mare boundary, such as on the lunar nearside, potentially close to the Luna 24 or Apollo 17 landing sites, or an area of cryptomare. Future work will investigate the range of impact-melt and lithic clast compositions in more detail. Age dating of individual components will also be performed.

**Figure 2.** a) NWA 10989 pyroxene compositions b) Ti# vs. Fe# for pyroxenes in the meteorite c) olivine forsterite contents d) plagioclase anorthite contents. The VLT field outlined in 2b) includes the data for Apollo 17 VLT pyroxenes [6], Luna 24 pyroxenes [7] and pyroxenes from several lunar meteorites [8],[9].

**Bulk Composition:** Bulk composition of NWA 10989 (18.5 wt. % Al$_2$O$_3$, 12.6 wt. % FeO, 0.59 wt. % TiO$_2$, 1.04 ppm Th, 25.5 ppm Sc, 2154 ppm Cr and 4.3 ppm Ir) is consistent with the petrographic classification as a mixed breccia. The FeO and Sc contents suggest roughly equal proportions of mafic and feldspathic material, supported by the shape of the chondrite-normalised REE pattern, which has a small negative Eu anomaly.


**Acknowledgements:** We thank Graham Ensor for providing the sample. Dr Andy Tindle is thanked for producing the Virtual Microscope image (Fig. 1a) at The Open University. This research was supported by a grant from STFC, UK (grant # ST/L000776/1 to M.A. and I.A.F.).
METEOROID IMPACTS ON THE SURFACE OF THE MOON AND DUST PARTICLE LAUNCHING. B. Atamaniuk¹, S. I. Popel², A. P. Golub³, H. Rothkaehl¹, E. A. Lisin³, Yu. N. Izvekova², G. G. Dol’nikov⁴, A. V. Zakharov⁴, and L. M. Zelenyi³, ¹Space Research Centre, Polish Academy of Sciences, Bartycka 18A, 00-716 Warsaw, Poland, batama@cbk.waw.pl, ²Space Research Institute, Russian Academy of Sciences, ul. Profsoyuznaya 84/32, Moscow, 117997 Russia, popel@iki.rssi.ru, ³Joint Institute for High Temperatures, Russian Academy of Sciences, ul. Izhorskaya 13/19, Moscow, 125412 Russia.

Introduction: It is now almost universally accepted that the dust over the lunar surface is a component of a plasma-dust system (see, e.g., [1-3]). The first lunar dust observations were made during the Surveyor and Apollo missions. The Surveyor lunar missions revealed that sunlight was scattered in the terminator region, and this led to the generation of the lunar horizon glow and streamers above the lunar surface [4]. Subsequent observations showed that the sunlight was scattered most probably by the charged dust particles originating from the lunar surface [5]. The analysis of the data obtained by the Surveyor landers led to a conclusion that the dust particles with a diameter of about 5 μm might levitate at a height of about 10 cm above the lunar surface.

The description [1-3] makes clear some features of dusty plasma system over the Moon. However, there are unsolved problems concerning its parameters and manifestations [6]. In particular, significant uncertainty exists as to the physical mechanism through which dust particles are released from the surface of the Moon. Adhesion has been identified as a significant force in the dust particle launching process which should be considered to understand particle launching methods [7].

The problem of the dust particle release from the lunar surface can be solved, for example, by considering meteoroid impacts onto the surface of the Moon [8]. Here, we consider lunar dust particle launching process due to meteoroid impacts. A significant attention is paid to the importance of the adhesive force.

The Force of Adhesion: In [7] dust particles with smooth surfaces have been considered. The effect of surface roughness results in significant attenuation of the effect of adhesion in comparison with the results [7]. Indeed, the calculation of the force of adhesion between a plane with an asperity of the radius r and a spherical particle of radius a gives

\[ F = \frac{\pi a S r}{24 \Omega^2} \left( \frac{r}{r + a} + \frac{a}{1 + (r / (2 \Omega))^2} \right) \]

where \( S \) is Hamaker’s constant, \( \Omega \) is the surface cleanliness, and \( \Omega = 0.132 \) nm characterizes the diameter of oxygen ion. For lunar regolith Hamaker’s constant is \( 4.3 \times 10^{-20} \) J; surface cleanliness varies in the range of 1 to 0 and for lunar dayside is calculated as \( S = 0.88 \) [9]. Calculations based on Eq. (1) show that the effect of roughness results in two-three orders of magnitude attenuation of the effect of adhesion in comparison with the case of a smooth particle (see Fig. 1). Nevertheless, even considering the roughness of lunar regolith particles, the electrostatic forces required to launch dust particles from the lunar surface, as a rule, do not exceed the adhesive forces. Dust particle launching can be explained if the dust particles rise at a height of about dozens of nanometers owing to some processes (e.g., meteoroid impacts, etc.). This is enough for the dust particles to acquire charges sufficient for the dominance of the electrostatic force over the gravitational and adhesive forces, and finally to rise above the lunar surface.

Dust Particle Release: When high-speed meteoroid impacts the lunar surface the substances of the impactor and the target are strongly compressed and heated. Under the action of high pressure strong shock wave is formed. The shock propagates and weakens moving away from the impact epicenter. Finally the weakening shock transforms into linear acoustic wave. The zones (around the impact epicenter) of evaporation of the substance, its melting, destruction of particles constituting lunar regolith, their irreversible deformations are formed due to the propagation of the weakening wave. Beyond the zone of irreversible deformations the zone of elastic deformation is created which is characterized by the magnitudes of the pressure in acoustic wave less than dynamic limit of elasticity.

Considering the balance between the maximum force of pressure in the blast wave and the sum of the adhesive, electrostatic, and gravitational forces we...
determine the radius of the zone around the impact epicenter which restricts the region where dust particles are released from the surface of the Moon due to meteoroid impacts. Furthermore, we estimate the speeds of the released particles, find their size-distribution (Fig. 2), and evaluate maximum heights of dust particle rise.

![Fig. 2. The size-distribution function of particles released from the lunar surface due to meteoroid impacts.](image)

The normalized distribution function shown in Fig. 2 is valid for various altitudes and indicates the presence of microparticles over the surface of the Moon. This fact distinguishes particles rising over the surface of the Moon owing to impacts of meteoroids from particles usually considered when describing the plasma–dust system in which nanoparticles and submicroparticles levitate over the Moon [1]. The consideration of only the processes typical of a dusty plasma (excluding strong perturbations such as impacts of meteoroids) allows the explanation of the presence of microparticles (with sizes of 2–3 μm) only over the region of the lunar terminator [10]. In all other cases, the sizes of levitating dust particles are no more than several hundred nanometers.

Thus, impacts of meteoroids constitute an important source of dust microparticles in the plasma–dust system over the surface of the Moon. The inclusion of dust microparticles appearing because of impacts of meteoroids can make a certain contribution to the description of scattering of solar light by dust particles over the region of the lunar terminator for the description of luminescence observed over this region by the Surveyor spacecrafts. Within the future Luna-Glob and Luna-Resurs missions, piezoelectric impact sensors can be used to detect and identify dust microparticles appearing in the plasma–dust system over the surface of the Moon owing to impacts of meteoroids [3]. The characteristic features of such particles are high velocities (about 10–100 m/s) and micron sizes.

**Summary:** To summarize, it has been shown that impacts of meteoroids are important for the separation of dust particles from the surface of the Moon. When considering processes significant for the separation of dust particles, it is necessary to take into account adhesion, whose effect is weakened if the roughness of the surface is taken into account. The number of collisions of meteoroids with unit area of the surface of the Moon per unit time has been determined and the ultimate tensile strength of lunar regolith owing to adhesion has been estimated [8]. Processes occurring at the collision of a fast meteorite with the surface of the Moon have been described. The characteristic parameters of the material evaporation zone, material melting zone, destruction zone of lunar regolith particles, zone of irreversible deformations of particles, and zone of elastic deformations of the regolith material have been determined. It has been shown that most particles leaving the surface of the Moon owing to impacts of meteoroids originate from the zone of elastic deformations of the regolith material. The number of dust particles separated from a unit area of the surface of the Moon per unit time because of impacts of meteoroids has been calculated for various altitudes over the Moon. The size distribution function of these particles has been determined. It has been shown that impacts of meteoroids constitute an important source of dust microparticles in the plasma–dust system over the surface of the Moon.

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PLASMA SHEATH IN A DUSTY PLASMA NEAR THE LUNAR TERMINATOR. B. Atamaniuk¹, S. I. Popeł², and L. M. Zelenyi², ¹Space Research Centre, Polish Academy of Sciences, Bartętcka 18A, 00-716 Warsaw, Poland, batama@cbk.waw.pl, ²Space Research Institute, Russian Academy of Sciences, ul. Profsoyuznaya 84/32, Moscow, 117997 Russia, e-mail: popeł@iki.rssi.ru.

**Introduction:** It is now almost universally accepted that the dust over the lunar surface is a component of a plasma-dust system (see, e.g., [1-3]). Figure 1 presents schematically the main elements characterizing the dusty environment over the Moon.

![Fig. 1. The main elements [4] characterizing the dusty plasma system over the Moon (the terminator, the photoelectrons, the near-surface dust particles, dust particles at high altitudes, photons of solar radiation (hα), and the solar wind) as well as the lunar lander at a high lunar latitude in the South Hemisphere.](image)

The first lunar dust observations were made during the Surveyor and Apollo missions. The Surveyor lunar missions revealed that sunlight was scattered in the terminator region, and this led to the generation of the lunar horizon glow and streamers above the lunar surface [5]. Subsequent observations showed that the sunlight was scattered most probably by the charged dust particles originating from the lunar surface [6]. The analysis of the data obtained by the Surveyor landers led to a conclusion that the dust particles with a diameter of about 5 μm might levitate at a height of about 10 cm above the lunar surface.

The description [1-3] makes clear some features of dusty plasma system over the illuminated part of the Moon. However, there are unsolved problems concerning its parameters and manifestations in the terminator region [7]. Here, we consider the terminator region [4], study dusty plasma properties there, determine the electric fields, and discuss a possibility of the rise of dust particles.

**Dusty Plasma Sheath:** The speed \( u \) of the terminator satisfies the conditions \( v_{Td} \ll u \ll v_T \), where \( v_{Td} \) is the dust (ion) thermal velocity. The terminator speed does not depend on time. This allows us to look for the plasma parameters in the vicinity of the terminator as functions of the only variable \( \xi = x - ut \) which satisfy the hydrodynamics equations for dust and Boltzmann distributions for electrons and ions. Furthermore, we use the orbit-limited probe theory to describe the dust particle charges \( q_d = -Ze \) and Poisson’s equation for the electrostatic potential \( \varphi \), where \( -e \) is the electron charge. We find

\[
\left( \frac{d\varphi}{d\xi} \right)^2 = 8\pi \left[ n_{e0}T_e \left( \exp \left\{ \frac{e\varphi}{T_e} \right\} - 1 \right) + n_{i0}T_i \left( \exp \left\{ \frac{e\varphi}{T_i} \right\} - 1 \right) + m_d u^2 n_{d0} \left( \frac{n_{d0}}{n_d} - 1 \right) \right],
\]

where \( T_{e(i)} \) is the electron (ion) temperature, \( m_d \) is dust particle mass, \( n_{e(i),0} \) is the unperturbed electron (ion, dust) number density characterizing dusty plasma system at the illuminated part of the Moon far from the region of the lunar terminator (corresponding in our consideration to \( \varphi \rightarrow 0 \)), \( n_{d} \) is the dust number density. The set of equations (1) has the steady-state solution describing the dusty plasma properties in the terminator region. The necessary condition for the steady-state solution to exist is

\[
u^2 \geq \frac{(n_{e0} - n_{e0})(Z_d)}{m_d \left( \frac{n_{d0}}{T_e} + \frac{n_{d0}}{T_i} \right)} \approx |Z_d| \frac{T_e}{m_d}.
\]

The condition (2) is easily fulfilled for the parameters of the lunar terminator and the dusty plasma system at the illuminated part of the Moon. This condition is the Bohm criterion for the dusty plasma sheath. The sheath is formed in the region of the lunar terminator. The solutions of Eqs. (1) are presented in Fig. 2.
Dust Number Density and Electric Fields: The blue curve in Fig. 2 displays the dust number density while the red one shows the electric field $E$. Almost everywhere in the region of the lunar terminator the dependencies of $n_d$ (curve I) and $E$ are given by the expressions

$$ n_d = \frac{n_{d0}}{\sqrt{1 + 3 \left( \frac{Z_d}{n_{d0}} \frac{n_{e0}}{n_{d0}} \frac{\sqrt{T_e}}{m_d u^2} \left( \frac{\xi}{\sqrt{2 \lambda_{Di}}} \right)^2 \right)^{\frac{1}{2}}}}. $$  \tag{3}

$$ E = \frac{\sqrt{8\pi n_{e0} T_i}}{3} \left( \frac{Z_d}{n_{e0}} \right)^2 \frac{m_d u^2}{T_i} \left( \frac{\xi}{\sqrt{2 \lambda_{Di}}} \right)^{\frac{1}{3}}. $$  \tag{4}

In the vicinity of the right boundary of the sheath $\xi = \sqrt{2 \lambda_{Di}}$ ($\xi < \sqrt{2 \lambda_{Di}}$), we obtain

$$ n_d = \frac{n_{d0}}{\sqrt{1 - \frac{4T_i |Z_d| n_{e0} u^2}{m_d u^2 m_i u^2} \ln \left( 1 - \frac{\xi}{\sqrt{2 \lambda_{Di}}} \right)}}. $$  \tag{5}

$$ E = \frac{\sqrt{8\pi n_{e0} T_i}}{1 - \xi/\sqrt{2 \lambda_{Di}}}. $$  \tag{6}

For $T_i = 7 \times 10^4$ K and $n_{e0} = 8.8$ cm$^{-3}$ (that corresponds to the temperature and the number density of solar wind protons); $|Z_d| \sim 10$, $n_{e0} \sim 10^3$ cm$^{-3}$, $m_d \sim 10^{-14}$ g (for 0.1µm-scale dust particles), and $u = 400$ cm/s an estimate based on Eq. (6) gives $E \sim 300$ V/m.

The above calculations are performed under the assumption of the plane (horizontal) lunar surface. Correspondingly, the directions of the electric fields considered above are horizontal, and their presence results in an increase of the component of dust particle speed parallel to the surface. In reality, the lunar surface is rugged. This means that the electric fields existing in the region of the lunar terminator have both horizontal and vertical components. The vertical component is, in general, on the order of horizontal that. Thus one can expect that a significant part of the electric field energy is transferred to the dust particle motion in the vertical direction. An estimate shows that this can result in rise of dust particles of the size of 2–3 µm up to an altitude of about 30 cm that, in turn, explains the effect of “horizon glow” observed at the lunar terminator by Surveyor lunar lander.

**Summary:** Thus, we can conclude that in the terminator region a plasma layer exists which is similar to a sheath. The function of this layer is to form a potential barrier in the region of the terminator so that the electron plasma species is confined electrostatically. Dusts rised at the illuminated part of the Moon in their relative motion with respect to the terminator must enter the sheath (terminator) region with a velocity greater than the dust acoustic velocity. In the terminator region an excitation of electric fields on the order of 300 V/m is possible. These electric fields can result in rise of dust particles of the size of 2–3 µm up to an altitude of about 30 cm that explains the effect of “horizon glow” observed at the lunar terminator by Surveyor lunar lander.

**Acknowledgements:** This work was supported by the Presidium of the Russian Academy of Sciences (program no. 7 “Experimental and Theoretical Studies of the Objects of the Solar System and the Planetary Systems of Stars. Transient Explosive Processes in Astrophysics”) and by the Russian Foundation for Basic Research (project no. 15-02-05627).

**References:**
SELMA: A MISSION TO STUDY LUNAR ENVIRONMENT AND SURFACE INTERACTION. S. Babrabash, Yoshifumi Futaana, Swedish Institute of Space Physics, Box 812, Kiruna, 98128, Sweden (stas@irf.se) and the SELMA Team.

Introduction: SELMA (Surface, Environment, and Lunar Magnetic Anomalies) is a mission to study how the Moon environment and surface interact. SELMA addresses four overarching science questions:

- What is the origin of water on the Moon?
- How do the “volatile cycles” on the Moon work?
- How do the lunar mini-magnetospheres work?
- What is the influence of dust on the lunar environment and surface?

SELMA uses a unique combination of remote sensing via UV, IR, and energetic neutral atoms (ENA) and local measurements of plasma, exospheric gases, and dust. It will also conduct an impact experiment to investigate volatile content in the soil of the permanently shadowed area of the Shekleton crater. SELMA carries an impact probe to sound the Reiner-Gamma mini-magnetosphere and its interaction with the lunar regolith from the SELMA orbit down to the surface.

SELMA was proposed to ESA as a M5-class mission in October 2016.

SELMA science objectives and instruments: The four science questions are broken down into science objectives as given in Table 1. The objectives associated with each science question are highlighted by the same background color.

The SELMA scientific instruments are shown in Table 2.

SELMA mission: SELMA is a flexible and short (15 months) mission including the following elements (Fig. 1) SELMA orbiter, SELMA Impact Probe for Magnetic Anomalies (SIP-MA), passive Impactor, and Relaying CubeSat (RCS). It launches on January 1, 2029 (flexible) by Souyz-Fregat launcher and perform direct transfer to the Moon (Fig. 2). After 5 days it reaches its nominal quasi-frozen polar working orbit 30 km x 200 km with the pericenter over the South Pole. Approximately 9 months after the launch SELMA releases SIP-MA) to sound the Reiner-Gamma magnetic anomaly with very high time resolution <0.5 s to investigate small-scale structure of the respective mini-magnetosphere. At the end of the mission the passive impactor impacts the permanently shadowed region of the Shekleton crater >10 sec before SELMA and SELMA orbiter flies through the resulted plume to perform high resolution mass spectroscopy of the released volatiles. The data are downlinked to ground and RCS. RCS stays on orbit for 2 more days to downlink the complete data set.
Table 1. SELMA science objectives

<table>
<thead>
<tr>
<th>SELMA science objectives</th>
<th>SELMA measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Establish the role of the solar wind and exosphere in the formation of the water</td>
<td>IR and UV spectroscopy, solar wind monitoring, proton flux at the surface via scattered hydrogen, exospheric gas-ses composition and density</td>
</tr>
<tr>
<td>bearing materials</td>
<td><strong>Measurements of scattered H0, H⁺, H⁻; secondary ions</strong></td>
</tr>
<tr>
<td>Investigate the process of the solar wind surface interaction</td>
<td>Mass spectroscopy measurements of the plume created by an impactor.</td>
</tr>
<tr>
<td>Determine the water content in the regolith of the permanently shadowed region and its</td>
<td>Exosphere gasses densities and composition with simultaneous monitoring of the solar wind, meteor impact, particle releases processes from the surface</td>
</tr>
<tr>
<td>isotope composition</td>
<td><strong>Ions and electrons, waves and field with a time resolution &lt;0.5 sec corresponding to the electron gyro-radius from 10s down to the surface</strong></td>
</tr>
<tr>
<td>Establish variability, sources and sinks of the lunar exosphere</td>
<td>IR and UV spectroscopy, plasma and fields, proton flux at the surface via backscattered scattered hydrogen</td>
</tr>
<tr>
<td>Investigate how the lunar exosphere content is related to impact events</td>
<td>Dust and meteor impact monitoring</td>
</tr>
<tr>
<td>Investigate a mini-magnetosphere interaction with the solar wind</td>
<td>Dust, plasma, field and wave measurements</td>
</tr>
<tr>
<td>Establish structure and topology of the magnetic field at the surface</td>
<td><strong>Moon exospheric mass spectrometer: Waves and electric field instrument</strong></td>
</tr>
<tr>
<td>Investigate the long-term effects of mini-magnetospheres on the local surface</td>
<td><strong>Lunar dust detector: M&gt;10⁻¹⁵ kg</strong></td>
</tr>
<tr>
<td>Investigate how the impact events affect the lunar dust environments</td>
<td><strong>Impact probe magnetometer</strong></td>
</tr>
<tr>
<td>Investigate how the plasma effects result in lofting the lunar dust</td>
<td><strong>Passive 10 kg copper spherical impactor</strong></td>
</tr>
</tbody>
</table>

Table 2. SELMA scientific instruments

<table>
<thead>
<tr>
<th>Remote sensing instruments</th>
<th>In-situ instruments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Infrared and visible spectrometer</strong></td>
<td>Lunar ion spectrometer</td>
</tr>
<tr>
<td><em>Spectral range 400 – 3600 nm</em></td>
<td><strong>M/ΔM &gt; 80</strong></td>
</tr>
<tr>
<td><strong>Wide angle and transient phenomena camera</strong></td>
<td>Lunar scattered proton and negative ion experiment: <strong>Energy range: 10 eV – 10 keV</strong></td>
</tr>
<tr>
<td><em>Visible, FoV 120°x60°</em></td>
<td><strong>Moon exospheric mass spectrometer: Waves and electric field instrument</strong></td>
</tr>
<tr>
<td><em>Meteoroid impact (&gt;100 g)</em></td>
<td><strong>Lunar dust detector: M&gt;10⁻¹⁵ kg</strong></td>
</tr>
<tr>
<td><strong>Moon UV imaging spectrometer</strong></td>
<td><strong>Impact probe magnetometer</strong></td>
</tr>
<tr>
<td><em>Spectral range 115 - 315 nm</em></td>
<td><strong>Passive 10 kg copper spherical impactor</strong></td>
</tr>
<tr>
<td><strong>ENA telescope</strong></td>
<td><strong>Plasma wave instrument</strong></td>
</tr>
<tr>
<td><em>Energy range 10 eV – 3 keV</em></td>
<td><strong>Lunar dust detector: M&gt;10⁻¹⁵ kg</strong></td>
</tr>
<tr>
<td><em>Angular resolution &lt; 10°</em></td>
<td><strong>Impact probe ion and electrons spectrometer</strong></td>
</tr>
<tr>
<td><strong>SELMA Impact Probe for Magnetic Anomaly sounding (SIP-MA)</strong></td>
<td><strong>Lunar dust detector: M&gt;10⁻¹⁵ kg</strong></td>
</tr>
<tr>
<td><strong>Waves and electric field instrument</strong></td>
<td><strong>Impact probe magnetometer</strong></td>
</tr>
<tr>
<td><strong>Impact probe ion and electrons spectrometer</strong></td>
<td><strong>Lunar dust detector: M&gt;10⁻¹⁵ kg</strong></td>
</tr>
<tr>
<td><strong>Time res. &lt; 0.5 s/3D</strong></td>
<td><strong>Impact probe magnetometer</strong></td>
</tr>
<tr>
<td><strong>Context camera</strong></td>
<td><strong>Passive 10 kg copper spherical impactor</strong></td>
</tr>
</tbody>
</table>
**PROSPECTing for Lunar Polar Volatiles: the ProSPA Miniature In-situ Science Laboratory.** S. J. Barber¹, P. H. Smith², I. P. Wright³, F. Abernethy⁴, M. Anand⁵, K. R. Dewar⁶, M. Hodges⁷, P. Landsberg⁸, M. R. Leese⁹, G. H. Morgan¹, A. D. Morse¹, J. Mortimer¹, H. M. Sargeant¹, I. Sheard¹, S. Sheridan¹, A. Verchovsky¹, F. Goesmann², C. Howe³, T. Morse³, N. Lillywhite⁴, A. Quinn⁴, N. Missaglia⁵, M. Pedrali⁵, P. Reiss⁶, F. Rizzi⁷, A. Rusconi⁷, M. Savoia⁷, A. Zamboni⁷, J. A. Merrifield⁸, E. K. Gibson Jr.⁹, J. Carpenter¹⁰, R. Fisackerly¹⁰ and B. Houdou¹⁰. ¹School of Physical Sciences, The Open University, Milton Keynes, MK7 6AA, UK (simeon.barber@open.ac.uk), ²Max Planck Institute for Solar System Research (MPS), Germany, ³RAL Space, UK, ⁴Airbus Defence and Space, UK, ⁵Media Lario Technologies, Italy, ⁶Technical University of Munich, Germany, ⁷Leonardo S.p.A., Italy, ⁸FGE Ltd., UK, ⁹ARES, NASA Johnson Space Center, USA, ¹⁰ESA ESTEC, Netherlands.

**Introduction:** The Package for Resource Observation and in-Situ Prospecting for Exploration, Commercial exploitation and Transportation (PROSPECT) is in development by the European Space Agency (ESA) for application at the lunar surface as part of international lunar exploration missions in the coming decade, including the Russian Luna-27 mission planned for 2021. PROSPECT will search for and characterize volatiles in the lunar polar regions to answer science questions and investigate the viability of these volatiles as resources.

ProSPA is the name given to the Sample Processing and Analysis element of PROSPECT. Its functions are to receive samples extracted from the lunar sub-surface by the ProSEED drill, and to perform a suite of analytical experiments aimed at understanding the nature, source, evolution and utility of the volatiles therein. These functions are distributed across two physical units – a Solids Inlet System (SIS) comprising a series of single-use sample ovens on a rotary carousel together with a sample imager, and a miniature chemical analysis laboratory incorporating two mass spectrometers and associated ancillary and control systems (Figure 1). The science output is anticipated to be the identity, quantity and isotopic composition of volatiles as a function of depth within the first 1.2 m of the lunar surface.

**Volatile Preservation:** The local regolith temperature in the sampled site is assumed to be ~120 to 150 K. A wide range of volatiles may be present in a variety of forms, including physically (loosely) bound and chemically (more strongly) bound species. A key challenge is to minimize the uncontrolled loss of volatiles before they can be sealed in the ProSPA oven for analysis. The stability (hence rate of loss) of lunar volatiles is a strong function of temperature [1] as well as particle size [2]. For this reason the drill and operations strategy will be optimized to minimize the heating of the regolith during sampling, and attention will be paid to the time-temperature profile of the samples following excavation. The SIS is thermally isolated from the “warm” enclosure of the chemical analysis unit, allowing the oven to be at 120 K or colder when the sample is directly transferred into it from the drill. After sample transfer the carousel is rotated to place the sample-containing oven under an imager which confirms the presence of sample and enables estimation of the sample volume (up to a few tens of cubic mm). Then the sample oven is rotated to the “tapping station” position where an actuator is used to seal the oven to a pipe which runs to the chemical analysis laboratory. The duration from sample extraction to sealing will be minimized to reduce volatile losses.

**Volatile Extraction:** Volatiles are extracted from the sample through heating within the sealed sample oven. A number of heating profiles are envisaged to accomplish a variety of analysis modes (Figure 2).

![Figure 1: Location of ProSPA units and ProSEED drill box on Luna-27 lander (credit IKI/Roscosmos)](image1)

![Figure 2: Example sample heating profiles](image2)
Evolved gas analysis: The oven is heated at a ramp rate of 6°C/min and the released gases are continuously analyzed by mass spectrometer to afford evolved gas analysis plots of the type previously presented for analysis of Apollo samples [3].

In Situ Resource Utilization (ISRU) demonstration: the oven is heated to 900 °C in the presence of added hydrogen feed gas to extract oxygen through reduction of mineral phases.

Steppe pyrolysis or combustion: gases released at a series of fixed temperatures from samples in vacuum or in oxygen respectively are sequentially processed for isotopic analysis in a magnetic sector mass spectrometer.

Volatile Analysis: Volatiles released through the previously described extraction processes are passed to the ProSPA chemical laboratory for analysis. This comprises an ion trap device for analytical mass spectrometry (target m/z range 2-200 amu) and a magnetic sector instrument for stable isotopic analysis (~per mil level precision), together with the associated gas handling and processing components including open/closed valves, metering valves, micro-reactors, pressure sensors, reference materials etc. The systems of the chemical laboratory are shown in Figure 3.

Instrument Heritage: To minimise development timescales in line with the schedule of the Luna-27 Roscosmos-ESA mission to the lunar south pole in 2021, the ProSPA instrument draws heavily upon European heritage in flight hardware. The Solids Inlet System is based upon similar systems flown on Rosetta Philae [4] and in development for ExoMars rover [5], adapted for the lunar environment and sample nature. The ion trap mass spectrometer is based on the light-weight (<500 gram all-in) device which made the first chemical analyses on the surface of a comet on board Rosetta Philae [6]. The magnetic sector instrument for isotopic analysis is based upon that developed for the Gas Analysis Package on the Beagle 2 Mars lander [7]. Further gas processing components, electronics and software share similar heritage and the team developing ProSPA is based on previous successful missions.

Current Status: ProSPA is currently in Phase B, with a Preliminary Design Review scheduled for Q4 2017. Theoretical and laboratory work is underway to develop and confirm key aspects of the instrument design and performance. The means for sealing the sample oven in the lunar environment has been investigated, including the design of elastomer seals resilient to moderate loads of dust on their sealing surfaces. A combination of experimental work and modeling will be implemented to demonstrate the adequate preservation of volatiles between the point of delivery of samples from the drill up to and including their sealing within the oven. The temperature release profiles shown in Figure 2 will be iterated with a view to reducing the duration of the extractions in order to minimise the resource requirements (power, time, energy). The current predictions are that ProSPA requires 10 kg and peak power of ~70 W.

Conclusions: ProSPA is a powerful and versatile scientific laboratory for the analysis of lunar volatiles. Using techniques developed in the laboratory and refined in previous missions it will identify, quantify and isotopically characterise (D/H, δ13C, δ15N, δ18O) samples extracted from up to 1.2 m depth by the ProSEED drill. The acquisition of contextual images of the samples and the use of on-board reference materials will enable the results from ProSPA to be interpreted in the context of existing lunar data-sets.

Acknowledgement: ProSPA is being developed by a consortium led by The Open University, UK, under contract to the PROSPECT prime contractor Leonardo S.p.A., Italy, within a programme of and funded by the European Space Agency.

References:
**VOLATILES IN HIGH TITANIUM BASALTIS FROM THE MOON.** J. J. Barnes\(^1,2*,3\), F. M. McCubbin\(^1**,\) J. W. Boyce\(^1\), A. N. Nguyen\(^1,3\), and S. Messenger\(^1\). 1ARES, NASA JSC, Houston, TX. 2School of Physical Sciences, The Open University, Milton Keynes, U.K. 3JETS JACOBS, NASA JSC, Houston, TX. *correspondence: jessica.j.barnes@nasa.gov, **presenting author

**Introduction:** Chlorine is an unusual isotopic system, being essentially unfractionated (\(\delta^{37}\text{Cl} \sim 0\%\)) between bulk terrestrial samples and chondritic meteorites [e.g., 1-2] and yet showing large variations in lunar, martian, and vestan (HED) samples (from \(\sim -4\) to \(+81\%\), 3-10]).

Among lunar samples, the volatile-bearing mineral apatite (\(\text{Cas(PO}_3\text{)}_3(\text{F,Cl,OH})\)) has been studied for volatiles in K-, REE-, and P (KREEP), very high potassium (VHK), low-Ti and high-Ti basalts, as well as samples representing the lunar highlands [3-8]. These studies revealed a positive correlation between in-situ \(\delta^{37}\text{Cl}\) measurements and bulk incompatible trace elements (ITEs) and ratios [7-8]. Such trends were interpreted to originate from Cl isotopic fractionation during the degassing of metal chlorides during or shortly after the differentiation of the Moon via a magmatic ocean. In this study, we investigate the mineralogical and textural occurrence of phosphates, and the volatile inventories of a group of samples for which new-era volatile data have yet to be reported – the high-titanium, high-potassium mare basalts (typically, >2000 ppm bulk K\(_2\)O).

**Samples and Methods:** We studied thin sections of three high-Ti, high-K basalts (also referred to as Type A basalts) from the Apollo 11 mission (10017, 10024, 10049). These samples have bulk K\(_2\)O contents between -0.28 and 0.33 wt.%, P\(_2\)O\(_5\) contents from 0.15 to 0.16 wt.%, and TiO\(_2\) contents from 10.6 to 12.6 wt.% [11-12]. They represent a sampling of the end-members of the high-Ti, high-K basalt group, whilst also displaying variations in ITE abundances. The basalts have crystallization ages ranging from approximately 3.5 to 3.7 Ga [11 and references therein].

Thin sections were Co coated and preliminary analyses and characterization work was conducted using the JEOL 7600F scanning electron microscope at JSC. Samples were initially X-ray mapped using energy dispersive spectroscopy (EDS) to locate P hotspots associated with the phosphates. Isotopic analyses of apatite in 10049 were conducted by iso- tope imaging on the JSC NanoSIMS 50L. The negative secondary ions of \(^{19}\text{O},^{19}\text{F},^{31}\text{P},^{30}\text{Cl},\) and \(^{37}\text{Cl}\) were collected simultaneously with electron multipliers. A Cs\(^+\) primary beam of \(~7\) pA was rastered over a range of areas (~64 to 324 \(\mu\)m\(^2\)). Well characterized apatite standards with a range of OH, Cl, and F contents and of known Cl isotopic compositions were used as primary reference standards for calibrating both isotope ratios and volatile abundances.

**Phosphates in high-K basalts:** Apatite occurs as a late-stage mineral almost exclusively in mesostasis areas within the samples we investigated thus far. It typically coexists with plagioclase, high-Fe pyroxene, silica, ilmenite, troilite, K-rich residual glass, K-Ba feldspar, Zr-bearing minerals, and REE-merrillite. Apatite is present either as (i) discrete crystals varying from basal to acicular, most are euhedral with some being sub-hedral, and (ii) apatite-merrillite intergrowths. The intergrowths vary in texture from hexagonal crystals containing both phosphates typically within the mesostasis to vein-like merrillite with minor anhedral apatite, the latter are more commonly located at the boundary of, or cross-cutting through, the main rock-forming minerals (e.g., pyroxene). The observed intergrowth textures are strikingly similar to those reported in lunar highlands samples and KREEP-rich basalts [e.g., 13-14]. Apatite crystal size varies amongst the samples studied (which themselves vary from very fine to medium grained basalts) from <1\(\mu\)m to ~60 \(\mu\)m in the longest dimension.

**Results of the chlorine isotopic analyses of high-K, high-Ti basalt:** We used isotope imaging on the NanoSIMS to obtain the Cl isotopic composition \([\delta^{37}\text{Cl}}\) (\(\%\)) = \((^{37}\text{Cl}/^{35}\text{Cl}_{\text{sample}}/^{37}\text{Cl}_{\text{standard}} - 1) \times 1000\) for five apatite crystals in 10049, which ranges from \(\sim -2.7 \pm 2\%\) to \(+8.5 \pm 1\%\) (2\(\sigma\)). Using the volatile calibration determined by NanoSIMS analysis of apatite standards, the F content of the apatite crystals analyzed in 10049 varied from 3.16 to 3.7 wt.% and the Cl content from 0.02 to 0.21 wt.%.

**Volatiles in high-Ti mare basalts:** Of the high-Ti basalts (>9 wt.% bulk TiO\(_2\)) only members of the low-K sub-group have been investigated previously for \(\delta^{37}\text{Cl}_{\text{Ap}}\); Apollo 11 samples 10044 and 10058, and Apollo 17 samples 70017, 70035, and 75055 [7-8,16] (Figure 1). In these samples, apatite is most commonly fluorapatite, is usually located within late-stage mesostasis areas, and the samples are typically devoid of REE-merrillite. Of the mare basalts analyzed, the high-Ti basalts show larger intra-sample H-isotope variations on the order of ~200 to 300 \(\%\) (2 SD) at relatively restricted OH contents when compared to low-Ti basalts [14-17]. Barnes et al. [18] show that the same appears to be true for Cl-isotope compositions, with intra-sample variations in chlorine isotope values of high-Ti basalts being generally higher than those for low-Ti basalts. Figure 1 shows the Cl-isotope compositions for apatite in lunar basalts compared with bulk rock Th abundances.
In comparison to the high-Ti, low-K basalts, apatite from the most geochemically evolved [12] Apollo 11 high-K basalt (10049) show lighter δ37Cl values, whilst displaying Th abundances similar to those of KREEP basalt 72275 (i.e., ~135 × C.I. chondrite).

**Figure 1:** Average Cl-isotopic composition of apatite from Apollo lunar basalts [3-4,7-8,18] versus bulk rock Th abundances [11-12, additional references in 18]. The data points for low-Ti basaltic lunar meteorite MIL 05035 are the averages from multiple studies [4,7,18]. Uncertainties represent the standard deviation (2 SD) on reported values. SMOC refers to standard mean ocean chloride.

**Petrogenesis of the high-Ti basalts in light of Cl isotopes:** Simply following the models of [7-8] for lunar rocks with high bulk abundances of ITEs we might expect the high-Ti, high-K basalts to contain apatite characterized by heavily fractionated Cl isotope compositions, i.e., Cl obtained from mixing between unfraccionated mantle Cl (~ 0‰) and the urKREEP reservoir (possibly fractionated to >+25‰, [19]). However, the data obtained for 10049 do not conform to either the early degassing or mixing models (Figure 1).

Current petrogenic models for the origin of the high-Ti, high-K basalts do not include urKREEP assimilation into the lunar magma ocean (LMO) cumulate sources. This is based on observations of (i) lower La/Sm ratios [12,20], (ii) relatively LREE-depleted profiles [12,20], and (iii) depleted initial Nd and Sr isotopic compositions [21] of the high-Ti, high-K basalts compared to KREEP. Neal and Taylor [20] suggested that source region heterogeneity rather than assimilation could explain the geochemical characteristics of the high-Ti mare basalts. In addition, the source regions for the high-Ti basalts may have been affected by metasomatism [22]. As Neal and Taylor [20] point out, if the hypothetical metasomatic agent was a KREEPy fluid, then that could explain the trend towards KREEP-like La vs K composition of Apollo 11 high-Ti, high-K basalts. Alternatively, assimilation of a lithology less evolved (lower La/Sm ratio) than KREEP could also reproduce the geochemical trends exhibited by the high-Ti, high-K basalts [e.g., 12]. The new data that we present provides evidence for the existence of regions in the lunar interior that are REE-enriched and contain Cl that does not share isotopic affinities with lunar urKREEP.

**Acknowledgements:** This work is supported by a NASA postdoctoral fellowship awarded to JJB and NASA’s LASER program grant #NNX13AK32G awarded to F.M.M.

CRYSTAL STORAGE AND TRANSFER IN LUNAR MAGMATIC SYSTEMS. S. K. Bell¹, M. E. Hartley¹, K. H. Joy¹ and J. F. Pernet-Fisher¹. ¹School of Earth and Environmental Sciences, University of Manchester, Manchester, M13 9PL, UK (samantha.bell@manchester.ac.uk).

Introduction: Mare basalts sampled by the Apollo missions show a range of chemical and petrological characteristics, as well as variable crystallisation histories [1]. Such properties reflect both diversity within the lunar mantle source [2,3] and differences in magmatic histories and eruption processes [4].

Apollo 15 volcanic rocks: At the Apollo 15 landing site, located on the eastern edge of Mare Imbrium (26.13222° N latitude, 3.63386° E longitude), two suites of mare basalts with similar eruption ages (~3.35-3.25 Ga) have been identified based on differences in whole-rock major element abundances [5]. The quartz-normative samples have low FeO (19-20 wt. %) and TiO₂ (1-2 wt. %) bulk rock compositions but a relatively high SiO₂ content of 47-49 wt. % [6]. The olivine-normative samples have bulk rock chemistries with comparatively higher FeO (22-23 wt. %) and TiO₂ (2-3 wt. %), and lower SiO₂ concentrations of 44-46 wt. % [6]. These two Apollo 15 mare basalt groups have an uncertain petrogenetic relationship and eruption histories. Current theories suggest that the quartz-normative group experienced a multi-stage cooling history with crystallisation occurring in mid-to-lower crustal magma chambers, during magma ascent and within lava flows on the lunar surface [7]. On the other hand, the olivine-normative group predominantly crystallised in lava flows on the lunar surface, following minor crystallisation at low-pressures in near-surface magma chambers [7,8,9].

Apollo 15 mare basalts display a wide range of textures including vitrophyric, porphyritic and highly vesicular samples. Textural variability between the two suites is observed, with quartz-normative samples showing a larger textural range than olivine-normative samples. This study will consider parent, cumulate and fractionate samples of both the quartz-normative and olivine-normative suites, examples of which can be seen in Figure 1.

Figure 2 shows the compositional differences of between the parent, fractionate and cumulate samples selected for this study from both quartz-normative and olivine-normative suites. The assignment of samples as either parent, cumulate or fractionate will also be compared to and reviewed in terms of the textural characteristics observed. Samples which chemically plot off the liquid line of decent are also considered.

Aims: We aim to better understand the processes that took place during magma storage and subsequent eruption of the Apollo 15 mare basalts using quantitative petrology, crystal relationships and mineral chemistry techniques. The three key questions to be addressed are: (1) Do lunar magmas propagate rapidly to the surface or do they stall and crystallise in magma chambers within the lunar crust? (2) Is crustal material assimilated during ascent? (3) Is there evidence of crystal mush formation, disaggregation and crystal entrainment?

Methods: Textural characteristics and mineral compositions of thin sections from both the quartz-
normative and olivine-normative groups will be identified using a combination of back-scattered electron (BSE) images, element maps and electron microprobe (EPMA) data.

Crystal size distributions will be calculated to identify signatures of fractional crystallisation and/or crystal accumulation within the two sample suites. QEMSCAN environmental scanning electron microscope (ESEM) mapping methods will be utilised to semi-automate the crystal size distribution data collection process, with results compared to those gained from manual methods [10,11]. Magma ascent rates and crystal residence times will also be calculated using diffusion modelling in zoned crystals [12,13].

Overview: The purpose of this study is to gain a better understanding of how differences in magmatic plumbing systems and eruption processes may have led to the diversity seen within Apollo 15 mare basalts. Preliminary findings will be presented on samples from the Apollo 15 mission with plans to analyse other mare basalts in the future, such as those collected on the Apollo 12. Our work will provide new insights to lunar magmatic systems and how eruptions styles vary in different regions across the Moon through time [14].

Acknowledgements: Thanks to NASA JSC curatorial team for allocation of samples and to an STFC studentship for funding.


Figure 2: A plot comparing FeO and MgO wt. % in parent, cumulate and fractionate samples of the quartz-normative and olivine-normative suites. Estimated fractionation and accumulation trends are shown in each case.
BEHAVIOR OF VOLATILE ELEMENTS DURING IMPACT EVENTS ON THE MOON. A. A. Berezhnoy, Sternberg Astronomical Institute, Moscow State University, Universitetskij pr., 13, 119234 Moscow, Russia, (ber@sai.msu.ru).

**Introduction:** Collisions of meteoroids with the Moon are considered as an important source of metals and hydrogen-containing species in the lunar exosphere. Recently enriched content of Na and K atoms in the lunar exosphere soon after maximum of Quadrantide meteor shower was detected by LADEE spacecraft [1]. In our previous papers quenching model of the chemical composition of impact-produced clouds formed after collisions of meteoroids with the Moon was already developed (see, for example, [2]). However, behavior of minor elements such as P, Cl, F, Ni, Cr, Mn, V, and Co during impact events on the Moon was not considered yet.

**Used Model:** Elemental composition of the target is assumed to be that of the bulk Moon [3]. The elemental composition of impactors is assumed to be that of CI chondrites and dust of the comet Halley in accordance with [4] and [5], respectively. Based on work [6], chosen target-to-impactor mass ratio of 5 corresponds to impact velocity equal to 14 km/s. The initial temperature and pressure in impact-produced cloud is taken as 10 000 K and 10 000 bars, respectively. The adiabatic constant γ is assumed to be 1.2.

At the beginning of cloud’s expansion the chemical composition of impact-produced cloud is in thermodynamic equilibrium. Quenching of the chemical composition occurs when hydrodynamic and chemical time scales became comparable. After quenching during further expansion of impact-produced cloud the chemical composition remains unchanged.

**Hydrogen behavior in impact-produced clouds:** At typical quenching conditions (T_q = 3000 K, P_q = 10 bar [2]) in clouds, produced during collisions of meteoroids from strongest annual meteor showers with the Moon, main H-containing species are H_2 and H_2O (see Fig. 1).

Amount of OH molecules, delivered to the lunar exosphere after photolysis of OH-containing impact-produced species, decreases with decreasing quenching temperature (see Fig. 1) and increasing size of impactors. Partial content of main H-containing species do not change significantly if impactors consisted of dust of comet Halley will collide with the Moon instead of CI chondrite impactors.

**Behavior of minor volatile elements during impact events:** Main Cl-containing species delivered to the lunar exosphere by impacts of meteoroids are FeCl, NaCl, and HCl (see Fig. 2). The equilibrium content of metal chlorides in impact-produced clouds is significantly lower than the content of metal oxides and hydroxides.

![Fig. 1. Equilibrium content of Cl-containing species in impact-produced cloud formed during collision of CI chondrite impactor with the Moon.](image1)

FLOWABILITY STUDY ON LUNAR SIMULANT AND ON-SITE MANUFACTURING. C. Bernillon, A. Cowley, M. Fateri, J. Reguette, and M. Sperl, DLR-Deutsche Zentrum für Luft- und Raumfahrt, Institut für Materialphysik im Weltraum, 51147 Köln, Germany (Miranda.fateri@dlr.de), ESA-European Astronaut Centre (EAC), 51147 Köln, Germany.

Introduction: Flowability of the lunar regolith plays an important role in developing the fundamental database required for future Moon missions [1]. Investigations on powder rheology of the regolith could help finding an optimum and safe landing site, prevent regolith deposition on rovers and improve the construction quality for future manufactured parts on the Moon.

Static and dynamic angle of repose have been studied so far by means of standardized protocols [2] as shown in Figure 1, and comparative investigations representing the powder flow behavior.

Powder flow via a hopper and rotating drum as common methods for measuring the flow behaviour have been investigated by different researchers [3-6]; however, the influence of the temperature under reduced gravity and under vacuum has not been studied yet. With regards to this, combining the temperature rise under vacuum as well as the lunar gravity will help to move a step forward regarding a better understanding of the lunar regolith behaviour on the Moon. Furthermore, knowledge about the optimum powder deposition and packing density using the Additive Manufacturing (AM) methods will further improve the knowledge regarding optimum construction conditions relevant to the lunar environment [7].

In this study, the lunar regolith simulant (JSC-2A) will be placed in an evacuated rotating drum subjected to different rotation speeds during a parabolic flight. A light source will increase the contrast inside the rotating drum. The behavior of the backlight scattered powder, through the movements of the particles, will be recorded during the experiment on board of a parabolic flight and the powder’s angle of repose and avalanche will be measured. Additionally, layer-wise packing density of the regolith for AM applications will be investigated with a developed layering device as presented in Figure 2.

Based on this, the powder bed density under reduced gravity should be adjusted by modified powder layering technique in order to improve the powder bed density and flowability for AM application on the Moon. Thus, in this study the powder packing density and flowability will be studied under reduced gravity and vacuum. Deposition parameters will be changed such as deposition speed, powder bed temperature and particle sizes as well as the layer-wise compaction.

Introduction: Infrastructure is increasingly recognized as a core foundation of U.S. national security and economic growth. Improving and maintaining national infrastructure has traditionally been understood to yield a variety of long-term benefits. In 2017, a new appreciation for infrastructure, the various types and their significant cross-over effects, is emerging as an important focus for policy and economic research.

National infrastructure is typically categorized as physical (agriculture, energy, defense industrial base) and social (education, R&D, international affairs competency). Furthermore, there is basic economic infrastructure which facilitates commerce and is responsible for ensuring the nation’s business runs smoothly. However, this paper suggests Innovation Infrastructure is a unique phenomenon and new class of productive activity whose impacts ripple powerfully significant across multiple industrial sectors and value chains. It also suggests that many civil space projects, most notably those of NASA, initially created as innovation infrastructure either wholly or partially transition into the nation’s basic economic infrastructure.

NASA is one of the nation’s most significant public agency producers of innovation infrastructure and understanding this capability could alter the strategy for future American space programs. Some major projects, such as the space shuttle or International Space Station, started out as innovation infrastructure, capable of producing new scientific knowledge, engineering and process advancements, but eventually transitioned into basic economic infrastructure, capable of facilitating commercial activity. A host of current policy problems - the economic development of low-Earth orbit, the diffusion of basic research and early stage technology into the broader ecosystem and an estimate of NASA’s impacts on the broader U.S. economy - reflect a pressing need to more diligently examine this phenomenon.

This paper addresses these questions directly by defining the unique innovation infrastructure that NASA produces, identifying its core contributions to economic growth and national security, and presenting a suite of policy options to strengthen civil space’s contribution to the nation.
Application of the LVS Subsurface Probe on the LUVMI Rover for a Lunar Volatiles Exploration Mission. J. Biswas¹, P. Reiss¹, J. Gancet², S. Sheridan³, S. Barber³, D. Dobrea⁴, L. Richter⁴ and Neil Murray⁵, ¹Institute of Astronautics, Technical University of Munich, Boltzmannstr. 15, 85748 Garching, Germany, (j.biswas@tum.de), ²Space Applications Services NV/SA Leuvensesteenweg 325, B-1932 Zaventem, Belgium, ³The Open University, Milton Keynes, MK7 6AA, UK, ⁴OHB System AG, Manfred-Fuchs-Str. 1, 82234 Weßling, Germany, ⁵Dynamic Imaging Analytics Ltd, Milton Keynes, MK3 6EB, UK

Introduction: We present the latest iteration of the Lunar Volatiles Scout (LVS), a novel instrument to access and characterise lunar volatiles in-situ. The LVS is currently being developed in a cooperation between Technical University of Munich (TUM) and OHB System as part of the Lunar Volatiles Mobile Instrument (LUVMI) study, conducted in the frame of the EU Horizon 2020 initiative and led by the Belgian company Space Applications Services.

LUVMI aims to develop a comprehensive lightweight (20-40 kg) rover for investigations on volatiles in and around permanently shadowed regions on the Moon. The platform is envisioned as a possible secondary payload to one of the currently planned missions to the lunar poles. It features an active chassis with four independently steerable wheels, an innovative light-field camera, the Volatiles Sampler (represented by the LVS), and the Volatiles Analyser (miniature mass spectrometer).

LVS Instrument Concept: The LVS, as presented by [1], is a novel instrument capable of probing 20 cm deep into lunar regolith. It consists of a central heating rod and an enclosing shell, which captures the released volatiles. The enclosing shell is equipped with an auger and can be rotated in a screw-like motion to reach insertion depths of up to 20 cm into the regolith. The heating rod will thermally release bound volatiles, which will then diffuse towards the mass spectrometer for gas analysis. Information on the chemical phase and the amount of released volatiles is recorded. The design of the heating rod was extended to incorporate a thermocouple in the tip of the rod, which will measure the initial regolith temperature at the insertion depth.

- Measure the initial regolith temperature at the penetration depth.

Figure 1: Preliminary CAD Model of the LVS

Derivation of Geotechnical Properties: A simple bearing capacity model, taking into account the regolith bulk density, gravity, angle of internal friction, and soil cohesion, was created to model the vertical force necessary to insert the LVS into the ground. The model shows good agreement with experiments at different bulk densities with a simple cone penetrator geometry as well as with an LVS prototype. Though simple, the model is regarded as a proof of concept for the derivation of cohesion, bulk density and angle of internal friction from penetration force measurements. A summary of the model and relevant results are presented.

Heating and Gas Extraction: A simulation model for the sample heating, implemented in COMSOL multi-physics, was presented previously [1]. The model is being extended to model the influence of sublimating water, both by accounting for the additional heat capacity and enthalpy of sublimation and by the enhanced thermal conductivity from the higher gas pressures. Currently, the model is used in trade studies to optimise heating duration, energy and power consumption, and the sample temperature distribution.

An experimental setup is being developed to verify the model for cryogenic conditions. For this purpose, samples of the regolith simulant NU-LHT-2M
are moisturized with 1 wt% of water, frozen with liquid nitrogen, and then exposed to vacuum while being continually cooled. This way, sublimation is avoided and the original water content is preserved. The samples are then heated and temperature profiles over time are measured at multiple points. The presentation shows an overview of the test setup, sample preparation procedures and compares preliminary results versus the simulation model.

**Determination of the abundance of released volatiles:** Preliminary experiments have shown that around 50% of the released volatiles escape through the open bottom end of the instrument [2]. The knowledge of this fraction is important to relate the amount of measured volatiles to the actual volatile content in the soil. The amount of lost volatiles depends on regolith bulk density, moisture content, temperature, and the pressure inside the instrument. Future research will investigate the influence of the

Future Work: In a stepwise approach, the established test setup with penetrator and heater will be extended to include the drive section of the LVS and the Volatiles Analyser. This will allow end-to-end experimentation and parameter studies with the fully integrated instrument to further refine the instrument design and raise its technology readiness level for future mission applications.


Figure 2: Sketch showing the extended test-setup for the characterisation of the LVS instrument
**Introduction:** when two planetary bodies collide the energy of impact is recorded as material displacement at the point of contact (unless there is mutual annihilation), creating both negative (a crater) and positive surface expressions (rim and peaks), plus scattered debris (ejecta). Each impact structure has a finite ‘lifespan’ due to entropic processes leading to disaggregation of the raised structures (by space weathering and thermal expansion) and infill of the excavation (gravity-led transportation and ballistics). The rate of disintegration is size-dependent and governed by several physical factors, such as the cohesion and porosity of the target materials (regolith thickness/bedrock), terrain slope, direct modification or destruction by larger impacts [1].

Production function models for interplanetary bodies and their likelihood of impact with time are well constrained for the last ~3 Ba [2].

Craters around 100 m in diameter on the Moon are produced by celestial rocky materials of mass ~4x10^5 kg and diameter ~6 m (~10 m if cometary) [3]. Since a body of this size would still produce a ~70 m crater on Earth, it is important to further constrain their present flux.

**Aims:** By looking at a lunar region that has been mechanically resurfaced within recent geological times (~110 Ma, [4]), we can in principle explore the distribution and rate of decay of small impacts in relation to their size and distribution across a representative range of terrains, ranging from those mostly affected by Tycho’s ejecta surge to unaffected ‘background’.

**Data:** Fig. 1 shows the region of this investigation and the unit boundaries drawn from observation of variations in surface texture, ‘qualitative’ cratering distribution, and albedo. Nomenclatures used in the text are: Mare Old (‘unaffected’ mare), MO; Uplands, UP; Sloped uplands, UP-SL; Light Mantle ‘North’, LM_n; Light Mantle ‘South’, LM_s; and Light Mantle, LM.

38,156 outlines of craters of diameter >7 m are also shown in Fig. 1B.

A comprehensive and multiple crater survey was carried out on a NAC image pair with 1.5 m/px resolution (see Fig. 1A) by the author using different magnification levels and starting from different area points each time to minimise human bias (due to fatigue and other factors). The results were then compared with those generated by citizen scientists and, in a subset, by a team of experts [5].

**Method:** the crater size data for each unit were compared. Histogram in Fig. 2A shows the density of craters per km² in 1 m bin size. Given the coincidence between the unaffected mare areas and the massifs tops, these values were set as ‘background’ and compared (Fig. 2B), in terms of percentage differences, with the other units (sub-grouped CC-LM and LM_n and _s).

![Figure 1](image1.png)

**Figure 1.** A - Area under investigation and named largest craters. Apollo 17 exploration path and stations. B – New boundary regions and 38,156 marked craters >7 m in diameter.

![Figure 2](image2.png)

**Figure 2.** A – Histogram of the number of craters (N) per km² (density) for craters D≥25 m in 1 m bins; B - Differences in terms of normalisation density (N) to MO-UP (assumed as ‘background’ density) and units grouped by similar crater distribution (averaged values, see legend).

When the size frequency data are normalised to 100 (%) an exponential trend emerges for crater sizes...
<100 m and, in particular, <25 m, as displayed in Fig. 3: \( N_{(D)} = 0.64e^{-0.18D} \), (eq. 1) where \( N_{(D)} \) is the percentage bin size representation, and \( D \) is the crater bin diameter in meters.

**Figure 3.** Normalized Crater Size Frequency histogram to 1 m bin representation, expressed as fractions of 100. FIT (dashed grey line) represents the best fit for all but one (MO) mare units \( (N_{(D)}=64e^{-0.16D}, R^2=0.98) \). The data are split into two groups in aid of clarity.

**Results:** Fig. 2 highlights three main size-frequency distribution trends: a comparable ‘background’ density (MO, UP, and, allowing for the enhanced crater destruction rate on slopes, UP_SL), Light Mantle areas and CC, and the Central Area (CA) showing a particular higher crater density for 16 and 20 meter bins. However, the general relative representation trend among bins is broadly coincident suggesting a common source. This is not in agreement with the recent work from [6] who concluded that a second, more recent avalanche could have affected the (here named) LM_s unit.

The representation of each crater bin within the regional range was normalised to 100 (%) and displays an exponential trend close to -0.2 (eq. 1 and Fig. 3). The CA represents the best fit with \( R^2=0.99 \).

**Discussion:** The histograms show that the distribution of small craters in the region \((≤ 25 \text{ m})\) was significantly modified by the arrival of a secondary surge, alleged to belong to the Tycho impact. In the denser area of the surge (CA), we see the size-frequency distribution follow an exponential trend that could reflect a saturation level for the lunar maria, at least in the sub-25 km crater range (as described by eq. 1). Moving away from this area, and arguably from the epicentre of the surge, we notice a gradual shift towards a ‘background-type’ distribution: CA→LM→LM_n→CC→LM_s→MO, i.e., a gradually weaker contribution from secondaries.

The small craters distribution atop the massifs (UP) and the maria (MO) is nearly identical, suggesting an equilibrium in their production level, possibly applicable moon-wide, an hypothesis needed to be tested further.

Based on the straight relationship formulated by Basilevsky (TMₐ =2.5*D, [7]), the small secondary craters excavated by the surge should all but eroded long ago (~50 Ma lifetime for the 20 m fraction, or ~70 Ma [8]). Given that the event is estimated at ~110 Ma [4], the crater count should have approached the background level by now. This discrepancy raises questions on either the erosion rate models or the age of the Tycho event itself.

Last, looking at the data in Fig. 3 it appears that all crater distributions affected by the surge share common characteristics in the size-frequency distribution, such as the ‘hump’ at the 12 m bin size. Is this characteristic to Tycho? Do other secondary surges (rays) show similar distributions unique to each primary event, an identifying signature?

**Conclusions:** following the analysis of size-frequency distribution of craters in a highly heterogeneous and well-studied region of the Moon, we propose that for the smaller crater sizes (in this work 7-25 m), a] an exponential curve of power -0.18D can predict the representation of bin sizes in a regime of ‘saturation’, while b] an equilibrium distribution would resemble that of MO-UP.

The saturation level within the Central Area (CA, Fig. 1) suggests that c] either the modelled rates of crater erosion on the Moon should be revised, or that the Tycho event was much later than the accepted estimate.

Last, the hypothesis that d] the size-frequency distribution of (clustered) small secondary craters may bear the signature of the source impact should be further tested.

**References:**
EXPERIMENTAL STUDY OF LUNAR DUST INDUCED WEAR ON SYNTHETIC SPUR GEARS.
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Introduction: A previous study [1] conducted at the Institute of Astronautics at the Technical University of Munich showed that the use of synthetic spur gears in space applications could be an alternative for common metallic gears. Along with lower mass, synthetic gears provide the advantage of lubricant-free operation [1]. Lubricant-free systems could be advantageous for long-term autonomous surface missions on celestial bodies like the Moon. This current study investigates the wear resistance of spur gears in the presence of simulated lunar dust particles.

During the Apollo era, several problems could be attributed to the presence of lunar soil material [2], such as clogging of mechanisms, abrasion effects and malfunctioning of seals, all of which are applicable to potential damage to spur gears.

Lunar regolith consists of sharp-edged particles. The shape of the particles results from a frequent bombardment of particles such as micrometeorites. The soil particles are crushed by the impacting objects. However, unlike on Earth, the resulting sharp-edged particles are not exposed to erosion processes caused by liquid water or wind, which would result in less abrasive particles like terrestrial sand [3]. A layer of lunar regolith-like shaped particles might also be found on the surface of other celestial bodies in the solar system lacking a significant atmosphere or liquid water.

Experimental Setup and Test Conditions: The experimental test setup used in this study is a further development of an existing setup for wear tests of spur gears. The original test setup was designed to investigate the wear of synthetic spur gears under thermal vacuum conditions but without the presence of abrasive particles [1]. The test setup consists of two identical pairs of spur gears to have a larger number of simultaneously tested samples. Each pair of spur gears consists of a larger steel spur gear with a diameter of 120 mm (module: 1, thickness of the spur gear 10 mm, normal pressure angle: 20°) and a smaller synthetic pinion under test with a diameter of 30 mm, for which the wear is characterized. The investigated pinions have a module of 1, a thickness of 7 mm and a normal pressure angle of 20°. The turning velocity of the pinions is 96 revolutions per minute. A torque of 0.68 Nm acting at the pinion was applied for all tests.

To use the test setup for lunar dust-induced wear experiments, a housing was developed and implemented which surrounds each pair of spur gears. The housing was designed to contain the JSC-1A particles falling off the spur gears. This reduces contamination of the vacuum chamber with analogue material particles, and prevents particles entering into bearings as well as the motor and attached parts. The upper parts of the housing are vented to ensure pressure compensation during vacuum tests. For tests with simulated lunar dust, a more powerful motor (Nanotec, stepping motor 4.2 A, holding torque: 3 Nm) was used to overcome the expected higher friction. The actual configuration of the test rig is shown in Fig. 1.

Fig. 1: Experimental test setup for lunar dust wear experiments

All parts of the experimental setup are designed for thermal vacuum tests. Previous tests [1] showed a significant dependence between wear coefficient and environment conditions regarding temperature and pressure. In the current study, we investigated wear from lunar dust of polyoxymethylene (POM) and polyetheretherketone (PEEK) spur gears under different test conditions, regarding temperature and pressure. Before the actual tests, the synthetic spur gears undergo a 100,000 cycle break-in phase at ambient pressure at +20°C, without using JSC-1A particles. Two synthetic spur gears of the same material were investigated at the same time under the same test conditions. Following the break-in test without dust, a total number of 300,000 cycles was applied with lunar dust simulant for the wear tests.

The wear tests were conducted using the lunar analogue material JSC-1A with grain sizes smaller than 105 μm. Larger particles were not considered in the tests, as larger particles would usually be prevented form entering into a gearbox by the seals and enclosed. The particles for the tests were sieved from the original analogue material. To achieve an equally distributed amount of particles on the tooth flanks, the larger steel wheels were tossed in the sieved lunar analogue material.
Before and after each wear test, the synthetic gears were measured by three different methods to quantify the wear. The masses of the gears were measured with an accuracy of ten micrograms, the geometry was measured by a CNC-controlled gear measuring center (P40 by Klingelnberg) and pictures of the profile of the gears were taken with a Canon EOS 5D Mark camera.

Results: The investigation of POM spur gears at ambient atmosphere shows that the regolith changes the profile of the spur gears differently after 100,000 cycles and after 300,000 cycles. After 100,000 cycles, the evolvent is slightly wavy because the regolith penetrates the surface of the synthetic gears. The mass of the synthetic spur gears is increased, because the JSC-1A particles get embedded in the tooth flanks of the spur gears and almost no wear could be measured. After 300,000 cycles, the mass of the synthetic spur gears decreased. However, the measured loss of mass is the sum of the loss from wear and the mass gain from regolith particles, which are embedded in the flanks of the spur gears. The changes between the profiles before and after the test (300,000 cycles) can be seen in Fig. 2.

![Fig. 2: Profile of the tooth of a synthetic POM spur gear before and after 300,000 cycles](image)

The wear of the POM spur gears occurs especially in the upper half of the tooth flanks. The wear in the upper area of the synthetic tooth flanks results in a rough surface of the tooth flanks, rather than a smoothly abraded surface. The abraded tooth flanks have surface irregularities that are caused by the lunar simulants particles.

Almost no wear could be measured by geometric comparison of the synthetic spur gears before and after test at the root of the flanks. An explanation could be that regolith got embedded into the tooth root an filled previously abraded areas. This is remarkable because the flank wear of synthetic gears is normally at the tooth tip of the synthetic gear, as well as at the tooth root of the synthetic gear [4]. The expected areas of maximum wear can be seen in Fig. 3, while with dust, only the tooth tip of the synthetic spur gear was worn.

![Fig. 3: Areas of maximum wear for synthetic gears (adapted from [4])](image)

It can be further assumed that, due to the embedded regolith particles, different surface properties might occur in some areas of the synthetic tooth flanks.

Furthermore, comparative data for the wear behavior of PEEK and POM spur gears at different temperatures and pressure levels will be presented.

Future Work: Future tests will expand the investigated temperature ranges and characterize additional synthetic materials with promising properties for spur gears. A new friction wheel test rig is designed to further characterize basic wear properties of various bulk synthetic materials, followed by additional spur gear tests with the most promising material candidates.

References:
MODERATELY VOLATILE ELEMENTS IN LUNAR BASALTS. D. Burney\textsuperscript{1,2} and C. R. Neal\textsuperscript{1,2}, Dept. Civil & Env. Eng. & Earth Sciences, University of Notre Dame, Notre Dame, IN 46556, USA (dburney@nd.edu; neal.1@nd.edu).\textsuperscript{2}Center for Lunar Science & Exploration, Lunar and Planetary Institute, Houston, TX 77058.

Introduction: The Moon was formed after a Mars sized body (Theia) struck the early Earth to form a disc of material that would later cool and condense to form the Moon. An impact of this magnitude would generate extremely high temperatures capable of melting and volatilizing a large amount of material. This Giant Impact hypothesis posits that the Moon should be depleted in volatiles with respect to Earth, and initial analyses of material brought back by the Apollo missions showed such a depletion [1-4]. Moderately volatile elements (MVEs) have the capability of recording high temperature condensation and evaporation events [5]. This can prove to be useful in determining fractionation events early in the Moon’s history.

Advancements in analytical techniques (e.g., Fourier Transform InfraRed spectroscopy – FTIR, nano-SiMS) have been able to measure trace abundances of volatile species (i.e.: CO\textsubscript{2}, H\textsubscript{2}O, Cl, F, & S) within lunar volcanic glasses and nominally hydrous mineral phases such as apatite [3-5]. The presence of highly volatile species implies the presence of the more robust MVEs which may have been recording condensation events soon after the Giant Impact. Accurately measuring these elements of interest (Zn, Rb, Ag, Cd, In, Ti, Bi, Pb, and Sb) comes with two difficulties: 1) They are generally present in very low abundances (low to mid-ppb) making them susceptible to spectral interferences, and 2) There is a lack of adequate standard reference materials (SRMs) with which to evaluate the accuracy of analyses.

Methods: Solution-mode inductively coupled plasma mass spectrometry (ICP-MS) was used to measure these MVEs in digested whole rock samples due to the instrument’s high ionization efficiency and low detection limits (ppt level). SRMs BIR-1 and BHVO-2 were repeatedly run using a method that quantifies and removes spectral interferences in order to obtain a concentration that has been corrected for major interfering elements. This method is described in detail in [6] and this workshop.

Discussion: The mare basalts are believed to be the result of the partial melting of chemically distinct regions of a cumulate formed during lunar magma ocean (LMO) crystallization. The compositions of this cumulate change as crystallization progresses from mafic Mg-rich in the beginning to Ti-rich in the later stages. The MVEs behave incompatibly in crystallizing magmas and are expected to be enriched in late stage cumulates. This enriched signature can be seen in KREEP, as well as A11 high-K basalts (Fig 1).

Distinct differences between the low-Ti and high-Ti basalts are also seen in Rb, Ag, Se, and Pb (Fig.1). These relationships cannot be attributable to incorporation of KREEP but indicate source region differences that appear to be difficult to reconcile with the LMO hypothesis. In terms of Rb-Ag relationships (Fig. 1a) the high-Ti glass is enriched in Ag relative to the high-Ti basalts, which in turn are enriched in Ag over the low-Ti basalts. The high-Ti basalts are generally enriched in Pb and Se (relative to Rb; Fig. 1b,c) over the low-Ti basalts, but the oirigne glass plots with the high-Ti basalts, so it is unclear if the high-Ti magmas are derived from different sources. Both the high-Ti and low-Ti basalt trends are subparallel in Fig. 1a-c and point towards KREEP (represented by KREEP basalt 15386 and KREEP impact melt 14310). In terms of Rb/Ag ratio, it would appear that the high-Ti basalts (on the basis of our data) are derived from a source that is relative homogenous in terms of MVEs, whereas the low-Ti basalts are distinct and come from sources with variable MVE contents (Fig. 1d). Further work is underway to further elucidate these relationships.

Figure 1: Relationships between MVEs from low-Ti and high-Ti mare basalts and high-Ti volcanic glass 74220.
Future space exploration goals call for sending humans and robots beyond low Earth orbit and establishing sustained access to destinations such as the Moon, asteroids and Mars. Space agencies participating in the International Space Exploration Coordination Group (ISECG) are discussing an international approach for achieving these goals, documented in ISECG’s Global Exploration Roadmap (GER). The GER reference scenario reflects a step-wise evolution of critical capabilities from ISS to missions on and around the Moon in preparation for the journey of humans to Mars.

As an element of this road mapping effort, the ISECG agencies have coordinated discussions with the scientific community to better articulate and promote the scientific opportunities of the proposed mission themes. An improved understanding of the scientific drivers and the requirements to address priority science questions that can be addressed by near-term human exploration in to the solar system (i.e. a deep space habitat in the lunar vicinity, lunar surface, or an asteroid). The output of this interaction has been the development of a Science White Paper that

- Identifies and highlights the scientific opportunities in early exploration missions as the GER reference architecture matures,
- Communicates overarching science themes and their relevance in the GER destinations,
- Ensures international science communities’ perspectives inform the future evolution of mission concepts considered in the GER

The paper aims to capture the opportunities offered by the missions in the GER for a broad range of scientific disciplines. These include planetary and space sciences, astrobiology, life sciences, physical sciences, astronomy and Earth science. The paper is structured around grand science themes that draw together and connect research in the various disciplines, and focuses on opportunities created by the near-term mission themes in the GER centered around 1) extended duration crew missions to an exploration habitat in cislunar space, 2) crewed missions to the lunar surface and 3) crewed missions to an asteroid.

The preparation of the Science White Paper has been coordinated and led by an external Science Advisory Group composed of scientists from a variety of nations. A dedicated working meeting was held in May 2015 at the European Lunar Symposium in Frascati to incorporate inputs and recommendations from international scientists. The first draft of this White Paper was then discussed at a COSPAR-ISECG-ESF workshop in Paris on 10-11 February 2016. The recommendations developed at the workshop provide further input that has been incorporated in to the final version of the ISECG Science White Paper, expected to be published in the spring of 2017. The authors aim to present the rationale and content and of this White Paper at ELS.
Introduction: Museo Lunar was founded by the first Spain-born astronaut Miguel Lopez-Alegria 7 years ago in commemoration of 40th anniversary of the arrival of man into the Moon in order to show how was the NASA ground station that tracked lunar landing module Eagle to the moon surface on the historic flight of Apollo 11: Fresnedillas Station.

Fresnedillas de la Oliva Station bellowed to the NASA Manned Spaceflight Tracking Network (MSFN). Built 50th years ago, It was the primary tracking facility in Europe which was operative until 1985 when its third 26m antenna was deactivated. This station hosted a wealth variety of technicians who not only supported the Apolo 11 mission, but they also gave instructions to head Amstrong to land on the Moon.

The history of Fresnedillas station was not end in Apollo stage. From there, technicians were tracking other manned missions, such as Skylab, ASTP (Apollo-Soyuz) and the first Space Shuttle flights with Columbia. For that reason, the 26 diameter antenna was turn into a paramount monument of space missions.

That is why the village of Fresnedillas is proud to feature the “Museo Lunar” which hosts over 300 original items related to those former missions. During the visit, people are delighted with a brief technical speech while they enjoy seeing the majestic communication transmission tower, watching astronaut food or gazing the commemorative medals made of the space module. But the visitors climax experience comes when they admire the original Apollo 17 glove belonging to the well known Gene Cernan (the last man of the Moon) They also are astonished due to mind-blowing astronaut space suits (which belong to Miguel and Pedro Duque) among other pieces. To give an extra point of view, museum host a brief variety of Russian items, giving the importance of the Russian program as well.

Due to the unique of space masterpieces, Museo Lunar of Fresnedillas must be a mandatory stop for every aerospace fan who wants to feel a realistic experience when they see real pieces which took part from the Moon’s research History.

References:
A NEW APPROACH TO THE AUTOMATED COUNTING OF THE SMALLEST LUNAR CRATERS.
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**Introduction:** Lunar crater counting is a mature discipline for the relative dating of lunar maria [1]. However, except for the very youngest lunar areas, such as crater ejecta blankets, surfaces are more or less saturated with the very smallest craters, in the sense that the oldest ones are eroded away at essentially the same rate as new ones are being created. But the detailed study of the tiniest craters visible in LRO NAC images [2] could enable the effects of illumination angle, slope and target properties to be evaluated [3]. The numbers of craters larger than 3m in diameter is so high (typically 10^9/km^2) that expert counting is really only practicable for small areas. Automated crater counting has the additional advantage that the results from multiple images of the same region can be combined to (a) eliminate false positives (b) include false negatives and (c) rectify poor fits. In addition, crater morphology [4] can be quantified and metre-sized boulders counted [5], both being potentially useful for modelling crater degradation. The very high abundance of small craters also makes counts statistically more significant.

**Counting Method:** Crater detection is based on the observation that, at relatively low sun elevation angles, craters are essentially circular and contain both a shadow and a highlight. Shadows are detected using gradually paler darkness thresholds and the corresponding highlights in the antisolar direction are located at the distance expected by the shadow size. Crater centres are located by maximising darker pixel values in the shadowed semicircle and lighter pixels in the sunlit semicircle. Rims are then located by increasing diameters until fits are no longer improved. Craters are assigned a freshness parameter (Prominent, Sharp, Distinct, Faint or Vague) based on contrast between the shadow and highlight. Larger craters (eg those greater than 100 pixels in diameter) are located by prepasses of the image at downgraded resolutions. Large images may be divided into strips and counts for each strip combined.

**Complications.** A number of factors complicate crater detection, including (a) overlapping craters (b) nested craters (c) dark or bright regions on sloping terrain and (d) boulders, all of which require special handling. Once a crater has been analysed (and all of its nested and overlapping craters processed), its pixels are flagged so that they are ignored when the shadow detection threshold is raised.

**Use of templates.** Once all craters in an image have been found, normalised templates are created for each combination of diameter and freshness. Each crater is then matched against the corresponding template and, if necessary, its centre and diameter is modified to optimise the match. If the match is poor, the crater may be rejected as a false positive.

**Use of multiple images.** LRO NAC images of the same area on the lunar surface, once calibrated and ortho-projected, should overlap precisely and yield identical counts. In practice, this will not be the case because, under some illumination conditions, some craters are lost in deep shadows and others are washed out on brightly sunlit slopes. In this work, a crater is rejected as a false positive if it is not located in at least one other image. Likewise, any undetected crater that is present in at least two other images will be added as a false negative. Diameters are calculated as integer pixel values. Crater centre co-ordinates are deemed to be on pixel boundaries for even pixel diameters and at pixel centres for odd pixel diameters.

**Benchmark tests:** Automated crater counting requires validation against published data. An area (in NAC image M146959973L just north of the Apollo 15 landing site) has been used by a project that compared results from a citizen science project with those of expert markers [6]. For four progressively more eroded craters A, B, C and D, the mean diameters in pixels from expert marking were given as 130 +/- 4.3, 117 +/- 4.3, 124 +/- 13 and 143 +/- 16 respectively, the standard deviations increasing with degree of degradation. Volunteer data showed more scatter. Diameters computed for these craters were 129, 120, 134 and 149 pixels, within the error margins. For craters down to the lowest common diameter (18 pixels), the mean ratio of computed diameter to mean expert diameter was 0.951 +/- 0.036.

**Selected test area.** The area selected for more detailed analysis was the landing site of the Soviet rover Lunokhod 1 in Sinus Iridum, which has already been well studied [7] so provided a second benchmark for this work. This is a relatively young mare which, unlike the Apollo 15 and 17 landing sites, is relatively remote from any highlands. Five 50 cm per pixel LRO NAC ortho-projected and calibrated images covering this area, having suitable but different solar illumination angles, were selected for study, namely M114185541, M135418902, M142495666, M166072850 and M173144480.

**Fit results:** Circles, representing the location and diameter of each crater identified, are combined with NAC images, enabling visual inspection to identify software limitations and problem fits.

**Crater abundances.** Crater abundance histograms are plotted, covering the 5 to 50 pixel diameter range, for all craters, and separately for each freshness class. Most false positives and false negatives are for craters less than 10 pixels in diameter and are
Faint or Vague. The decrease in crater count with increasing diameter is steeper for fainter craters than for the more distinct ones, implying longer survival times for larger craters in each freshness class.

**Abundance ratios.** The ratios of crater counts in pairs of adjacent freshness classes (e.g., Vague/Faint, Faint/Distinct) tend to decrease with increasing diameter, again consistent with there being a longer survival time for larger craters within a given freshness class. For 10 pixel diameter craters, for example, there are about twice as many craters in one freshness class (e.g., Faint) as there are in the next sharper one (e.g., Distinct). This would suggest that Vague craters are about 80 times older than Prominent ones. But a more robust freshness parameter is clearly needed before being able to quantify relative ages in this way, because contrast varies with solar illumination, even when using calibrated images.

**CSFDs.** Cumulative Size Frequency Distribution graphs (CSFDs) plot the logarithm of counts of all craters having diameters greater than D against the logarithm of D. The least squares fit straight line through this data has the negative exponent of $-2.35$, lower than the slope at larger crater diameters and reflecting crater saturation in this size range.

**Crater densities.** The density of all matched craters down to 5 pixels (i.e., 2.5m) in diameter in the test area is about 11,000 per sq km. The sampling area around each pixel in a density map is 0.25 sq km. The density map reveals small (typically +5%) variations across the region, but rather more in the immediate vicinity of larger fresh craters, as would be expected. Such variations, if not completely random, could relate to the local terrain or have been influenced by secondaries.

**Conclusions:** Automated crater counting can be an effective means for studying lunar craters with diameters below 20m. Multiple images will enable crater profiles to be measured, to become a more robust measure of relative age. The capability to detect boulders inside craters may be useful indicator of age and regolith thickness. Computer modelling of crater degradation may reveal contributions made by (a) obliteration (b) blanketing (c) small scale erosion and (d) secondary cratering. The recent discovery of small craters that have been formed on the lunar surface since 2009 [8] also offers the real prospect of establishing a definite time frame over which these processes occur.

THE WIDENING DISTRIBUTION AND EXTENT OF LUNAR SWIRLS AS OBSERVED BY LAMP. J.T.S. Cahill¹, A.A. Wirth¹, A.R. Hendrix³, K.D. Retherford⁴, B.W. Denevi¹, A.M. Stickle¹, D.M. Hurley¹, K.E. Mandt⁴, Y. Liu⁴, T.K. Greathouse⁴, F. Vilas¹, and D. Blewett¹. ¹JHU/APL (Joshua.Cahill@jhuapl.edu), ²Case Western Reserve University, ³Planetary Science Institute, and the ⁴Southwestern Research Institute-San Antonio.

Introduction: The sinuous lunar surficial features known as ‘swirls’ are amongst the most intriguing regions on the surface of the Moon. Several hypotheses for their formation have been put forward and include 1) magnetic shielding from solar wind [2], 2) cometary or meteorite swarm scouring of the shallow regolith [3-5], or 3) electromagnetic charge induced levitation and sorting of lunar dust [6, 7].

Three initial examinations of swirls have been performed in the ultraviolet (UV) [1, 8, 9], each one examined shorter wavelengths. Denevi et al. [1] mapped out swirls in the Lunar Reconnaissance Orbiter Camera (LROC) Wide Angle Camera (WAC) near-UV (NUV), observing that the most distinguishing characteristic of swirls in this wavelength region is a low 321/415 nm ratio coupled with moderate to high swirls in this UV (NUV) region is a low 321/415 nm ratio coupled with moderate to high albedo. They also demonstrate that immature regolith becomes brighter (i.e., bluer) with exposure to space weathering. Denevi et al. [1] further note that some swirls cannot be discerned in the optical maturity index (OMAT) or band-depth images. Finally, in a precursor to the work presented here, Cahill et al. [9], examined LAMP global Lyman-α (Ly-α) albedo (121.6 nm) maps and noted UV evidence consisting of low albedo for swirls coincident with regions noted by Denevi et al. [1] as well as in previously undocumented areas.

Herein we take the next steps leveraging the unique viewing geometry and wavelength range LAMP observes at night to first comprehensively map lunar swirls as observed in the FUV. Secondly, we compare our observations with previous work in order to detail what can and cannot be observed in the FUV relative the NUV, and vice versa.

Data Sets: LAMP continues to provide insights into the upper ~100 nm of the regolith. LAMP is a FUV (57-196 nm) push-broom photon-counting imaging spectrograph [10]. LAMP has also routinely collected both day and nighttime data of both polar and equatorial regions of the Moon. Here, global nighttime Lyman-α (Ly-α; 121.6 nm) normal albedo data are examined for low-albedo features as they relate to the detection and mapping of lunar swirls (Fig. 1). This data set is unique in comparison to all other LRO data sets in that it collects naturally reflected light at night of surfaces diffusely lit by solar Ly-α scattered off of interplanetary H atoms from all directions. This is a simplification, of course, as the Ly-α skylight intensity varies with respect to the motion of the solar system and point sources from UV-bright stars, which are more plentiful in the southern hemisphere owing to the Galactic plane [10, 11]. As a result, the signal-to-noise of the LAMP nighttime data varies with latitude, increasing from north to south. Other maps analyzed include the LROC WAC color [12, 13] and Lunar Prospector (LP) fluxgate magnetometer [14] data.

Swirls... Low-Albedo?: Indeed, unlike the NUV and visible where lunar swirls are
known to show high reflectance relative to their surroundings, in Ly-α they have low albedo due to changes in material optical properties below ~180 nm.

**Mapping Methodology:** LAMP global Ly-α albedo maps were surveyed for low-albedo features with sinuous ‘swirl-like’ characteristics. During this process a WAC 415 nm reflectance mosaic was used for regional context. To maintain an initial independent LAMP assessment, this initial step was taken without referring to swirl boundary maps detailed by Denevi et al. [1] or LP magnetic anomaly maps [14]. Once low-albedo regions were identified, they were compared to LP magnetic anomaly maps as well as WAC color composite maps. This resulted in four classes of low-albedo features, shown in Fig. 1 and 2: 1) Independently verified, (in red; i.e., regions identified independently by both FUV and NUV surveys, respectively), 2) Ly-α identified (in light blue; i.e., only observed in the 121.6 nm band), 3) NUV identified/FUV confirmed (in yellow; i.e., swirls not initially noticed in the initial FUV survey, but documented by Denevi et al. [1] and subsequently confirmed in Ly-α), and 4) Plausible swirls (in purple; i.e., low-albedo features with an ambiguous morphology or setting and associated with weaker magnetic strength anomalies).

**Observations & Discussion:** Consistent with Denevi et al. [1], swirls are detected in LAMP Ly-α in the regions of Reiner Gamma, Mare Marginis, Rima Sirsalis, Crozier, Airy, Gerasimovich, Dewar, and South Pole-Aitken basin (Fig. 1 & 2). Swirls have previously been identified in all of these regions, however Ly-α often shows boundaries encompassing NUV and visible boundaries and often also show additional nearby sinuous low-albedo regions, swirls, not previously identified. That said, there are numerous areas with swirls that go initially unseen in Ly-α. Some of these (shown in yellow) are subsequently identified with additional NUV or magnetic data context, others are not.

An analysis of these regions shows they have lower Ly-α albedo and higher magnetism values on average relative to their surroundings (Fig. 3). Swirl regions denoted by Denevi et al. [1] are consistent with these characteristics. Interestingly, low-albedo regions denoted as ‘Plausible swirls’ while showing similar average Ly-α values as swirls identified with high certainty, have lower values of total magnetic field strength (but higher magnetic field strength than ‘off swirl’ regional analyses).

**Fig. 2:** Swirls mapped over western SPA (Top) nighttime Ly-α with swirls mapped, (Bottom) WAC 321/415 nm.

**Fig. 3:** Histograms of swirl characteristics detailing (Left) Ly-α and (Right) total magnetism $B$. (Dotted) Study of Denevi et al. [1] mapped swirl regions. (Black) Regions nearby, but off swirl regions.
Introduction: The Package for Resource Observation and in-Situ Prospecting for Exploration, Commercial exploitation and Transportation (PROSPECT) is in development by ESA for application at the lunar surface as part of international lunar exploration missions in the coming decade, including the Russian Luna-27 mission planned for 2021.

Establishing the utilization potential of resources found in-situ on the Moon may be key to enabling sustainable exploration in the future. The purpose of PROSPECT is to support the identification of potential resources, to assess the utilization potential of those resources at a given location and to provide information to help establish the broader distribution. PROSPECT will also perform investigations into resource extraction methodologies that maybe applied at larger scales in the future and provide data with important implications for fundamental scientific investigations on the Moon.

Objectives: PROSPECT aims to assess the in-situ resource potential of lunar regolith at any given location on the Moon. In order to achieve this PROSPECT is required to:

- Extract samples from depths of at least 1m.
- Extract water, oxygen and other chemicals of interest in the context of resources.
- Identify the chemical species extracted.
- Quantify the abundances of these species.
- Characterize isotopes such that the 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 solar wind implanted volatiles from the regolith through heating and aims to extract oxygen and other chemicals of interest as resources from minerals by a variety of techniques.

System Functions:

Drilling and sampling: PROSPECT includes a drill that is required to access the subsurface to depths of at least 1m. Once at the required depth a sampling tool removes small samples, whilst preserving sample temperature. Samples must then be extracted and handled whilst minimizing alteration of the samples.

The drill is derived from that being developed for EXOMARS [1] and the Rosetta drill [2]. Modifications are considered to account for unique lunar mission requirements and material properties.

Sample heating and chemical extraction: Samples are sealed in ovens, derived with heritage from those developed for EXOMARS [3], Rosetta and activities performed through the German LUISE programme. Samples can then be heated to temperatures as high as 1000°C. Heating in vacuum extracts ices and solar wind implanted volatiles and pyrolyses some volatiles from minerals. 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 [4], oxidation using fluorine [5] and reduction using hydrogen and methane [6].

Gas compositional analysis: Evolved gasses can be analyzed using an ion trap mass spectrometer [4] for masses up to around 200AMU. This gives a qualitative measure of the composition.

Gas chemical processing: Target gasses are prepared for isotopic analysis through refinement or conversion to other chemicals [4]. Such conversion can prepare chemicals which are better suited than the original compounds to analysis using a mass spectrometer and can remove isobaric interferences.

Gas isotopic analysis: Isotopes of the elements of interest are measured using a magnetic sector mass spectrometer, along with measurements of reference standards [4]. Using this technique accurate analysis is achieved, allowing comparison with laboratory measurements on Earth.

Conclusions: PROSPECT is a package for the investigation of lunar volatiles and other potential resources with potential applications for both exploration and fundamental science. The package builds on extensive flight heritage and a unique set of capabilities, developed over decades by a number of groups across Europe.

PROSPECT is in development for flight on the Russian led Luna-27 mission as part of the first phase of lunar resource characterisation [7] and could be available as part of international missions in this time frame.


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The Industrial team is led by Leonardo, Italy with development of the chemical laboratory led by Open University UK.
VIRTUAL REALITY IN SUPPORT OF FUTURE LUNAR EXPLORATION: AN ILLUMINATION ANALYSIS CASE STUDY. A. E. M. Casini1, P. Maggiore1, N. Viola1, A. Cowley2, V. Basso3 and L. Rocci4,

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Introduction: As stated by [1], lunar vicinities and the Moon surface are certainly of interest for the next generation of exploratory enterprises. A Cislunar station will be the natural evolution of the currently experience of the International Space Station (ISS) in Low Earth Orbit (LEO) and will actively support the human and robotic operations on the soil of our natural satellite, providing logistical support. A permanent manned settlement is then envisioned, especially endorsed by the ESA vision of the “Moon Village”. The abundance of resources and volatiles of the Moon could be useful to generate, with In Situ Resource Utilization (ISRU) technologies, all the necessary equipment and consumables for limiting the Earth dependability and lowering the Initial Mass to Low Earth Orbit (IMLEO). All the lunar activities are not limited to them, but should also account to the incremental architecture strategy which has posed human Mars missions as the ultimate goal for stating the exploration of the Solar System. In this vision, the Moon is then an ideal test bed to validate enabling technologies.

Since those kind of space missions are becoming more complex from a design point of view, especially for crewed endeavours, Virtual Reality (VR) could help to find optimized solutions in shorter times compared to the standard tools nowadays used. In fact a virtual shared environment, used in combination with a Concurrent Design (CD) approach, could better address the challenges of the early stages of the project. In these early design phases, the final configuration of a system is still unknown, but most of the decision taken will have a major effect in the resulting product. Using a Model Based System Engineering (MBSE) methodology, in which virtual models are accessible to all the experts involved to shape a certain product, it is possible to also optimize operations, training processes, and ergonomics aspects which may be overlooked. Cost saving is one of the result, in addition to a maximization of the overall mission’s scientific return.

The idea of this work is to use VR to simulate the illumination condition at the lunar south pole. The particular orography coupled with the very low inclination of the Moon rotation axis with respect to the ecliptic plane, results into very particular light conditions. Permanently shadows crater are present, which can engrave icy water mixed with regolith grains, as well as highly illuminated spots, whose are favourable location for base elements (e.g. solar panels).

Virtual simulations: Site selection strategy is one of the most critical aspects of space missions. Especially at the lunar south pole, it is important to choose an appropriate area where to locate the base elements. Ideally, the chosen region should be near permanently shadow craters to allow their exploration and resources verification, should guarantee a nearly constant communication link with Earth ground stations, and not too far from a peak of light to moreover ensure an easier thermal control.

Starting from Kaguya and LOLA cloud point data, two Digital Elevation Models (DEMs) were generated to model the geology of the Shackelton crater rims. Once having correctly located the DEMs with respect to the Sun (using ephemerides), real time shadows have been generated into virtual scenes by the graphical engine of the VR software used. Via processing the images obtained (binary conversion and stacking), two illumination maps have been obtained for the time-frame 2020-2030.

The results obtained from the simulations are in line with the data presented by [2].

Conclusions: Some illumination maps have been generated using a virtual environment. This first proof-of-concept has demonstrated that VR tools could be adopted not only for graphical and educational purposes, but also as real engineering device to study some aspects of a mission to the lunar surface.

Future plans consider to integrate a virtual simulation environment into the standard suite of tools used into a Concurrent Design Facility (CDF) to enhance the decision making process. The final goal is to implement all the building block of the outpost as a computer-based mock-up, which is able to reproduce both physical and functional behaviours. Thanks to the first-person interactive view of the system, also training purposes could be address as for Extra Vehicular Activity (EVA). Ergonomics and operations aspects (e.g. procedures to interact with a payload rack) are also part of disciplines considered into the knowledge-based optimization process.

SHOCK-INDUCED TEXTURE IN LUNAR MG-SUITE APATITE AND ITS EFFECT ON VOLATILE DISTRIBUTION. A. Cernok1, J. Darling2, L. White2, J. Dunlop2, and M. Anand1,3. 1Open University, School of Planetary Sciences, Walton Hall, MK7 6AA, United Kingdom (ana.cernok@open.ac.uk), 2University of Portsmouth, School of Earth & Environmental Sciences, Burnaby Road Portsmouth, PO1 3QL, United Kingdom; 3Department of Earth Sciences, The Natural History Museum, London, SW7 5BD, UK.

Introduction: The lunar Mg-suite are plutonic rocks which represent an episode of crustal building following primordial differentiation of the Moon [e.g. 1]. They range in crystallization ages from 4.43-4.1 Ga [2]. This suite of rocks includes dunites, troctolites, and norites and comprises 20-30% of the lunar crust up to a depth of ~ 50-60 km. Apatite is the most common volatile-bearing mineral in lunar rocks, which made them an ideal target for in-situ studies of volatiles [summarized in 3]. This study focusses on pristine highland samples that have experienced different levels of shock metamorphism [4]. Therefore, they are valuable samples for understanding how the content of water and other volatiles, as well as their isotopic signature respond to shock.

Samples: We studied two highly shocked norites, 78235 & 78236 [5]. These coarse grained cumulate rocks are comprised of ~ 30% orthopyroxene, ~ 55% Ca-rich plagioclase and maskelynite, ~ 15% glass and traces of SiO2 minerals, clinopyroxene, Fe-metal, torilite, Cl-rich fluorapatite, merrillite, baddeleyite, chromite, and Nb-rutile [e.g. 6]. In polished sections these samples display variety of shock-induced features: melt veins, vesicles, maskelynite, heavy fracturing of minerals and wavy extinction. This study builds on the previous work [7, 8] which reported H2O, Cl, δD and δ37Cl composition of apatite from these rocks. Twoapatites within 78236 (Ap1 and Ap5) contain very different water contents (~ 200-300 ppm vs. 550-1600 ppm), while the second grain also shows high intra-granular inhomogeneity (Fig. 1). δD values between the grains do not show such high discrepancies: δD = +157 ± 163 ‰ to +196 ± 240 ‰. So far, no satisfactory explanation as to how these discrepancies in water content arose has emerged. Our integrated EBSD, CL and Raman analyses have revealed important features which may help address these inhomogeneities.

Analytical procedure: This study represents an integrated analyses of petrographic context and internal texture of apatite combined with previously reported in-situ volatile content and isotopic measurements. The search for apatite grains within thin-section was performed using the EDS elemental X-ray mapping procedure using a Secondary Electron Microscope (SEM). The petrographic context was evaluated by EDS-spot analyses of the minerals surrounding apatite. Cathodoluminescence (CL) detector mounted on a SEM was used to investigate homogeneity or internal zoning of selected apatite grains. Phase identification and distribution was carried out by Raman spectroscopy. Lattice orientation and internal structural disorder of selected apatites was studied by Electron Backscatter Diffraction (EBSD). We plan to analyse the sample 78236 by NanoSIMS, to understand if apatites within this similar rock display comparably similar H2O and δD signatures to that of 78235.

Results: EDS mapping revealed ~ 10 apatites in each thin-section which have lengths greater than 5 µm, the largest grain having a surface area of ~ 50 x 15 µm². All apatites have anhedral grain shape, mostly showing sub-equant crystal habit. Apatite is found in association with 1) predominantly plagioclase/maskelynite; 2) predominantly Opx, 3) equally associated with different minerals (plagioclase, Opx, Cpx, silica, merrillite).

EBSD scanning across different apatites revealed that those grains entirely surrounded by plagioclase/maskelynite mostly show very weak or no diffraction, appearing quasi-amorphous. Detailed (300 nm step-size) analyses of selected well-diffracting

Figure 1. CL, EBSD band contrast and texture component map of apatite (Ap5) in 78235. Yellow dashed line outlines the grain boundary of apatite (a); c-cpx, f – iron, m – merrillite, s – silica, p – plagioclase. CL picture is slightly zoomed out.
Apatites indicated degraded crystallinity, as expressed by very low band contrast (BC) values (< 40) (Fig. 1). BC is a quality factor that describes the average intensity of the Kikuchi bands with respect to the overall intensity within the Electron Backscatter Pattern. Internal structure of those grains is highly fractured and segmented, with variable size of fragments among different apatites, as well as within individual grains. Based on the texture component maps, we conclude that no recrystallization of apatite had taken place and that the individual segments within single grains are similarly oriented. However, continuous gradients in texture component map show up 25° of misorientation within single grain, an evidence for severe crystal-plastic deformation. The effect of shock impedance of the major minerals on the associated accessory phases was seen for other minor minerals, e.g. baddeleyite [9].

CL imaging of apatites indicated no complex zoning. Simple, cloudy textures recognized in several grains can be related to the regions of poor crystallinity revealed by EBSD. An example of irregular cloudy zoning is seen for Ap5 in Figure 1. The regions which appear brighter in CL, corresponding to darker, more degraded regions of BC but also follow the set of cracks which are pervasive through the whole grain.

In-situ Raman spectroscopy. Detailed 2D Raman maps of Ap1 revealed very fine-scaled, sub-µm intergrowth of apatite and associated Opx (Fig. 2). The entire region of apatite close to the Opx inclusions shows mixed Raman signal of apatite and Opx (Fig. 2). This region also showed mixed composition in EDS, brighter cloudy zoning in CL, as well as the most degraded crystallinity in BC. Associated with this region is a NanoSIMS spot of lower water content (~200 ppm). According to the imaging, this region of apatite has experienced more intense distortion than the unmixed region of the same grain. However, a slight decrease in water content cannot be attributed to the impact devolatilization, as it may be associated with the fine-grained intergrowth with Opx, which contains less water than apatite. The curious intergrowth of apatite with Opx was described much earlier [6] but to our knowledge it has not been studied in more detail since.

Ap5 grain is closely related to Cpx (augite composition), plagioclase (anorthitic), merrillite, iron and silica (Fig. 1). Here we observe the opposite – the region of apatite further from the Cpx contains less water (~ 500 ppm); the region close to the Cpx, which appears less crystalline, is more water rich (~1600 ppm). The region in Ap5 which is Cpx-free, but shows the same CL zoning and low BC contrast due to severe structural distortion, also contains higher water content (~1200 ppm, Ap5#4 in Fig. 2). We do not find evidence for Cpx fine-intergrowth with apatite. The results suggest that the late-stage apatite crystallized alongside silica and Cpx in an Opx-free assemblage contain more water than the apatite associated with Opx. The Ap5 shows higher water content in regions which show lowest crystallinity, suggesting enrichment through an impact. We are currently studying other highland samples to confirm this observation.

![Figure 2](image-url)  
**Figure 2.** Selected Raman spectrum of Ap1 in 78235 (blue), compared to database. The spectrum shows a mixed phase of apatite and Opx collected within the blue square presented on the inset BSE image, compared to enstatite spectrum (green). Au is a gold-filled NanoSIMS pit. Other minor phases (< 5 µm length) in contact with apatite are Cr-spinel, Cpx, and silica.

On most of the remaining apatites, Raman spectra was acquired by spot analyses. Unlike EBSD, Raman has not revealed entirely amorphous apatites. Acquired spectra show good crystallinity also in regions which appear poorly crystallized in BC (e.g. spectrum in Fig. 2). The apatites surrounded by plagioclase or maskelynite, which show the most degraded crystallinity among all apatites studied, show Raman spectra of decreased quality – low signal to noise ratio, less intense peaks and slight peak broadening, but can be easily assigned to apatite. We believe that Raman and EBSD show complementary results. Interaction volume of Raman analysis (1-2 µm) is greater than that of EBSD (few tens of nm), and therefore samples a mixture of sub-micron crystallites surrounded by amorphous medium. EBSD, on the contrary, is very site-specific and sets constraints on the size of crystallitles to less than the step size of analyses (300 nm). Additional TEM work is needed to address the crystallinity issue properly, but a recent study [9] has made similar observations in case of baddeleyite.

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**NEW INSIGHTS AT MAFIC MATERIALS AND IMPACT MELT AT ARISTARCHUS CRATER FROM M3 AND LROC.** S. D. Chevrel$^{1,2}$, P. C. Pinet$^{1,2}$, Y. Daydou$^{1,2}$, Université de Toulouse; UPS-OMP; IRAP; Toulouse, France, CNRS; IRAP; 14, avenue Edouard Belin, F-31400 Toulouse, France (serge.chevrel@irap.omp.eu).

**Introduction and objectives:** Materials excavated and deposited during crater formation give information on the composition of deep-seated materials. Through the cratering processes most of the excavated materials are melted more or less preserving spectral mineralogical features. This melting occurs at different degrees and during cooling at different rates, a range of textures from glassy (“pure melt”) to coarse-grained crystalline (recrystallized melt) is likely to be seen within and around the crater. Also, during the excavation process significant lithic fragments can be entrained in the melts. Due to scaling effects the proportion of clasts in the impact melt is expected to be higher on the Moon than on the Earth [1]. Thus lunar impact melt spectra can show a complex behavior, being a function of both the starting material and the conditions of melting and/or cooling of the impacted materials.

Our objective is to document the distribution and the degree of melting of the materials in a crater in order to understand both the nature of the target and the cratering processes. We present here a study of the Aristarchus crater using a combination of spectral (M3 from Chandrayaan-1) and high resolution morphological (LROC from LRO) data.

**Region of study and earlier work:** The Aristarchus crater is a young impact crater (175 Ma [2]) of 42 km in diameter which is reasonably documented from earlier spectral studies, e.g. [3,4,5]. This crater shows various morphologies and fresh materials, with exposed rocks (boulders) in its walls and rim [2]. Deep-seated materials excavated (from a depth of 3 to 4 km [5]) give locally access to the composition of the regional crust [4,5] which is not well exposed in this portion of the Moon (PKT). The freshness of the morphological units and materials for the well-preserved Aristarchus crater are important factors to better understand impact cratering processes, by linking morphologic features and composition.

Previous studies based on Clementine data (e.g.,[4]) showed that the Aristarchus crater formed in a complex target (straddling the edge of a Plateau), having excavated, melted and mixed deep-seated crustal (or pluton), and Imbrium ejecta materials. This setting and the resulting effects of the impact on the target materials (degree of melting and recrystallization) led to exposures of complex materials which are not straightforward in interpreting remote sensing spectra.

**Results:** The present study has been made on a subset of the M3G20090418T132620_V01 image (140m/pixel; 540-3000nm; 85 bands) from the M3 instrument (Figures 1, 3). A first assessment aims at exploring the spectral variability by means of an integrated band depth area parameter for the absorptions bands at 1000 and 2000 nm calculated under an overall continuum which is modeled by a polynomial of degree 2 [7]. Both prominent mafic absorption features are found (spectra A and PX as examples) and almost featureless spectra (dark blue spectra) (Figs. 2a, 2b).

Spectrum for each pixel of the image has been fitted using Modified Gaussian Model (MGM) [6] based on model parameters (position, strength, and width of absorption bands) established for laboratory spectra of terrestrial pyroxenes and olivines and their combinations [7,8]. We give here examples of areas (in red) showing the presence of olivine alone and olivine associated with either some orthopyroxene and/or clinopyroxene (Fig. 1.A) and olivine associated with both orthopyroxene and clinopyroxene (Fig. 1.B).

![Figure 1](image.png)

Figure 1. 1.A: areas showing the presence of OL and OL + OPX and/or CPX. 1.B: areas showing the presence of the three components OL + OPX + CPX, as modeled by the MGM.

Clearly, a mineral diversity does exist in the crater and in the following we emphasize the systematic mapping of the most olivine-rich bearing materials, expanding on the olivine mineral detection from previous studies in the southeastern part of the crater (e.g. [3,4,5]).

Pixels with olivine-rich materials identified through the MGM model are shown in red in figure 3. These red units form a radial pattern, and are associated with low albedo impact melt in the ejecta on the walls and outside the crater, in its southeast quadrangle. A selection of spectra for these units (Figs. 2a, 2b) shows that
olivine is the dominant component, associated with at least another phase as revealed by the associated 2150-2250 nm spectral feature. The large morphologically and spectrally homogeneous area noted A in figure 3 is the richest one in olivine, or the less contaminated by another component since the band towards 2000 nm is the weaker (figure 2.b). The spectral characteristics and hence the nature of this additional component, either a pyroxene and/or a Fe-bearing glass, is not presently modeled by the MGM. We note that the spatial location of this spectrum (white cross in figure 3) is the same as for the olivine-rich endmember taken in a previous study using Clementine data [4]. The spectra of the areas noted B and C on the one hand, and D and E on the other hand (Fig. 3), respectively show a less and a comparable or more pronounced band at 1000 nm than for area A (see figure 3.b). Differences also appear in the depth of the 2000 nm band. Area F is located on the floor close to the central peak; MGM modeling clearly shows the presence of both olivine and clinopyroxene.

We then combine our spectral outputs with morphological data at high resolution (metric scale) from LRO [9]. This morphological information is quite useful for guiding the interpretation in terms of degree of melting of the target materials and their distribution. Area E corresponds to a patch of impact melt lying on the terraced wall, and displaying numerous blocks on its surface (Figure 3.c). From morphological evidence the spectral signature of the olivine might predominant-

Figure 2. Left: (2.a) Selected spectra: A (olivine-rich component) and PX respectively, shown by the black crosses in the purple units (at right); (2.b): continuum removed spectra). Right: Integrated surface band depth parameter for the absorptions bands at 1000 and 2000 nm (see text). Dark Blue: low values. Purple: high values.

Figure 3. Left: M3 image of the crater Aristarchus crater (42 km in diameter). Red areas are rich olivine-bearing materials identified using the MGM model (see text). Right: Reflectance (a) and continuum removed (b) spectra of the areas shown at left; (c) LRO image (ARISTARCLOA_E237N3125_5M) at decametric resolution of area E.
INTERESTING CASES WHEN DATING LUNAR LOBATE SCARPS. J. D. Clark¹, C. H. van der Bogert¹, H. Hiesinger¹, and H. Bernhardt¹, ¹Institut für Planetologie, Westfälische Wilhelms-Universität, Wilhelm-Klemm-Str. 10, 49149 Münster, Germany (j.clark@uni-muenster.de).

Introduction: Scattered globally across the Moon are compressional features called lobate scarps, which are the surface expression of low-angle thrust faults [1-4]. Numbering over 3,200, the scarps were predominantly formed via late-stage contraction of the lunar surface; however, tidally-induced stresses have also contributed to the Moon’s stress state [5]. Although they share similar morphologic features, lunar scarps are relatively small compared to those of other terrestrial planets (e.g., Mars, Mercury, and Earth), typically only <10 km in length and tens of meters in relief [5-9]. Located in the back limb of some scarps are small-scale graben (with depths as shallow as 1 m), likely caused by flexural bending [10, 11].

Based on their generally crisp appearance and cross-cutting relationships with small-diameter craters, lobate scarps are among the youngest landforms on the Moon (<1 Ga) [5,12-14]. On a larger scale, scarps themselves typically occur in a series of up to 10 scarps, called scarp complexes (Fig. 1) [12].

We conducted several studies on lobate scarps using various cratering counting methods. Here, we present two interesting cases to show that ages can be derived for these young tectonic features: (1) We investigated the Mandel’shtam scarp complex (6.2°N, 161.2°E), because it is one of the longest scarp complexes on the Moon, and (2) we examined the wrinkle ridge-lobate scarp transition of West Serenitatis to probe whether the fault represents a single or multiple event(s), and determined its origin.

Data and Methods: For both cases, we used NAC (Narrow Angle Camera) image data from the Lunar Reconnaissance Orbiter [15]. Count areas and crater size-frequency distribution (CSFD) measurements were done using CraterTools in ArcGIS [16]. In Craterstats [17], we plotted and fit the CSFDs using the techniques described in [18]. Absolute model ages (AMAs) are derived with the chronology function (CF) and production function (PF) of [19], for lunar craters > 10 m and 100 km in diameter.

Curious Cases: Lobate Scarp Complex. Located in the farside highlands, the Mandel’shtam lobate scarp complex (Fig. 1) is comprised of eight distinct scarps with a total length of ~80 km. The complex’s name derives from the close-by large Mandel’shtam craters, which range from ~25 – 60 km in diameter.

Age determinations by [13] place the craters at Imbrian to pre-Nectarian in age (~3.5 to 4.2 Ga). Using crater degradation rates, [12] derived ages for the scarps within the Mandel’shtam complex. Individual scarp ages range from 100 ± 70 to 190 ± 70 Ma, with a calculated complex age of 180 ± 50 Ma [12]. However, with the more recent scarp dating technique of [13] and the abundance of high resolution images from the LROC, we reexamine the scarp ages [15]. Our ages were mostly younger than those derived by [12]. The AMAs range from 33 Ma to 187 Ma, with ages varying along the scarp showing that fault movement appears to occur randomly within the complex [20]. We were able to get multiple counts for each scarp, however, most AMAs varied along an individual scarp. Nearby ejecta and steep slopes are typical influences on the crater population. This demonstrates the importance of selecting a proper count location.

Wrinkle Ridge-Locate Scarp Transition. Although wrinkle ridges and lobate scarps are usually observed independently from one another, we find these features located on the western edge of Mare Serenitatis which appear to be associated [21]. The entire length trends E-W and is ~19 km. Beginning

Figure 1. Simple geologic map of the Mandel’shtam scarp complex (6.2°N, 161.2°E) displaying the lobate scarps (red lines) over a WAC mosaic. Surrounding craters are mapped with a yellow outline.
directly west of Dorsum Gast, the sinuous and boulder-covered ridge traverses the mare basalts until reaching the highlands boundary, where it transitions to lobate scarp morphology.

Because of the complex tectonic circumstances, we applied multiple crater counting methods to the lobate scarp and wrinkle ridge to find the optimal approach. We first attempted at using the method of [13], however, the uphill-facing limbs of the lobate scarp have steep slopes resulting in anomalously young ages due to mass wasting and AMAs derived for the wrinkle ridge were at equilibrium for all craters less than 300 m. Second, the uphill-facing scarp provided an opportunity to take CSFD measurements directly from the scarp face (Fig. 3). Typically, lobate scarps have steeply sloping scarp faces when they offset a near horizontal surface, however, here the geometry is slightly rotated, making the scarp face completely horizontal. This technique could not be applied to the wrinkle ridge as the presumed fault face has a steep slope and is covered by boulders. Lastly, we applied the buffered crater count (BCC) technique on the lobate scarp and wrinkle ridge due to the sufficient number of superposing craters (> 10 m) on both features. The BCC technique determines ages for linear features independently from the surrounding geologic units [22]. Unlike conventional crater counting, where only craters with centers inside the count area are included, the BCC technique only includes craters that superpose the linear feature. From there, a buffer is calculated from the diameter of each crater [23].

AMAs derived using the BCC technique (Fig.4) indicates that the last fault movement for the lobate scarp and wrinkle ridge occurred during the same time at ~50 Ma ago [24]. Furthermore, the CSFD measurements of the scarp face from all scarp segments show a similar AMA (Fig.4, green, [24]). The features’ similar AMAs supports a link between the two landforms. We propose that the recency of tectonic activity of the ridge-scarp transition is likely the result of late-stage global compression, where zones of weakness on the edge of the basin locally form wrinkle ridges and transition into the highlands to form lobate scarps [12,21,25,26].

Introduction: Regolith is the interface between the pristine planet and the space environment, and is the lens through which we observe both. Bombardment meteorites and cosmic rays carve a record of evolutionary history into regolith grain size distribution, chemistry and mineralogy. The regolith on the moon is the result of more than 4 billion years of meteoroid impacts with a parent impactor size range over twelve orders of magnitude, from tens of kilometer asteroids to micrometer particles of cosmic dust. At the low end of the meteorite mass distribution, bombarding meteorites garden the top few centimeters of regolith.

Regolith models are the way we untangle the evolutionary history of regolith. The pioneering regolith mixing model presented by Gault et al. (1974) [1] presents the rate of overturn as a function of time. The Gault et al. (1974) model is based upon the probability of a successful overturn event and employs a statistical method based on Poisson law, scaling relationships between meteoroid mass and resulting crater size and the meteoritic flux. A point on the lunar surface is considered “turned over” if at any time it has been influenced by an impact event. Area of influence is controlled by scaling relationships between meteoroid mass and resulting crater size. The frequency of influence is controlled by meteoritic flux.

We have implemented the existing Gault et al. (1974) model and demonstrated its use with updated input values; in particular, we have updated impact flux rates and included more detailed and contemporary impact crater scaling laws. Updates and model refinements allow us to test the analytic model and explore features beyond its original design; for example, mixing due to secondary impacts.

Values for meteoritic flux are informed by contemporary observational data. Flux can be estimated from the bolide observations compiled by Brown et al. (2002) [2]; the power function relationship [2] describe is corroborated by crater counts [3, 4], and lunar impact flash observations [5, 6]. In contrast, Gault et al. (1974) assumed a flattened mass flux distribution for meteorites < 10^3 g, which has since been shown to be a sampling bias caused by loss of resolution [4, 5, 6]. This assumption causes our model and the Gault et al. (1974) model to diverge at depths less than 0.3 mm [Figure 1].

We also reworked the model to include a more accurate treatment of crater shape, replacing Gault et al. (1974)’s spherical caps with the parabolic topography of simple crater bowls [7, 8, 9] and a more detailed treatment of crater size using the cratering efficiency laws and parameters presented by Holsapple (1993) [10].

Secondary Impacts: The Gault et al. (1974) model does not include the effects of secondary cratering, which is now recognized to be extremely important in regolith development [11, 13]. Preliminary results show secondary impacts produce much faster overturn to greater depths than treating primaries alone [Figure 1]. These preliminary results are approximately consistent with the mixing rate of 2 cm every ~100,000 years inferred by Speyerer et al. (2016) [11] from observations of lunar dark spots in Lunar Recanasiian Orbiter Camera (LROC) [14] temporal pairs.

The values used to generate the contour shown in the figure represent a lower limit. Because regolith dampens the production of high-velocity ejecta during an impact [15] the velocity of secondary impactors is taken to be 0.5 km/s [16], the minimum required to generate an explosive crater. Lower limit values are taken from McEwen et al. (2005) [13] for number and size distribution of secondaries per primary impact.

Figure 1: Figure 1: Comparing models showing the depth of overturn in 100,000 years. All but Speyerer et al. (2016) show a lower limit case [1, 11, 12], with material buried X meters deep having a 50% probability of being turned over at least Y times in 100,000 years.

Application and Testing: The model can be tested against the lifetime of lunar “cold spots,” deposits of small young craters that exhibit anomalously low nighttime temperatures in LRO Diviner radiometer data [17, 18]. Thermal modeling suggests that cold spots are ~10 cm thick [19, 20, 21]. Size frequency distributions indicate that they are ephemeral, persisting no longer than several hundred thousand years [21]. Over this short timescale and at these shallow depths, the model can predict the timeframe.
over which cold spots are worked into the back-
ground by impact-driven mixing.

Small meteorites are more frequent, however the top few centimeters of regolith are mixed by meteor-
ites across the impactor size distribution over billions of years. Apollo core samples present an opportunity
to test the model up to meter depths and at longer,
Million and billion year timescales. Impacts rework
exposed soil to depths that depend on the scale of
impact craters and impact flux rate - the controlling
parameters of this model. A depth profile of in situ
exposure age has been experimentally determined
from samples returned from Apollo 15, 16 and 17
[22, 23, 24]. We test calculated mixing results
against observed relationships between near-surface
exposure ages of lunar soil samples and reworking
depths in the regolith layer.

To further test the model at billion year times-
scales and meter depths, we assess overturn results in
comparison to the lifetime of Copernican crater rays.
The possession of rays characterizes large Coperni-

can era craters, and these rays are known to persist
only about a billion years [25, 26]. Knowing the
depth of ray deposits [26, 27, 28] and assuming thor-
ough overturn, we test the model by predicting the
time it would take for rays to be evolved into the
background by impact bombardment. At the billion
year timescale, assuming the relatively low modern
meteorite flux is no longer valid. We look to the cra-
tering record throughout lunar history to inform flux
parameters at billion year timescales [3, 29, 30, 31,
32, 33, 34, 35].

Discussion: While modeling explosive craters to
centimeter or decimeter depths is reasonable, micro-
meteorites that impact similarly sized grains of rego-
lith do not generate simple crater bowls. We expect
the effects of grain-on-grain impacts to flatten over-
turn contours at shallow depths; Gault et al. 1974
qualitatively included grain-on-grain impacts as a
justification for flattening the mass distribution [36].

Quantitatively exploring the transition from mixing
to catastrophic breakdown for small scale meteorite-
regolith interactions is a natural next step for the
model.

Introduction: The operational capabilities of the European Astronaut Centre (EAC) in terms of training and support for human spaceflight operations on the ISS are well known. With increasing attention now being given to post-ISS human spaceflight and exploration scenarios, teams at EAC and the broader ESA are collaborating on projects that would leverage the capabilities and experience available from EAC to further these exploration objectives.

In order to address analogue capability gaps identified previously by ESA studies [1], EAC has embarked on a number of exploration enabling initiatives at the centre in Cologne. Of notable impact is the development of a large scale regolith test ground area and attendant analogue habitat module. This exploration facility is named LUNA, and will provide the capability to run high-level integrated simulations, combining a habitat, lunar terrain, a Mission Control Centre (MCC) and related communications simulations. The location of the facility will allow for ease of access to ESA personnel, but the facility is also envisaged to be readily accessible to researchers as well.

The planned facility will comprise of a large regolith test bed area located between the existing EAC facility and DLR EnviHab building situated in Cologne, with a half spherical fully enclosing dome structure housing the testbed. The perimeter of the structure is given with a diameter of 34m – the effective surface operations area is projected to be approximately 900m², inclusive of experiment preparation areas. The testbed will comprise of a lunar regolith simulant sourced from the local Eifel region volcanic and basalt sources.

A second exploration initiative at EAC is the “Spaceship EAC”, which aims to utilise the spaceflight experience of the centre to develop and validate operational concepts and lowTRL-level technologies in support of lunar human exploration scenarios. The individual concept/technology development and demonstration projects within the “Spaceship EAC” initiative are coordinated with ESA centres (mission scenarios, technology roadmaps) and exploit synergies with EAC facilities and operational competence as well as with the surrounding DLR campus and European research groups.

In this talk, we will outline the current plans and progress for LUNA as well as the activities and projects of the Spaceship EAC.

References:
UNDERSTANDING LUNAR REGOLITH NOBLE GAS BUDGETS: ENABLING SCIENCE FROM THE ESA PROSPECT PACKAGE. N. M. Curran1, K. H. Joy1, E. Füri2, J. Carpenter3 and The Prospect User Group4. 1SEES, University of Manchester, Oxford Road, Manchester, M13 9PL, UK (natalie.curran@manchester.ac.uk). 2CRPG, Nancy, Fr. 3ESA ESTEC, Noordwijk, NL. 4European Space Agency International Collaboration.

Introduction: Future missions to the Moon including the forthcoming Roscosmos Luna-27 south polar lander, aim to investigate potential resources and volatiles budgets at the lunar surface. The PROSPECT package is an ESA contribution to Luna 27, which provides the capability to drill into the sub surface of the Moon to ~ 1 m depth, and collect regolith samples [1]. The samples will be transferred to a miniature chemistry laboratory (called ProsPA) and analysed for their volatile content and isotopic signature [2]. The aim of PROSPECT is to define the surface budget of lunar volatile species (including water, nitrogen, carbon, oxygen and the noble gases) and understand the sources of those volatiles – key lunar science objectives [3] – and to assess the in situ resource utilisation potential of the Moon for future lunar and planetary robotic and human exploration efforts [4-7].

Aims: Other presentations at this conference will discuss the importance of different aspects of the PROSPECT User Group activities. Here, we focus on a discussion of the science enabled by potential ProsPA measurements of noble gases trapped within the lunar regolith, and outline our current efforts to produce a database of previously reported noble gas measurements from lunar regolith samples.

Science from lunar regolith noble gases: Apollo, Luna and lunar meteorite regolith samples offer a diverse collection of material that includes all the dominant rock types on the Moon [8]. The noble gas budgets of regolith can help decipher the regolith evolution and crustal modification processes that occur on a planetary surface. Including mechanism which can help to determine: i) the regolith history and turnover rates (exposure age, burial depth and the surface exposure – maturity) of samples from different periods of lunar history [9]; ii) evolution of the solar wind [10-11]; iii) understanding bombardment rates and delivery of meteoritic material to the Moon at different times [12-13].

PROSPECT Activities: For PROSPECT, several questions are critical in assessing the extent to which the extraction and analysis of noble gases is feasible:

Understanding the potential sources of volatiles: What are the end-member noble gas contributors to the different lunar regolith that may be sampled by PROSPECT? For example, lunar polar regolith environments may include mineral and glass fragments that contain a wide range of different contributions [14-15] including radiogenic derived, implanted solar wind, cosmogenically produced, and absorbed lunar atmosphere. Polar ices and cold environments may also be key sink sites [16-17] for exogenously (e.g., ‘planetary’ signature) added components from volatile rich asteroids and/or comets [18-19].

Extraction and analysis planning: (1) Temperature of gas release: At what temperatures are the different components liberated from a regolith sample during extraction and heating? Noble gases, and other volatiles, will be liberated from the extracted sample initially through sublimation and then through different heating cycles (continual or stepped) in a furnace [2]. Planetary mission traditionally have limitations on sample gas extraction methods; for example, the maximum temperature oven systems on robotic landers/rover can achieve are usually in the range of 1000°C [20-21]. The full extraction of all noble gases generally occurs during complete sample melting (>1200°C). The volume correlated cosmogenic and radiogenic components are typically released at high (>1000°C) temperatures. Whereas, surface-correlated solar components generally dominate the lower temperatures. The behavior of noble gases trapped in lunar polar ice reservoirs is poorly understood, although the super cold temperature (~233°C) of water ice expected at the polar regions has the potential to trap noble gases [23-24]. Therefore, it is important to understand at what temperatures noble gases are released from a regolith-like sample and, in the case of limited oven temperatures, the extent to which noble gases can be analysed to produce scientifically useful results if a sample is not completely melted. Such science aims include understanding the: (i) Cosmogenic component of lunar regoliths to enable corrections and determination of hydrogen and nitrogen isotopes [13, 24]. Noble gases are notably important for understanding the cosmic ray exposure history of lunar samples (as a function of sample chemistry, shielding depth and nuclide production rate). (ii) Regolith antiquity: Argon isotopes (relationship of ‘parentless’ 40Ar to solar wind derived 36Ar) can provide an indicator of the timing of regolith closure from solar wind interaction, helping to constrain the time of past impactors [12, 22] and delivery of water ice to the lunar poles from these volatile-rich impactors.

Sample mass: We also need to understand how potential sample masses planned for the PROSPECT gas release experiment (~10 mg) relate to previously determined lunar sample data to identify and understand limitations and potential problems that may occur on the Moon during analysis (e.g., instrumental detections limits, saturation of instrument, blank and memory effects) and plan for different gas preparation approaches.
Lunar Regolith Noble Gas Database: To address both instrument and mission science drivers for noble gas analysis on PROSPECT and future planetary missions, we are developing a database of existing literature data for lunar regolith samples (soils, regolith breccias, sub-surface drill cores and lunar meteorites).

The database so far includes data for over 200 different samples from ~40 refereed published papers. Data recorded includes: literature source reference, sample name and type, analysed masses, noble gas isotope concentrations (He, Ne, Ar, Kr, Xe) and uncertainties, and temperature of the gas release. We also report the calculated radiogenic, trapped and cosmogenic components of each measurement as reported in the original paper. We have not undertaken any data quality or filtering of the original reported data. We welcome authors to contact us to contribute their data (including historic Apollo and Luna mission era unpublished datasets).

Results: The database highlights knowledge gaps within the Apollo and lunar meteorite noble gas dataset. Many of the Apollo 12, 14, 15 and 17 soils have limited published noble gas budgets, and the similar is true for Apollo breccias from the Apollo 12 and 14 sites and many of the lunar meteorites. Fortunately, plentiful data has been published from the Apollo 16 regolith and soil sample set, which is most similar in feldspathic composition to the nature of the south polar ‘highlands’ landing site Luna 27 will be sampling.

Within the noble gas data there are huge variations (e.g., $^{36}$Ar, <0.05 to ~1300 × 10$^{-6}$ cm$^3$.STP/g: Figure 1) in noble gas concentrations from mission to mission as well as from different igneous rock types collected from within an Apollo landing site. The available data for the lunar regolith shows that the majority of samples are dominated by a trapped (“solar”) component (Figure 2) as a result of their large surface/volume ratio and long surface exposure). Whereas, lunar meteorites show more of a range in trapped and cosmogenic components, likely from the varying depths they are excavated from.

Summary: Noble gas records of lunar rocks provide us with a vital tool for understanding the delivery of volatiles to the lunar surface and in most cases provide the only temporal constraints on samples analysed. Our aim is to use the database and temperature release profiles to provide an insight into the requirements for higher temperature (>1000°C) gas extraction methods on planetary missions. The database will provide a framework of the noble gas inventory of previously sampled lunar regolith that can be used and compared with future missions to the Moon.

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Figure 1. $^{36}$Ar/$^{38}$Ar (solar wind component, in cm$^3$.STP/g) verses, Antiquity age (calculated using the bulk rock ($^{40}$Ar/$^{36}$Ar)$_{SW}$ and equation 2 of [12]) for Apollo regolith samples.

Figure 2. $^{21}$Ne/$^{20}$Ne vs. $^{20}$Ne/$^{22}$Ne for >250 neon literature data points for Apollo soil, regolith breccias and drill cores. The cosmogenic (Cos) and solar end-members (SW – solar wind and ISW – fractionated solar wind) are also shown on the graph. Inset graph is a close up of the solar dominated region including ~200 of the data points.
HIGH-RESOLUTION PHOTOMETRIC OBSERVATIONS OF LUNAR SWIRLS AND FRESH IMPACT CRATERS. Brett W. Denevi¹, Aaron K. Boyd², Ryan N. Clegg-Watkins³, Bruce W. Hapke⁵, Megan R. Henriksen², Mallory J. Kinczyk⁶, Mark S. Robinson², and Hiroyuki Sato². ¹Johns Hopkins Applied Physics Laboratory, Laurel, MD 20723, USA (Brett.Denevi@jhuapl.edu). ²School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287, USA. ³Department of Earth and Planetary Sciences, Washington University in St. Louis, St. Louis, MO 63130, USA. ⁴Planetary Science Institute, Tucson, AZ 85719, USA. ⁵Department of Geology and Planetary Sciences, University of Pittsburgh, Pittsburgh, PA 15260, USA. ⁶Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, NC 27695, USA.

Introduction: Lunar swirls are high-reflectance surface features [e.g., 1,2] (Fig. 1) co-located with crustal magnetic anomalies [3]. Models for their formation include reduced or altered space weathering due to solar wind shielding [e.g., 3–7], scouring of the surface by cometary impacts to expose fresh material and/or compact the regolith [8,9], and compositional [10] or magnetic [11] sorting of the soil. Discriminating between these formation models will provide new information about the nature of lunar space weathering, magnetic anomalies, and lunar surface processes.

Past studies of lunar swirls have suggested that swirls are more forward scattering (reflect relatively more light at high phase angles) compared to fresh crater ejecta [8,12–14]. These photometric differences were interpreted as indicative of distinct physical properties for the swirl regolith such as variations in the mm-scale regolith structure or removal of fines [12–15]. Such small-scale regolith textural differences are not thought to be preserved over long periods of time, and thus this evidence has been used to suggest that swirls formed recently in lunar history. However, thermal infrared observations from the Diviner Lunar Radiometer show that swirls do not show anomalous thermophysical behavior expected for such regolith properties [7]. Here we examine new photometric observations from the Lunar Re-

Figure 1. High-phase LROC NAC observations of swirls at Reiner Gamma (top, image M1236922564, 103° phase) and Mare Ingenii (bottom, image M1227376037, 104° phase).
Discussion: Resolved photometric parameter maps of the Moon revealed that fresh highland impact crater ejecta is among the most backscattering of all lunar materials [19]. This is likely due to differences in sub-pixel scale roughness [20,21] or the presence of optically thick clasts [19], and suggests that fresh materials exposed by impacts may have distinct photometric properties due to physical properties that result from the impact process, rather than their immature nature alone. Thus impact craters may progress from highly backscattering (i.e., those that show contrast reversals in high-phase observations at the extreme end) to more typical scattering properties as they lose their distinctive textural differences through gardening. Because our modeling results suggest that swirls have scattering properties similar to non-swirl regolith, this implies they have typical regolith textures and their formation does not require a recent event to account for their photometric characteristics. These interpretations are largely based on the Firsov characteristics, and further radiative transfer modeling is underway to confirm these initial results.


Figure 2. Fresh impact craters (arrows) within the Firsov swirls seen at low (2°) phase on left, high (109° phase) on right. Top arrow shows ejecta that is higher in reflectance than surrounding regolith at low phase, but the reverse at high phase. Bottom arrow indicates ejecta that is higher in reflectance at all observed phase angles.
Lunar Oxygen: One of the major challenges of future Moon missions is the supply of the spacecraft and crews with vital resources, like water, oxygen, and rocket fuel. The in-situ production of some resources on the Moon could significantly reduce the amount of mass needed to be launched from Earth.

The most needed, and at the same time most abundant resource on the Moon is oxygen. The main problem is that oxygen release requires high temperatures due to the strong chemical bonds in the minerals. The process with the most benign operating conditions is hydrogen reduction of the titanium-iron oxide mineral ilmenite (Eq. (1)) and subsequent water electrolysis (Eq. (2)) [1]:

$$\text{FeTiO}_3 + H_2 \rightarrow \text{Fe} + \text{TiO}_2 + H_2O$$ \hspace{1cm} (1)

$$\text{H}_2\text{O} \rightarrow \text{H}_2 + \frac{1}{2}\text{O}_2$$ \hspace{1cm} (2)

Concentrated Solar Power: To date, space-flight has exclusively used PV for solar energy generation. One important reason is that thermodynamic cycles need huge additional cooling panels because radiation is the only way to get rid of the surplus heat. But if concentrated solar power were applied for reaction (1), the excess heat could be used for preheating of the reagents, be disposed of with the tailings, or even be stored and used as heat source in the lunar night.

Fluidized Bed: A chemical reactor for the lunar ilmenite-hydrogen reaction must meet several requirements, like continuous operation, the ability to heat and process large amounts of lunar regolith, a long solids residence time, and a good mixture with the gas reagent. All these conditions can be satisfied with a low expansion fluidized bed reactor. Fluidization is the operation by which solid particles are transformed into a fluid like state through suspension in a gas (or liquid) [2].

Reactor Development: The Plataforma Solar de Almería (PSA) is a research centre for concentrated solar power in the south-east of Spain. In recent years, there has been developed and assembled a solar reactor for the hydrogen reduction of ilmenite (reaction step (1)). The goal was to build a full scale reactor for testing on Earth, demonstrating solutions for as many as possible challenges it will face on the Moon.

The centre-piece of the reactor is a fluidized bed with a capacity of 25kg of lunar regolith. Feeding and removal of the solids is done in continuous mode by auxiliary fluidized pipes, completely avoiding moving parts in contact with the particles. The concentrated solar power enters the reactor vertically through a quartz window on the top, allowing direct heating of the particles without the need of a heat exchanger wall. The gas supply includes a recirculation pump, flow controllers, and the electrolyzer for reaction step (2). Special attention has been given to the off-gas treatment. This includes cooling, two-step hot gas cleaning from remaining fines, and active separation of the desired product water from the gas stream.

Despite of the complexity of the system, it can be operated by only one person due to the high level of automation of the different control features.

Lightweight Solar Concentrator: By far the biggest piece of a solar power plant is the sun-tracking and concentrating system (i.e. the mirrors). A novel design for this components has been proposed by the authors [3], consisting of a flat sun tracker (heliostat), and an off-axis parabolic concentrator combining the tasks of concentration and redirection in one piece (fig. 2). Its main advantages are that no active cooling is required and that a foldable and lightweight design seems doable. Until today, hardware has not yet been developed.
**System Testing:** Initial testing of the solar reactor was realized in three phases. The used particles are commercial terrestrial ilmenite with a grain size of 150μm. Phase 1 consisted of tests with air as fluidization gas, with the purpose to determine general behaviour of all components and to gather critical engineering data. The bed temperature was limited to 400°C to avoid possible problems with the oxygen in the gas stream. Phase 2 was executed with an inert gas (argon) as fluidization gas and is characterized by the stepwise increase of the operation temperature up to the design temperature of 900°C. At the writing of this text (Feb 2017), this phase was nearing completion. In Phase 3, hydrogen will be added carefully to the inert gas to demonstrate the desired chemical reaction (Eq. (1)). Special care will be given to guarantee that the extracted water comes really from the chemical reaction and not from other sources, e.g. hydrated minerals in the solids.

**Outlook:** After completion of the initial tests, several modifications of the feedstock are foreseen to better approach realistic lunar operation conditions. They include the increase of the hydrogen supply finally up to 100%, the use of smaller ilmenite particles to enter in a better fluidization regime (so-called "Geldart type A"), and finally to utilize a mix of the ilmenite and lunar soil simulant with a wider range of grain size to better approach the real lunar soil. Goal is to demonstrate a water production rate of 700g/h, enough to produce oxygen to breathe for a crew of eight or to be used as oxidizer for three launches per year of an Apollo-style lunar module.

Further development and research is needed to adapt the system to the lunar vacuum and the low lunar gravity. This last one requires a detailed study of the fluidization properties under 1/6 g. Finally, a thorough characterization of the real lunar feedstock is necessary, beginning with grain size and shape distribution, over processability by (gentle) milling and screening, until the possibility of ilmenite enrichment e.g. by magnetic separation. The achievable ilmenite concentration and hence the needed gross solids throughput is decisive for the power demand of the reactor, directly determining the dimensions of the concentrator. Furthermore, the presence of trace elements in the lunar soil must be taken into account to take measures to avoid or remove unwanted by-products that could accumulate in the system and/or harm the electrolyzer.

Finally, another thinkable application of this solar thermal reactor concept is the extraction of water from hydrated soil on Mars using atmospheric CO₂ as fluidization gas.

**References:**  
**Introduction:** Current European plans for a Moon Village will imply long presence of humans on the lunar surface. Further developments of technologies of the Environmental Control and Life Support System (ECLSS) are needed. It keeps the right conditions for astronauts to survive inside the Moon base. Resupply options will be more expensive than they are currently on the International Space Station, due to the larger distance. Therefore, ECLSS with technologies offering a higher closure and even higher reliability will need to be considered. A hybrid system, composed by a mixture of physico-chemical components and biological components could be a solution for such mission requirements, due to a long mission duration. An algae photobioreactor is a promising option to complement a physico-chemical system. The algae can (partially) fulfil some of the major tasks of the ECLSS: extract the carbon dioxide from the atmosphere, produce oxygen and provide nourishment. Algae major constituent are proteins. To ensure an equilibrated diet, up to 30% of the astronauts’ food could be substituted by algae. However, up to date no algae have been used for an ECLSS component in space, and therefore some previous steps are required. This presentation reviews the current state, the questions that still need to be answered and proposes tools/solutions.

**Algae for space applications:** Several algae species have been investigated in the last decades, some of them being more efficient in oxygen production, others more adequate for food production, and others convenient regarding cultivation handling etc. Species considered for space applications are particularly *Chlorella vulgaris*, *Euglena gracilis*, *Scenedesmus obliquus*, and *Spirulina platensis*. [1,2]

Short experiments with a maximum of 30 days have been carried out in COSMOS 1887, COSMOS 2044, VOSTOK, Soyuz-28, Salyut-6 and Mir. The experiments mainly focused on the investigation of photosynthesis, growth under microgravitation and higher radiation exposure. [3,4]

On the other hand, several experiments focusing on the algae as part of a closed system have been / are currently being carried out on Earth. For example, a 30 days experiment in a hermetically-sealed room with one man has been conducted by Starikovich, containing *Chlorella vulgaris* to produce oxygen and also used as part of the diet. [5] Another example is the MELISSA (Micro-Ecological Life Support System Alternative) project of ESA currently developing/testing a five compartment closed-loop system, containing a 7 litre compartment with the algae *Spirulina platensis*. [6]

**Open questions:** Even if research is being currently carried out in this field, there are still some open questions / aspects that require further investigation, before algae can be used as part of the ECLSS:

1. Long-term experience
2. Genetic stability over several generations
3. Influence by contaminants
4. Radiation effects
5. Low mass photobioreactor hardware
6. Operation under Moon gravitation
7. Sizing the system
8. Downstream processing to food

**Proposed solutions: Research at the Institute of Space Systems (IRS):**

Several projects are currently taking place at the Institute of Space Systems, that can provide information to help answering the above questions:

**Algae cultivation on the laboratory:** Since 2010, algae are being cultivated at the IRS. The selected species is *Chlorella vulgaris*, which has been investigated several times in space conditions. It is an unicellular and spherical organism with a 4-10 μm diameter. It is cultivated in a nutrient solution and its weak colony-forming and high-value nutrients make it a potential candidate for space applications. The same culture has been cultivated at IRS since 2010 in Flat Plate Airlift (FPA) reactors (6 L and 26 L) from the company Subitec. [7] The FPAs are constantly illuminated (no day/night cycle is required). Although the culture is kept as “clean” as possible, no axenic culture is used, as it makes long-term cultivation nearly impossible. CO₂-rich air is introduced in the bottom of the reactor. The rising gas bubbles mix the algae mixture and ensure the distribution of CO₂ for the whole culture. These experiments on the laboratory help gaining knowledge in long-term cultivation and occurring side contaminants.

**ISS experiment:** The FPA system requires a certain level of gravity due to buoyancy of CO₂ and air bubbles in the liquid. Therefore, a different reactor design is currently being tested, as part of the PBR@LSR project, together with Airbus Space and Defence and DLR. It is a pump-driven liquid-loop through meander design with a gas exchange membrane. The experiment to be launched to the ISS in 2018 includes all required hardware, just in a small scale, for an ECLSS photobioreactor: LEDs, sensors, pump (to make the algae circulate), a liquid exchange device (to provide nutrients, and extract algae), etc. The experiment is going to be operated for 180 days. [8] Through this experiment, the
knowledge on the hardware required and the necessary procedures for a photobioreactor for space applications is being acquired.

Figure 1. PBR@LSR sketch [9]

European Modular Cultivation System (EMCS) proposed upgrade. The IRS contributes to the EU project TIME SCALE (Technology and Innovation for Development of Modular Equipment in Scalable Advanced Life Support Systems for Space Exploration) in the frame of Horizon 2020, together with seven more consortium partners from Europe. The project’s main objective is to develop an EMCS advanced life support system breadboard and demonstrate the operational capability for the ISS. [10] The task of IRS is to provide an Algae Cultivation Compartment (ACC) design, which should allow carrying out both technology testing (life support) and biological research for algae under different gravity conditions, for example Moon and Mars. Up to 4 ACCs could be mounted at the same time in the EMCS, two per rotor. Two different ACCs have been designed: one can include up to four mini-photoreactors, to test for example different reactor designs, and the second design includes 4 “cassettes”, where algae can be cultivated on agar plates, allowing pure biological research, such as algae cell responses to darkness and/or hypoxia under µg. The first design could be used to test if the reactor currently used in the laboratory would work properly on Moon-gravity conditions.

Figure 2. TIMESCALE EMCS Algae Cultivation Compartment

Simulation tool “Environment for Life-Support System Simulation and Analysis” (ELISSA). This tool has been developed at the IRS since the mid-90s and allows the analysis and validation of new ECLSS designs as well as system optimization for different mission scenarios. The time discrete simulation tool offers a wide library of both physico-chemical and biological components. The components have been modelled using currently available reference data, either from specifications of existing technologies, experimental data or from physical/chemical fundamentals from the literature. [11] A special focus is currently being made on the photobioreactor model, implementing data obtained from the IRS laboratory data. Further results from the ISS experiment will also improve the model. For a Moon base, ELISSA can be used to size a photobioreactor and its requirements (nutrients, water, power, generated heat), for a specific crew size. Moreover, it allows the comparison of a system using ISS-like technology against a system including an algae photobioreactor. The results will give an estimate at which mission duration the photobioreactor system presents an advantage regarding system mass.

Conclusions: Algae on the Moon could provide high benefits for the ECLSS by reducing carbon dioxide, producing oxygen and edible biomass leading to mass reduction and redundancy. However, before a photobioreactor can be integrated to an ECLSS some further research is required, for example investigation of the effects of radiation or lower gravity, sizing the system or selecting the required hardware for the photobioreactor. The experiments from the Institute of Space System and current tools (the experience gained with laboratory experiments over seven years, the ISS-experiment, the EMCS proposed upgrade and an ECLSS simulation tool) can help answer some of these open questions.

**Introduction:** The geologically young, complex crater Copernicus (Figure 1a), with its laterally heterogeneous target rocks, offers a great opportunity to track the fate of different lithologies after they were (partially or completely) melted during the crater formation event. The study of impact melt deposits at Copernicus thus holds important clues to understand the impact melt emplacement and its evolution, including melt mixing (lateral & vertical). Here, we provide an integrated view of the impact melt distribution, melt mineralogical diversity and morphological character to gain insights into the cratering process, especially the impact melt systematics.

**Geologic Setting:** The geology around Copernicus crater is complex, with Imbrium basin (located towards the North) and mare deposits of Oceanus Procellarum forming the two major regional geological entities. Mineralogically, Copernicus appears to have excavated both highlands and basaltic material, the spatial distribution of which is quite non-uniform. The crater has been extensively studied by both telescopic and spacecraft datasets, highlighting several scientifically intriguing aspects of Copernicus including the presence of olivine-bearing central peaks [e.g.1, 2, 3]. Several new perspectives have been added to the understanding of Copernicus crater by recent lunar missions and include the discovery of a mineralogically-distinct impact melt feature [4], multiple origins of olivine lithology [5] and detection of Mg-Spinel lithology at Copernicus [6, 7].

Numerous mapping efforts have been carried out highlighting the major units in the area [e.g. 8, 9]. The stratigraphic sequence at Copernicus crater before impact has been suggested [8, 10] to be (from top to bottom): i) Mare Basalts, ii) Imbrium Ejecta, iii) Noritic crust, iv) Olivine-bearing lithology. We are building on these efforts and have now utilized data from modern sensors to further expand and update the knowledge of Copernicus crater, with detailed studies of the impact melt occurrences.

**Impact Melt Geologic Mapping:** Impact melt deposits at Copernicus crater have been mapped based on their morphological character on a scale of 1:25,000 (Figure 1b). The geographical extent of the mapping effort covers the crater floor and the wall. The primary data used to map the impact melt deposits is Kaguya Terrain Camera (TC) which has a spatial resolution of ~10 m/pixel [11]. We have mapped 10 impact melt associated units with significant areal coverage. The melt distribution map exhibits several interesting trends as well as spatial correlations with other crater units.

![Figure 1](image-url) Impact melt occurrences & their character at Copernicus crater. (a) LROC WAC image of Copernicus crater providing the context. (b) Geological map of impact melt deposits. (c) Location map of representative exposures of various lithologies on the crater floor.
a) The Smooth Unit (clast-poor, red) is localized in the NW quadrant which also represents the lowest elevation on the crater floor [4]. This setting indicates a possibility that perhaps melt from higher elevations on the crater floor may have drained and pooled into this region. Alternatively, the clast-poor unit may have undergone higher subsidence during cooling of the melt pile compared to clast-rich regions on the crater floor.

b) The Hummocky Unit (clast-rich, magenta) is mostly restricted to the western and the eastern regions of the crater floor. It might represent the original distribution of the clasts on the floor. Alternatively, the hummocky unit might also be the result of wall collapse during the crater modification stage.

c) The Large Blocks Unit (cyan hashed) represents relatively large and coherent, melt-coated blocks on the crater floor. Their occurrence in close proximity to the central peaks potentially suggests their genetic association (source depth) with the central peaks.

It is intriguing to note that some of these observed trends are similar to mapped impact melt units at other young craters [12] hinting at some systematics in play and therefore the hope to extract some useful geologic information from mapping of impact melt deposits.

**Mineralogical Assessment of Impact Melt Deposits:** The general mineralogical trends at Copernicus crater are well known [e.g. 13] with the northern section being more feldspathic and the southern part of the crater being more mafic (interpreted to be basaltic in nature). However, using high spatial and spectral resolution datasets from recent lunar missions, we have carried out detailed mineralogical assessment of the impact melt deposits along with their high resolution geologic context (Figure 1c).

We have identified some interesting mineralogical trends on the crater floor:

a) **Low Ca-pyroxene and Olivine-bearing lithologies Dominate in the NW quadrant.** Majority of the low Ca-pyroxene exposures are located in the NW section of the crater floor and lie within the morphologically smooth (clast-poor) melt unit (red). Some of these exposures, together with the surrounding soils, define a mineralogically-distinct impact melt unit and illustrate the heterogeneous mineralogy of impact melt deposits on large spatial scale [4].

Majority of the olivine-bearing exposures identified on the crater floor are also found to be located within the NW quadrant and within the smooth melt unit. Most of these exposures are far away from the olivine-bearing central peaks (and so may have a different source/origin [5]) and are also spatially distinct from the low Ca-pyroxene bearing exposures in the vicinity.

b) **Isolated Occurrences of Crystalline Plagioclase.** Although the northern section of Copernicus is known to be feldspathic (based on weak absorptions and relatively high albedo of the region), we could only locate two small exposures of crystalline plagioclase: in the eastern and southern parts of the crater floor. It is conceivable that the majority of feldspathic exposures have been extensively shocked and do not exhibit a crystalline absorption band.

c) **High Ca-pyroxene bearing lithology is more pervasive.** In contrast to the spatial distribution of low Ca-pyroxene and olivine-bearing exposures, high Ca-pyroxene occurs throughout the crater floor. This widespread distribution may have been caused by the large scale material movement during the cratering process. However, based on the rather systematic trends in the case of other mineralogies, we interpret the widespread exposures of high Ca-pyroxene as evidence for a more pervasive basaltic cover that extended to the north. There were likely variations in the thickness of the basaltic pile with the southern region being thicker which is also consistent with the mineralogy of the ejecta deposits.

**Summary:** The detailed mineralogical and morphological studies of impact melt deposits at Copernicus crater highlight their rich diversity and have led to the recognition of several interesting trends. The NW quadrant of Copernicus is unique from multiple perspectives, hosting the largest smooth melt accumulation on the crater floor as well as majority of the low Ca-pyroxene and olivine-bearing exposures, all located within a broad topographic low. The generally feldspathic northern section of Copernicus does not directly translate into abundant crystalline plagioclase occurrences, especially on the crater floor. The high Ca-pyroxene exposures are however, more pervasive in nature.

These trends in the mineralogy and morphology of impact melt deposits are potentially representing the pre-impact target properties. If true, these trends then suggest that despite the chaotic nature of the cratering process involving large scale movement of the melt and ejecta, impact melt properties might still be helpful in reconstructing the geologic setting before impact.

INVESTIGATING THE NATURE OF CRYSTALLINE AND SHOCKED ANORTHOSITE ON THE MOON. K. L. Donaldson Hanna¹, E. R. Bamber², N. E. Bowles¹, J. T. S. Cahill³, B. W. Denevi¹, and B. T. Greenhagen¹. ¹Atmospheric, Oceanic and Planetary Physics, University of Oxford, Oxford, UK (KerridonaldsonHanna@physics.ox.ac.uk), ²Department of Earth Sciences, University of Oxford, Oxford, UK, and ³Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA.

Introduction: The surface of the Moon provides evidence of a long history of bombardment in the inner solar system, from the multi-ring basins that dominate the nearside down to millimeter-scale craters due to micrometeorite impacts. Early telescopic observations and orbital measurements of the lunar surface at lower spatial resolutions identified exposures of material within craters and basins thought to be evidence of the primary anorthositic crust that had been shocked during the impact process [e.g. 1-3]. These identifications were based on observations of high albedo regions with featureless near infrared (NIR) spectra, which are characteristics believed to be consistent with shocked or non-crystalline plagioclase (the dominant mineral phase in anorthosite). However, recent high spatial (20 to 500 m/pixel) and high spectral resolution (9 to 296 spectral bands) remote observations have confirmed the presence of pure, crystalline anorthosite in those same regions using the diagnostic absorption band near 1.25 μm indicative of crystalline plagioclase in these regions [e.g. 4-7]. While the spectrum of crystalline plagioclase has a diagnostic absorption band, the strength of this band can be weakened by at least two known surface processes (1) space weathering and (2) shock metamorphism [e.g. 1, 2, 6, 7]. This results in a spectrum nearly devoid of its initially observed absorption feature.

As multiple processes can remove the diagnostic NIR absorption of plagioclase, shocked anorthosite cannot be unambiguously identified based solely on NIR spectra. Recent investigations [6, 8, 9] have used a combination of the high spatial and high spectral resolution Moon Mineralogy Mapper (M³) data along with geologic context from the Kaguya/SELENE Terrain Camera and Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC) to identify shocked anorthositic blocks of material within the central peak of Theophilus crater and the Inner Rook Mountains of Orientale Basin. In addition, Denevi et al. [10, 11] recently demonstrated that crystalline anorthositic material could be distinguished from shocked and/or melted anorthositic materials across ultraviolet (UV) wavelengths in laboratory measurements and in global observations of the Moon by the LROC Wide Angle Camera (WAC). However, a detailed investigation into the observed characteristics of shocked anorthosites across a wide spectral range has yet to be completed. In this initial investigation, we combine remote sensing observations across a wide spectral range, from UV through thermal infrared (~0.3 to 25 μm; TIR) to characterize shocked anorthositic material in impact craters and basins on the Moon.

Figure 1. LROC WAC and NAC images of Theophilus crater (11.4° S, 26.4° E; A, B, and C) and M³ spectra (D and E). Red pixels and spectra highlight crystalline anorthosite units and green pixels and spectra highlight shocked anorthosite units.

Figure 2. LROC WAC spectra extracted from crystalline anorthosite (red) and shocked anorthosite (green) regions that were identified in M³ data (Figure 1).

Data and Methods: This initial study integrates M³, LROC, and Diviner Lunar Radiometer (Diviner) observations for Theophilus and Jackson craters as well as Orientale Basin. Level 2 M³ reflectance data across the 0.4 – 3.0 μm spectral range for each optical period (OP) are utilized to prepare color composite maps using integrated band depths (IBD) at 1 μm, 1.25 μm, and 2 μm to highlight areas spectrally
dominated by mafic minerals (e.g., pyroxene and olivine) and crystalline plagioclase [e.g., 6, 7]. M3 spectra are extracted for relatively high and low 1.25 µm IBD areas to confirm the presence of crystalline plagioclase-rich units and possible shocked units with featureless NIR spectra, respectively.

Seven-band LROC WAC UV mosaics are used in the investigation of each crater and Orientale Basin. Color composite images utilize 321 nm/415 nm and 321 nm/360 nm ratios thought to highlight different spectral features of crystalline and shocked and/or melted anorthosite [10, 11]. Spectra are extracted for regions with (1) high 321 nm/415 nm and low 321 nm/360 nm values and (2) low 321 nm/360 nm and low 321 nm/415 nm values to confirm the identification of crystalline anorthosite and shocked and/or melted anorthosite regions, respectively. To assess the nature of each anorthosite lithology WAC observations are compared with M3 observations.

Finally, Diviner four-band TIR emissivity spectra and Christiansen Feature (CF) maps over each crater and Orientale Basin are derived from Diviner daytime radiance data. Data are binned and averaged at 128 pixels per degree and converted to emissivity spectra and CF maps as described in [12]. During this process, Diviner emissivity spectra and CF positions are corrected for local lunar time, latitude, and topography [13]. Additionally, the space weathering correction of Lucey et al. [14] is applied to remove the albedo effects caused by maturity. These are then used to characterise the TIR spectral changes due to shock by comparing with WAC and M3 analyses.

**Results:** Here we initially focus on Theophilus crater as portions of the central peak were previously analyzed in detail and observed to have units of shocked and crystalline anorthosite [8, 9]. As seen in Figure 1, the northeastern part of the central peak shows clear distinction between the crystalline (red pixels) and shocked (green pixels) lithologies.

As seen in Figure 2, WAC spectra were extracted from the areas identified as shocked anorthosite using M3 data. These UV spectra show a downturn at 415 nm thought to be characteristic of shocked anorthosite, although the up-turn at 360 nm is unlike lab spectra of shocked samples which continue to steepen relative to mature highlands spectra [10, 11]. WAC spectra taken from areas identified as crystalline anorthosite in M3 are slightly different from their corresponding lab spectra and spectra of crystalline areas in other craters, with a down-turn starting somewhere between 360 and 415 nm for Theophilus as opposed to at 360 nm for lab spectra [10, 11]. Better spectral resolution is required to confirm that this is a real difference.

After comparison to the WAC color composite map it appears that the disparities may simply be due to the comparatively lower spatial resolution in WAC compared to M3 data (400 m/pixel vs. 140 to 280 m/pixel, respectively), which leads to poor sampling over each area, obscuring features in the acquired spectra. The size of specific areas identified as either shocked or crystalline anorthosite is relatively small adding to the difficulty. Closer observation of the WAC color composite map does indicate small (<5 pixel) clusters of crystalline anorthosite in the same areas as those identified by M3 (with spectral features of these areas closely matching those obtained from laboratory spectra of crystalline anorthosite samples [10, 11]).

Diviner CF data for the central peak of Theophilus crater shows no obvious difference in CF values for shocked and crystalline anorthosite units as identified in the M3 and WAC data. These initial results corroborate earlier laboratory studies that showed no change in the CF position as anorthositic materials were shocked to varying degrees of pressure [e.g., 15, 16].

**Future Work:** Future work will focus on the integrated analyses of Jackson crater and Orientale Basin to begin to characterize shocked anorthosites across a wide spectral range (UV, NIR and TIR). In addition, detailed characterizations are needed to understand the general distribution of shocked anorthositic materials within impact craters and basins, especially in relation to the distribution of crystalline anorthositic material. Understanding this distribution of shocked materials will provide a better understanding of impact induced shock systematics in materials on planetary surfaces, our natural laboratory.

**References:**

THE LUNAR ROCK SIZE FREQUENCY DISTRIBUTION FROM DIVINER INFRARED MEASUREMENTS. C. M. Elder and P. O. Hayne, Jet Propulsion Laboratory, California Institute of Technology (Catherine.Elder@jpl.nasa.gov).

Introduction: The main process that currently modifies the lunar surface is bombardment by meteorites [1], which breaks bedrock and rocks of all sizes into smaller rocks and eventually regolith. Rocks on the lunar surface today offer a snapshot of this process. Understanding the current lunar rock population can inform studies on regolith formation and evolution and the formation mechanisms of different geologic units. Additionally, quantifying the rock population at a proposed landing site is a critical step in assessing the probability of a safe landing.

Currently, surface rock populations are determined using visible imagery or multispectral thermal infrared data. Visible imagery can be used to count rocks to determine their abundance and size distribution. The Lunar Reconnaissance Orbiter Camera (LROC) has a resolution of 0.5 m/pixel [2], but a definitive detection of a rock requires that the rock span at least 2-3 pixels, so LROC cannot typically detect rocks smaller than 1 m across. Multispectral thermal infrared data has been used to measure the rock abundance (the percent of a surface occupied by rocks) [3]. This is possible because rocks and regolith have different thermal inertias; fine grained regolith has a low thermal inertia and cools quickly after sunset, whereas coherent rock has a high thermal inertia and remains warmer than regolith throughout the lunar night. Warm temperatures have a stronger effect on radiance at shorter wavelengths, so observing a planetary surface at multiple wavelengths enables the detection of sub-pixel rocks. [4] leveraged this anisothermality by using a 1D model to calculate expected rock temperatures and solve for the regolith temperature and rock abundance that best matches Diviner observations of the Moon. However, a 1D rock temperature is essentially that of an infinite slab of rock, and in reality, small rocks are able to cool faster than large rocks. [4] estimate that temperature calculated from a 1D model should be appropriate for rocks larger than 1 m. Therefore, there is currently no remote sensing method that is able to detect rocks smaller than 1 m on the surface of the Moon. Here, we present preliminary results from a new method using multispectral thermal infrared observations throughout the lunar night to measure the lunar rock size frequency distribution including rocks down to the centimetre scale.

Methods: We map the lunar rock size frequency distribution by 1) modelling the temperature of rocks of different sizes (instead of applying results from a 1D model to all rocks); 2) making an initial guess for the rock size frequency distribution and generating a model radiance; and 3) comparing this model radiance to Diviner observations and performing a least-squares fit to find the best fit rock size frequency distribution for each Diviner pixel. We use COMSOL Multiphysics, a finite-element commercial software package, to conduct 3D thermal modelling of rocks of different sizes and at different latitudes. For our preliminary results, we have modelled rocks with diameters of 1 cm, 10 cm, and 1 m (Figure 1), but we plan to model a total of six different rock sizes. We assume that the size frequency distribution of lunar rocks follows an exponential function:

\[ F(D) = ke^{-qD} \]

where \( F \) is the cumulative fractional area covered by rocks of size \( D \) or larger, \( k \) is the total fractional area covered by rocks, and \( q \) governs the rate of drop-off at large rock sizes. This has been shown to yield a good fit to the size-frequency distribution of rocks at locations on both Mars, Earth [5] and the Moon [6], and it is expected from fracture and fragmentation theory [5]. Using model rock temperatures, model regolith temperatures, and an initial guess for the rock size frequency distribution \( k \) and \( q \), we produce a model radiance for Diviner channels 6, 7, and 8 at ten different times during the lunar night. We then compare the modelled and measured radiance and solve for the best fit values for \( k \) and \( q \).

Preliminary Results and Discussion: Our preliminary results (calculated from model temperatures of 3 rock sizes) are shown in Figure 2. shows both the rock abundance \( k \) map and a map of the rock size frequency distribution parameter \( q \). These results were calculated using data binned to a low resolution for faster computation times; a higher resolution will be used in future work. In contrast to previous work [4], we find local areas of high rock abundance in both the maria and highlands. This suggests that the new technique successfully detects rocks smaller than possible with previous methods. Rocks as small as 10 cm can pose a threat to landing safely.
on the Moon, so this new technique will be helpful in selecting safe landing sites for future lunar missions.

Although we don’t see a maria/highlands contrast in the rock abundance map, we do see a contrast in the $q$ map. The maria have a lower $q$ which suggests they have more large rocks compared to the highlands. This is expected, because the regolith layer is thinner on the maria than the highlands [7], so a larger fraction of impactors are able to penetrate the regolith layer and eject rocks from the bedrock below.

**Future Work:** Thus far, we have only modelled the diurnal temperature curves for three rock sizes. Including temperatures representing more rock sizes should increase the accuracy of the rock size frequency distribution fit, so we will conduct 3D thermal modelling for at least three additional rock sizes to ensure that we are able to capture the actual shape of the rock size frequency distribution. We will validate our results using visible imagery from both LROC and lunar landers such as Surveyor or Apollo.


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*Figure 2*: The rock abundance map (top) and the rock size frequency distribution parameter $q$ map (bottom) where a higher $q$ indicates relatively fewer large rocks. The magenta lines denote the boundary between the highlands and the maria. Note that these results use data binned to a low resolution for a faster computation time.
ATOMOSPHERIC OCCULTATION OBSERVATION FROM SCIENTIFIC SATELLITE TO MOON-BASED PLATFORM. Cheng Fan\textsuperscript{1,3}, Yong Xue\textsuperscript{1,2}, Jie Guang\textsuperscript{1}, \textsuperscript{1}State Key Laboratory of Remote Sensing Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing 100094, China chengfjane@163.com, \textsuperscript{2}Department of Electronics, Computing and Mathematics, College of Engineering and Technology, University of Derby, Kedleston Road, Derby DE22 1GB, UK vx9@hotmail.com, \textsuperscript{3}University of Chinese Academy of Sciences, Beijing 100049, China.

Introduction: Atmospheric Occultation observation technique has been explored during Stratospheric Aerosol Measurement (SAM) which was carried out on Nimbus-G satellite in 1978. It is a kind of cutting chip on the atmosphere detection with high spatial coverage and high vertical resolution. The solar occultation technique has been first reported in the study of stratospheric aerosols by McCormick\textsuperscript{1}. The use of the stellar occultation technique in space has been reviewed by Smith and Hunten in 1990\textsuperscript{2}. The advantages of occultation observation technique are obtained from a relative measurement without the necessary of an absolute calibration of the instrument and the altitude of the measurement can be known only from the position of the spacecraft not the pointing of the instrument\textsuperscript{3}.

Occultation technique has been used to the Global Ozone Monitoring by Occultation of Stars (GOMOS)\textsuperscript{4} for monitoring of ozone and other trace gases in the Earth’s middle atmosphere\textsuperscript{5}. Spectroscopy for the Investigation of the Characteristics of Atmosphere of Mars (SPICAM) is the first instrument orbiting a planet other than Earth that is dedicated to the technique of stellar occultation. From the more than 500 star occultations observed by SPICAM, vertical profiles of CO2, ozone, and dust/clouds/aerosols have been yielded \textsuperscript{6}. Atmospheric Occultation observation obtained certain effect in the research of the atmospheric profile and other atmospheric phenomena, which makes it become a hot topic.

With the development of the aerospace Earth observation technology, a large number of atmosphere, ocean and land data with high accuracy and high space-time resolution can be obtained. The space borne platforms show great power in description of some large scale atmospheric, oceanic and terrestrial phenomena. In recent years, the understanding of the Earth has becoming more and more important, especially the Earth needs to be researched as a whole when dealing with global geoscience problems\textsuperscript{7}. There are still a lot of limitations in term of time and space for the scientific satellites, although the satellite data is more and more comprehensive. Therefore, finding a stable and long-standing platform to improve the capability in large scale earth observation is necessary.

The moon has many unique advantages in wide swath, continuous observation and large effective coverage which contributes to the monitoring and understanding of global change. Moon-based platform can make it possible for a long integral time and broader field of vision because of the longer distance between the earth and the moon, compared with the scientific satellite orbit heights. As the natural satellite of the Earth, the moon with a stable geologic structure and a large loading capacity can provide a stable observation for the accurate measurement and a group of different sensors can be placed on the moon, which helps to collect the data from ionized layer to Earth’s surface or even subsurface under the same imaging condition. The absence of an appreciable lunar atmosphere, avoiding atmospheric distortions and permits observations with a spatial resolution limited solely by the telescope size and without limitations on spectral coverage\textsuperscript{8}. The lifetime of lunar observation is much longer than that of scientific satellites, which is necessary for the global change research.

Moon-based atmospheric occultation technique can get a longer observation time, so as to improve the resolution of atmospheric direction along the profile with a greater range of observation. Airglow is the faint glow of the upper atmosphere, which can be seen in the whole world. Time and space distribution of airglow is affected by atmospheric gravity waves, tidal waves, planetary wave and other atmospheric dynamics process. Moon-based occultation technique could be used for upper atmospheric complex physical process research and even the earth large-scale scientific phenomena. This paper mainly discusses the advantages and the potential applications of the atmospheric occultation observation from the moon-based platform. Based on the study of the existing occultation algorithm of the scientific satellite, we are going to develop a moon-based atmospheric occultation observation model. Since there is difficult to carry out the experiment on lunar surface to obtain continuous real data, making simulation is a powerful tool on this research.

References:

\textsuperscript{1} W. P. Chu, and M. P. McCormick, “Inversion of stratospheric aerosol and gaseous constituents from spacecraft solar extinction data in
the 0.38-1.0-microm wavelength region,” *Applied optics*, vol. 18, no. 9, pp. 1404-13, 1979.


MOON VILLAGE ACTIVITIES. B. H. Foing1,2 & Moon Village Collaborators*, 1ESA ESTEC, 2ILEWG International Lunar Exploration Working Group (Bernard.Foing@esa.int)

Summary: We give an update of Moon Village activities and events that took place in 2016 and early 2017. The Moon Village is an open concept proposed by ESA DG with the goal of a sustainable human and robotic presence on the lunar surface as an ensemble where multiple users can carry out multiple activities. [1-3].

Why a Moon Village?
Multiple goals of the Moon Village include planetary science, life sciences, astronomy, fundamental research, resources utilisation, human spaceflight, peaceful cooperation, economical development, inspiration, training and capacity building.

How did the Moon Village start?
ESA director general has revitalized and enhanced the original concept of Moon Village discussed in the last decade. Space exploration builds on international collaboration. COSPAR and its ILEWG International Lunar Exploration Working Group (created in 1994) have fostered collaboration between lunar missions [4-8]. A flotilla of lunar orbiters has flown in the last international lunar decade (SMART-1, Kaguya, Chang’Eal1 &2, Chandrayaan-1, LCROSS, LRO, GRAIL, LADEE). Chinese Chang’E 3 lander and Yutu rover, and upcoming 2017 other landers from 2017 (GLXP, Chang’E 4 & 5, SLIM, Luna, LRP) will constitute a Robotic Village on the Moon.

Fig 1: a possible step towards the Moon Village using robotic with 3D printing to consolidate inflatable domes against radiation and meteorites before the arrival of astronauts

Relevant Moon Village MV activities 2016 & 2017
A number of Moon Village talks and/or interactive jam sessions have been conducted at International workshops and symposia 2016 and early 2017:
-Paris IAF/COSPAR/IAA spring meetings [16]
-Colorado Springs Space Symposium [17]
-Vienna EGU European Geoscience Union [18]
-Hague/ESTEC European Lunar Symposium [19]
-NASA Ames, Exploration Science Forum [20]
-Turkey, COSPAR, cancelled, abstracts online [21]
-Guadalajara, IAC Intl Astronautical Congress [22]
-Maryland LEAG (1-3/11) [23]
-Oxford U, History of the Moon (19/11) [25],
-Cranfield U, Symp. on Manufacturing 2075 (7/12) [26]
-Moon Village talks and activities at ESTEC Open day [27]

Fig 2: enthusiastic public endorsing the Moon Village concept after a talk given during ESTEC open day, and asking to become Moon Villagers

Moon Village Workshops at ESA Centres
Since 2015 Moon Village Workshops were held at ESA centres:
-EAC/DLR/ESTEC workshops + Eifel area campaigns: Aug 2015 [33], Nov 2015 [34], Feb 2016 [35], Dec 2016 [36]

They were held with senior experts as well as Young ESA professionals to discuss general topics and specific issues (habitat design, technology, science and precursor missions; public and stakeholder engagement). Many workshops were complemented with ILEWG EuroMoonMars simulation campaigns.
Moon Village workshops with community
Moon Village Workshops or Jam sessions were also conducted at international symposia or in collaboration with specific universities or institutes:
- TodaysArt Moon Village workshop, ars science performance ESTEC/The Hague 19-23 Sept [38],
- VU Amsterdam/ESTEC 23 Nov-11 Dec [39],
- ArtScience The Hague/ESTEC 7-18 Nov [40],
- Stuttgart Architecture 18 Nov 2016 & 10 April 2017[41],
- W de Kooning Acad. (Applied Arts) Rotterdam Dec 16 [42],
- Rotterdam, Finance experts/ESTEC [43],
- Utrecht, Water Management Urban Planning Experts [44]
- King of Moon Village ESTEC/WdKA (Feb, 2017)

Perspectives for Moon Village
A number of Moon Village activities are planned for the near and long term future. “The Moon Village will rely both on automatic, robotic and human-tended structures to achieve sustainable moon surface operations serving multiple purposes on an open-architecture basis. This initiative should rally all communities (across disciplines, nations, industries), and could make it to the top of the political agendas as a scientific and technological undertaking but also political and inspirational endeavour of the XXI century.”

*Acknowledgements: We thank Prof J. Wöerner (ESA DG) for energizing the concept of Moon Village. We thank co-conveners of Moon Village Workshops and ILEWG EuroMoonMars field campaigns in 2016 (including C. Jonglez, V. Guinet, M. Monnerie, A. Kleinschneider, A. Kapoglou, A. Kołodziejczyk, M. Harasymczuk, I. Schlacht, C. Heinicke, D. Esser, M. Grulich, T. Siriguët, H. Vos, M. Mirimo, D. Sokolsky, J. Blamont) and participants to these events. We thank A. Cowley, C. Haigeré, P. Messina, G. Ortega, S. Cristoforetti, ESA colleagues involved in Moon Village related activities. We thank colleagues from ILEWG, Young Lunar Explorers, the International Lunar Decade Group, the Moon Village Association and Moon Village International Support Group and “Moon Villagers” at large.

References
[17] https://www.spacesymposium.org/
[20] https://fels2016.arc.nasa.gov/
[21] https://mesf2016.arc.nasa.gov/
[22] https://www.cospar-assembly.org/abstractcd/COSPAR-16/
[26] http://www.stx.ox.ac.uk/happ/events/history-moon
[27-36] Moon Village talks & workshops at ESA Centres
[37-44] Moon Village workshops organised with community
FORMATION OF IMPACT BASINS ON THE MOON – INSIGHTS FROM NUMERICAL MODELLING, GRAVITY AND REMOTE SENSING DATA. T. Fröchtenicht¹, K. Wünneemann¹ and Meng-Hua Zhu², ¹Museum für Naturkunde, Leibniz Institute for Evolution and Biodiversity Science, Invalidenstr. 43, 10115 Berlin (Tomke.Froechtenicht@mfn-berlin.de), ²Space Science Institute, Macau University of Science and Technology, Taipa, Macau (mhzh@must.edu.mo).

Introduction: The surface of the Moon was shaped by large-scale impact basins. 50-60 of such basins are identified with well-preserved morphologies but there might be more structures hidden under the present landscape. Besides the present-day morphology as the most prominent feature of large basin structures, such impact events also significantly altered the gravity field (so-called mascons), affected the local petrography, and the thermal history of the Moon ([1], [2], [3]). The formation of impact basins is influenced by target properties (e.g. crustal thickness and thermal gradients in crust and mantle) and most obviously by the size, composition (mass), and velocity of the impactor. In previous studies lunar impact basins have been investigated (e.g. [1], [4], [5], [6]) to obtain a better understanding of the formation and subsequent evolution as a function of varying target conditions.

In particular, detailed gravity data from the GRAIL (Gravity Recovery and Interior Laboratory) mission provide further insight and additional constraints on the formation mechanism ([7], [8]). High-resolution topography data, gathered by the LOLA (Lunar Orbiter Laser Altimeter) instruments, constrain the crater morphology and yield new estimates about the ejecta thickness ([6]).

In this study, the Orientale basin is used as the benchmark for further systematic numerical modelling studies of all impact basins on the Moon. With respect to the ejecta distribution, based on morphological data sets, a formation model of Orientale has been developed ([6]). The simulation predicts an impactor of 100 km in diameter and a velocity of 12 km/s. Alternatively, the study of [9] focuses on the subsurface structure, especially in the area of Orientale’s rings. The two separate modelling approaches differ in terms of the assumed kinetic energy of the impactors: Zhu et al. ([6]) assume twice kinetic energy than Johnson et al. ([9]) propose. For an impact velocity of 12 km/s and a density of the impactor of 3314 kg/m³, this difference corresponds to a difference in impactor diameter of 100 km versus 74 km. A lower kinetic energy results in a smaller transient crater size and, thus, a smaller amount of ejected material. In other words, less kinetic impact energy results in a thinner ejecta blanket in the vicinity of the Orientale basin.

In this study, we aim to the development of a new model that satisfies both observational constraints, including the ejecta distribution and subsurface structure based on the gravity data. In addition, we will quantify the deposition of ejecta and the production and distribution of impact melt.

Methods: We use the iSALE2D shock physics code ([10], [11]), a further development of the SALE hydrocode ([12]) to simulate the formation of large basins. We considered Orientale Basin as a test case, using parameters from previous simulations ([5], [6]). The crust consists of gabbroic anorthosite, mantle and projectile of dunite. As Orientale is located at the boundary of the lunar highlands, we considered a 40 km and 60 km thick relatively cold crust ([6]).

As observational constraints we use topographic data from LOLA and Bouguer gravity from GRAIL. Furthermore, a crustal thickness model ([13]), based on GRAIL gravity data, is used in our model.

Results: In a first step we have modelled the formation of the Orientale basin consistent with observational constraints such as the present day morphometry (e.g. rim/ring structures), the gravity field (mass concentrations in the bedrock), and the thickness of the ejecta deposits as a function of distance to the crater. Our model confirms the previous estimates, also based on iSALE simulations ([6]), that a 100 km diameter body impacting the lunar surface at 12 km/s formed the Orientale basin. The alternative model [9], also based on iSALE simulations, with a 74 km diameter projectile has a significantly smaller transient crater and the ejecta distribution does not match the observed decrease of the thickness of the ejecta blanket with distance.

Fig. 1 shows a cross section through the 100 km-diameter-impactor model running from the crater centre up to a radius distance of 600 km. Fig. 1(a) presents the Bouguer gravity profiles from the model (model response, \(g_{\text{model}}\)) and the measurements from GRAIL (\(g_{\text{GRAIL}}\)). From Fig. 1(a), we can find that the Bouguer gravity reaches its maximum in the centre of the crater caused by mantle material coming close to the surface. Low mantle densities in the crater’s centre correspond to high temperatures in the upwelling mantle (Fig. 1(b), 1(c)). The low-density crustal layer can explain lower Bouger anomalies at distances > 350 km. The general trend of calculated Bouger anomalies follows the shape of the GRAIL measurements.

The red and green lines in Fig. 1(b) and Fig. 1(c) show observed topography data and the crustal thickness model based on GRAIL data. The crustal thickness model agrees with our model for distances > 350 km, where relatively little deformation occurs during the impact. However, in the central part our
model significantly deviates from the crustal thickness model ([13]).

Discussion and Outlook: Our model can be improved regarding the fit of Bouguer anomalies to GRAIL data. Especially in the centre of Orientale ($r = 0$ km) and where the upwelling mantle covers the crustal slab ($r = 200-300$ km) our model suggest much more complex structural deformation than that can be inferred from the crustal thickness model. Our model predicts a slab, dipping towards the crater centre and ending at a depth of 70 km in the mantle, whereas the crustal model predicts a crust becoming thinner towards the crater centre and overlay the crater with a thickness of ca. 10 km (Fig. 1(b)).

The alternative model with a lower kinetic energy and a projectile diameter of 74 km shows a better agreement with the crustal thickness model according to [9], but cannot explain the observed ejecta thickness. We consider the amount of ejecta as the best measure of transient crater size and, thus, impact energy, which rules out the low-impact-energy model. Better agreement with the gravity data for the higher-impact-energy model (100 km diameter impactor) may be achieved by considering dilatancy and adjusting other target properties. We are currently running a suite of models to test the effect of a range of target parameters to minimize the discrepancy between model and observation constraints.

As a further study, we will use tracers to record the thermodynamic conditions in the target material and to quantify the emplacement of ejecta.

The resulting, improved model for Orientale will be the basis for studying all basins on the Moon. Modelling of the entire basin record will also contribute to our understanding of the thermal evolution of the Moon.

Introduction: Lunar volcanic glasses (LVGs) collected during the Apollo missions represent one of the key samples for investigating the isotopic composition and origin of water trapped in the Moon's interior [1-4]. However, the hydrogen (D/H) isotope signature of the LVGs has been modified during their exposure at the lunar surface for millions of years as a result of solar wind (SW) implantation and cosmic ray induced spallation reactions, triggered by high-energy galactic (GCR) and solar cosmic rays (SCR) that can penetrate lunar matter to depths of several meters and a few centimeters, respectively. Secondary ionization mass spectrometry (SIMS) offers a means for analyzing hydrogen isotopes in the interior of the glass beads, away from the rim that contains implanted SW-derived hydrogen. Nonetheless, the proportion of cosmogenic deuterium needs to be assessed in order to derive the D/H ratio of indigenous lunar water, and, ultimately, to compare lunar hydrogen isotope signatures with those of potential Solar System sources (solar, terrestrial, chondritic, cometary). Therefore, knowledge of the cosmogenic deuterium production rate \( P_D \) at the Moon's surface is critical if the D/H ratio is to be used as an indicator for the origin(s) of water.

Analytical approach and results: We have recently re-evaluated the lunar \( P_D \) value through SIMS analyses of hydrogen isotopes in olivines from eight Apollo 12 and 15 mare basalts [5, 6]. These in situ measurements were complemented by \( \text{CO}_2 \) laser extraction static mass spectrometry analyses of cosmogenic noble gas nuclides (\( ^{3} \text{He}, ^{21} \text{Ne}, ^{38} \text{Ar} \)) in bulk rock fragments in order to obtain new estimates of the cosmic ray exposure (CRE) ages of the basalts. Based on the \( ^{21} \text{Ne}_{\text{cosm}} \) production rate modeled by Leya et al. [7], the studied mare basalts cover a wide range of CRE ages between 60 and 422 Ma. The D ion intensities measured on the olivines show a clear increase with increasing CRE ages. This is interpreted as evidence for the in situ production of cosmogenic D by cosmic ray induced spallation reactions during exposure at the Moon’s surface. The linear relationship between the D concentrations and the CRE ages is consistent with an average \( P_D \) value of \( 2.2 \times 10^{-12} \) mol (g rock)\(^{-1} \text{Ma}^{-1} \) for the past few hundreds of million years. This value is more than twice as high as the previous estimates for the GCR production of D in lunar basalts [8, 9].

Discussion: For water-rich olivine-hosted melt inclusions [3], as well as for the many mare basalt apatites with water concentrations ≥1000 ppm [10], the new \( P_D \) value has virtually no effect on the corrected hydrogen isotope ratios. In contrast, our findings imply that for water-poor lunar samples such as the LVGs [3, 4], the proportion of cosmogenic D has been severely underestimated. When the new \( P_D \) value is applied, the corrected D/H ratios of 74002 LVGs are no longer consistent with an \( \text{H}_2\)-degassing process [4]; instead, the hydrogen isotope signatures of the ‘orange’ Apollo 17 LVGs and olivine-hosted melt inclusions can be explained by mixing of solar hydrogen and isotopically heavier lunar water with a \( \delta D \) value on the order of \( +250 \pm 70 \% \). The hydrogen inventory of the ‘driest’ or most-degassed glass beads is dominated by the solar component, possibly due to rapid inward diffusion of hydrogen implanted at the grain surface by the SW, or, alternatively, assimilation of SW-derived hydrogen from the lunar regolith or exosphere by the erupting melt.

Conclusions: The primitive high-Ti Apollo 17 LVGs and olivine-hosted melt inclusions point to a \( \delta D \) value of \( +250 \pm 70 \% \) for water in the lunar mantle source, provided that they retain the original pre-eruptive isotope ratio. This value is consistent with a carbonaceous chondrite heritage [11]. Alternatively, the D/H signature of the lunar mantle may have been fractionated from an originally Earth-like composition as a result of volatile loss during formation and differentiation of the Moon [12].

Our new estimate of \( P_D \) [5] can be used to correct the D/H ratio of ‘water’ trapped within mafic samples that have been exposed to cosmic ray irradiation within the upper ~10 cm of planetary surfaces lacking atmospheric shielding and magnetic field protection. It is not appropriate for deriving the proportion of cosmogenic D in apatite. Given that the production rate of cosmogenic D is a function of the chemical composition (i.e., the abundance of the target elements O, Mg, Al, Si, Fe [8]), the \( P_D \) value would be significantly lower in apatite than in olivine.

DIVINER LUNAR RADIOMETER HIGHLIGHTS FROM THE LRO CORNERSTONE MISSION.
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Introduction: After nearly eight years in operation NASA’s Lunar Reconnaissance Orbiter (LRO) Diviner Lunar Radiometer (Diviner) continues to reveal the extreme nature of the Moon’s thermal environments, thermophysical properties, and surface composition. Diviner is the first multispectral thermal infrared instrument to globally map an airless body with relatively high spatial and temporal resolution. Thus Diviner observations form a cornerstone of thermal infrared studies of the Moon and airless bodies with important considerations for future datasets from the Moon, Mercury, small bodies, and icy satellites.

Diviner Lunar Radiometer: To date, Diviner has acquired observations over 15 complete diurnal cycles and 7 seasonal cycles. Diviner daytime and nighttime observations have essentially global coverage, and more than 85% of the surface has been measured with at least 8 different local times. Diviner’s extended operations have also enabled observations of the lunar surface with a wide range of viewing geometries. The spatial resolution during the mapping orbit was ~200 m and now ranges from 150 m to 1300 m in the current elliptical orbit. Calibrated Diviner data and maps of visible brightness, temperature, rock abundance, nighttime soil temperature, and silicate mineralogy are available through NASA’s Planetary Data System Geosciences Node.

Diviner was designed to accurately measure temperatures across a broad range from midday equatorial regions such as the Apollo sites (around 400K), typical nighttime temperatures of less than 100K, and extreme permanent shadowed regions colder than 50K. The coldest multiply-shadowed polar craters may have temperatures low enough constrain lunar heat flow [1]. Nighttime temperatures are driven by the thermophysical properties, including rock abundance and soil thermal inertia, which are used to investigate impact crater formation and evolution processes [2]. Multichannel infrared spectroscopy can constrain silicate mineralogy, including compositional heterogeneity in the lunar crust [3]. In addition to lunar properties, during the current LRO Cornerstone Mission (CM), we use new observation campaigns to characterize thermal emission behaviour fundamental to airless bodies with fine-particulate surfaces, including epiregolith thermal gradients and thermal-scale surface roughness.

Cornerstone Mission: With a vast dataset of nadir-pointing diurnal data on hand, we now look to use Diviner’s spacecraft-independent gimballing capabilities to make special regional and global observations. Approximately half of Diviner data from the CM are one of four types of special observations: Lunar eclipse, twilight campaigns, targeted off-nadir EPFs, and global off-nadir campaigns.

Lunar Eclipses. The sharp thermal pulse associated with lunar eclipse provides the best opportunity to study the thermophysical structure of the upper few cms on the regolith. However, eclipses are infrequent and observations are limited to areas around the LRO ground track. During the CM, we will observe one partial eclipse on 7 August 2017 and two total eclipses on 31 January 2018 and 27 July 2018.

Twilight Campaigns. While there are limited opportunities to view lunar eclipses, all areas on the Moon experience similar rapid temperature drop immediately after local sunset. However, this analysis requires very high temporal density coverage across lunar “twilight.” During the CM, we will target ROIs for repeated observation on adjacent orbit tracks (~4 lunar minutes apart) during the 17:45 to 18:45 time period. The LRO orbit affords us opportunities to make these measurements nearly globally and in many areas there are multiple opportunities.

Targeted Off-Nadir EPFs. The lunar surface is both very rough and highly insulating on scales of mm to cm, which produces range of temperatures (anisothermality) within any scene [4]. To fully characterize this behaviour requires multispectral thermal infrared observations with systematically varying viewing and illumination geometries. This improved understanding of the emission phase function (EPF) will feed directly into models of heat transfer on airless bodies and volatile transport and sequestration. During the CM, we will measure EPFs for ten representative targets.

Global Off-Nadir Campaigns. During the CM we will produce global maps with approximately 50 degree emission angles, both low and high phase at eight different local times (four day and four night). These data compliment an existing 70 degree emission angle, low phase campaign and enable an extension of the targeted EPF science to global scales.

Summary: This presentation will focus on recent Diviner results addressing a diverse range of scientific questions and will highlight exciting new observations from LRO’s Cornerstone Mission.

BEHAVIOUR OF THE NEAR-INFRARED WATER/OH ABSORPTION DEPTH AT THE LUNAR SWIRL REINER GAMMA. A. Grumpe1, C. Wöhler1, A. A. Berezhnoy2, V. V. Shevchenko2, 1Image Analysis Group, TU Dortmund University, Otto-Hahn-Str. 4, D-44227 Dortmund, Germany, {arne.grumpe | christian.woehler}@tu-dortmund.de, 2Sternberg Astronomical Institute, Universitetskij pr., 13, Moscow State University, 119234 Moscow, Russia, {ber | shev}@sai.msu.ru.

Introduction: Lunar swirls are structures on the lunar surface which can be distinguished from their surroundings by their high albedo without exhibiting any direct topographic profile. All known lunar swirls are associated with local magnetic anomalies (e.g. [1, 2] and references therein). One possible formation mechanism for lunar swirls is magnetic field induced shielding from the solar wind, thus preventing darkening of the surface material due to spaceweathering [1]. An alternative hypothesis is the impact of a huge number of small grains of meteoritic material originating from a comet nucleus torn into small pieces by tidal forces, thus bringing immature material from a depth of only a few tens of centimetres to the surface without creating a topographic profile ([3] and references therein). The local magnetic field may even have been a direct consequence of the cometary impact [4].

Surficial water and/or hydroxyl (OH) has been detected on the lunar surface based on near-infrared reflectance spectroscopy using Moon Mineralogy Mapper (M3) data [5, 6] by analysis of the absorption band at wavelengths around 2.8-3.0 µm [6]. The most popular explanation for the occurrence of this surficial water/OH is the adsorption of solar wind protons followed by reactions with oxygen atoms bounded in the surface material (e.g. [7]).

In this study the OH absorption depth of the swirl Reiner Gamma is mapped at different illumination conditions using reprocessed M3-derived spectral reflectance data. The formation hypotheses for swirls are discussed in the light of the obtained results.

Data and Method: The M3 level-1B (spectral radiance) data available on the Planetary Data System (pds-imaging.jpl.nasa.gov/volumes/m3.html) were converted to normalised spectral reflectances based on the framework described in [8]. A crucial processing step is the removal of the thermal emission component, requiring an accurate estimation of the lunar surface temperature. For this purpose we applied the method of [8], which is an extension of the thermal equilibrium based approach of [9] and accounts for the surface roughness in a way similar to [10]. For the reflectance spectra obtained after subtracting the accordingly determined thermal emission component from the M3 radiance spectra, the integrated OH band depth as defined in [8] (here termed OHIBD) was computed and mapped for the region around the central part of Reiner Gamma.

Results and discussion: M3 1579 nm radiance mosaics for lunar morning (08:19 local time) and midday (11:53 local time) illumination are shown in Fig. 1. The corresponding maps of the OHIBD and an additional partial map, acquired at 15:45 local time, are shown in Fig. 2. The average OHIBD of the mare surface surrounding Reiner Gamma, located near the equator at 7° N, shows only a weak decrease between morning and midday, which is in contrast to the pronounced decrease of the OHIBD between morning and midday described in [8] for the crater Boguslawsky located at 73° S. In the morning, the OHIBD of parts of Reiner Gamma is weaker by up to 20% than the surrounding mare surface but not all swirl-related bright surface areas appear in the OHIBD map. At midday, hardly any contrast is visible any more. In the afternoon, structures related to Reiner Gamma are not apparent in the OHIBD map. These results are in contrast to the band depth map of Reiner Gamma in [1], which shows near-zero band depth values for the high-albedo parts of Reiner Gamma, a strong difference in band depth between the swirl and its surroundings, and a nearly perfect inverse correlation between albedo and band depth. This contradiction between the results of [1] and our OHIBD maps are probably due to the fact that in [1] the method of [11] is used for thermal emission removal, which is meanwhile known to yield inaccurate surface temperature estimates (see e.g. [12]).

If the common assumption is made that surficial lunar water/OH is formed by solar wind adsorption processes, our results indicate that the surface is only weakly and incompletely shielded from the solar wind by the local magnetic field.

Based on simulations of the proton density in and around lunar mini-magnetospheres, it is shown in [13] that the presence of localised magnetic fields may lead to patterns of depletion and enhancement of the density of deflected solar wind protons at the lunar surface, resulting in variations of the degree of spaceweathering-induced surface darkening. In particular, the simulations in [13] predict near-zero proton densities, i.e. complete shielding, in the central part of the magnetic anomaly, and the appearance of the simulated structures shows a general similarity to the observed albedo variations at Reiner Gamma. However, for the simulations in [13] magnetic flux densities of several 10^2 nT are assumed, while according to [14] Reiner Gamma is associated with a magnetic field exhibiting flux densities below 50 nT at ~18 km altitude and below 35 nT at ~28 km altitude. This difference between the measured flux densities of [14] and those assumed in the simulation
setting of [13] may explain our M³-derived observations of a low or absent OHIBD contrast between Reiner Gamma and its surroundings.

Fig. 1: M³ channel 50 (1579 nm) radiance mosaics at local times 08:19 (top) and 11:53 (bottom).

Here one may consider a possible equilibrium state, similar to the “steady-state implanted H” of [15], between adsorbed and diffused [7] or photo-lysed [16] water/OH at low latitudes: The partially shielded swirl surface may adsorb slightly less water/OH than its surroundings, such that the equilibrium level of water/OH is reached later than in the surroundings. As a consequence, the swirl-related structures in the OHIBD maps disappear in the course of the lunar day as apparent from Fig. 2.

All in all, our results suggest that additional processes, such as cometary impact related surface alterations, should be considered to explain the swirl’s albedo structures.

**Conclusion:** In this work we have presented maps of the M³-derived integrated water/OH band depth for the lunar swirl Reiner Gamma at different daytimes. Our results indicate that the surface is likely to be only weakly and incompletely shielded by the local magnetic field, thus supporting the cometary impact hypothesis.

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**References:**


Fig. 2: OHIBD maps at local times 08:19 (top), 11:53 (middle) and 15:45 (bottom).
ENHANCING EXOGEOLOGICAL FIELDWORK BY HUMAN-ROBOTIC PARTNERSHIP DURING ANALOG EXTRAVEHICULAR ACTIVITY SIMULATION AT EIFEL VOLCANIC REGION: ILEWG EUROMOONMARS

Introduction: Human-robotic partnership will play an important role in future planetary exploration. Personal carriers, robots and autonomous scouting drones will enhance and optimize extravehicular activity time and science yield from each expedition. Currently teams of researchers and scientist around the world are working on analog simulations to create a proof of concept devices and operations for such collaboration [1].

During the EVA simulations performed in Eifel, Germany region the set of European Space Agency & ILEWG scientists and research collaborators has tested the human-robotic partnership, EVA procedures and schedule for geological sampling of the sedimentary layers in former volcanic activity location.

Eifel volcanic activity region
The simulation took place in Eifel volcanic region in the vicinity of Mendig, Germany. The place has been chosen because of the past volcanic activity and rich and yet easy to access sedimentary layers of the geologic samples [2]. The simulation crew has identified two distinct locations that were representative examples to test the human-robotic interactions together with geologic Extravehicular Activity (EVA) procedures [3]. Professional trained geologists had chosen suitable place to conduct the as soon as the crew arrived at the location of the simulation.

Extravehicular Activities
During the simulation the crew prepared three distinct EVAs. The analog astronauts simulated:
- test rover operations in rough terrain,
- identify and collect biological sample for further analysis for identification of signs of life,
- test the rover lights and ability to support astronaut work in no light conditions,
- test the influence of poor lightning condition on rover control using video navigation aids,
- test in-the-field rover control using portable antenna and sidearm joystick.

Identified issues
During EVA scenarios team was able to identify several issues. Most of those issues were connected with communication and mission organization. The problems has been reported and elaborated upon to create a lessons learned article.

References:
This year, 2017, is the 10th anniversary of the launch of Selenological and Engineering Explore (SELENE, nicknamed KAGUYA). Japan is now preparing the next stage of lunar exploration. The first one is the Smart Lander for Investigating the Moon (SLIM) of about 100kg total mass, which will launch in 2019 and will demonstrate autonomous pin-point landing technologies. As the next step after SLIM, some groups are studying Moon exploration, not only from the viewpoint of science, but also from the viewpoint of post-International Space Station human exploration activity. Unprecedented Zipangu Underworld of the Moon/Mars Exploration (UZUME) is one such proposed mission, aiming to explore the underground voids or caverns such as lava tubes of the Moon and Mars.

The existence of lava tubes has been predicted since the last century based on terrestrial analogues, and many authors have described their potential to provide shelter from radiation, micrometeorite bombardment, and wide temperature oscillations on the lunar surface [e.g., 1,2]. However, until recently, the entrances of lunar lava tubes had not been discovered.

In 2009, three deep pits, gigantic vertical holes, that have aperture diameters and depths of several tens of meters to one hundred meters were discovered in the image data of Terrain Camera (TC) onboard SELENE [3–5]. These holes are located in Marius Hills, Mare Tranquilitatis, and Mare Ingenii. They are possibly “skylights” opened on caverns. Similar hole structures have been also discovered on Mars [6–8].

The United States Lunar Reconnaissance Orbiter (LRO) Narrow Angle Camera (NAC) identified more pits on the Moon [5,9–11], including the holes that SELENE TC had discovered. The lunar pits and hole structures can be classified into three types based on their locations: floors of large craters, the mare regions, and the highlands. The pits on the crater floors may have formed by depression and/or degassing of cooling impact-melt lavas, a different mechanism from those in mare regions.

“Pit” is used as a general term for depression structures. However, the deep pits that SELENE TC discovered appeared to be different from other shallower or smaller pits, and may be entrances to underlying subsurface voids [5]. Thus, we adopt the term “hole” to refer to the deep pits, such as the Marius Hills Hole (MHH), Mare Tranquilitatis Hole (MTH), and Mare Ingenii Hole (MIH).

Whether these holes are connected to lava tubes extending as far beneath the surface as terrestrial ones do was an open question after the discovery of the holes.

However, recently, Chappaz et al. (2016)[12] reported the possible existence of a long “empty” lava tube by analyzing GRAIL gravitational data. Haruyama et al. (2017)[13] analyzed radar echo data acquired by the Lunar Radar Sounder (LRS) onboard SELENE, and found that LRS data appear to confirm the existence of void structures along a possible lava tube near the MHM. These encouraging results indicate that we are beginning to discover large safe spaces where we humans may one day build a village or town on the Moon. Lunar holes and their associated subsurface caverns like lava tubes can be regarded as not only an “estate” for human habitability, but also as a key resource for lunar science. From a science perspective, lunar holes offer both (1) places where fresh materials may be easily observed and sampled, and (2) access to caverns that provide a safe, quiet environment to execute scientific observations. In addition, the knowledge of these holes and lava tubes on the Moon will be helpful for humans to explore the potential for extraterrestrial life and habitable environments, and the possibility of long or permanent residence on Mars.

We are now considering plans to explore lunar and Martian holes and underlying caverns. The project name is Unprecedented Zipangu Underworld of the Moon Exploration (UZUME) [14].

We will present a summary of recent study results for lunar holes and associated caverns. Furthermore, we will also introduce the UZUME project.

FORMATION OF LUNAR COLD SPOTS BY IMPACT VAPORIZATION AND BALLISTIC SEDIMENTATION, P. O. Hayne¹, O. Aharonson², J. L. Bandfield³, J-P. Williams⁴, B. T. Greenhagen⁵, T. Powell⁶, P. Russell⁷ ¹Jet Propulsion Laboratory, California Institute of Technology, Pasadena, USA (Paul.O.Hayne@jpl.nasa.gov), ²Weizmann Institute of Science (Israel), ³Space Science Institute (USA), ⁴University of California, Los Angeles (USA), ⁵Applied Physics Laboratory, Johns Hopkins University (USA), ⁶Case Western Reserve University (USA).

Introduction: Lunar “cold spots” are a class of impact-related features exhibiting morphologies consistent with granular flow surrounding very young craters [1]. Discovered in nighttime thermal data from the Diviner instrument [2] on the Lunar Reconnaissance Orbiter spacecraft, they are characterized by extensive, low-thermal inertia regolith forming ray-like patterns around a central crater (Fig. 1). Thousands of cold spots have been catalogued, with a statistical size-frequency distribution consistent with a population ~200 kyr old [3]. Cold spots appear to be a prominent lunar (and perhaps planetary) feature, yet their formation remains enigmatic. Here, we present a model for cold spot formation, which can potentially explain their observed thermal behavior.

Data: We analyzed data from Diviner during lunar night, twilight, and during several lunar eclipses from 2014 to 2016, and infrared data from the Air Force Research Laboratory’s 3.7-m Advanced Electro-Optical System (AEOS) during two lunar eclipses [4]. Nighttime and eclipse temperatures indicate the thermophysical properties (conductivity $K$, density $\rho$, heat capacity $c_p$) of the regolith within the skin depth: ~10 cm during lunar night, and ~1 cm during eclipse. A key result from these observations is that the cold spots show an anomalously low thermal inertia ($\sqrt{K\rho c_p}$) within the diurnal skin depth, and anomalously high thermal inertia in the eclipse skin depth (Fig. 2). Secondly, thermal modelling [1] indicates ejecta emplacement cannot be the only cause of the observed thermophysical anomalies; some modification of the regolith must occur in situ.

Model: Our proposed cold spot formation model consists of two components: (1) impact vaporization, and (2) ballistic sedimentation. The first process scours the surface through gas-particle interactions, removing a fine-grained “fairy castle” structure, and the second process decompresses the underlying regolith through particle-particle collisions. The expected result of these processes is a surface with higher thermal inertia in the upper ~1 cm, and lower thermal inertia in the next ~10 cm, than the surrounding regolith (Fig. 3). Over time, the fairy castle structure re-forms, and the regolith is re-compacted by micrometeorite impacts.

Impact Vaporization. While the dynamics of impact-induced vapor clouds are not well understood, the process is typically modelled as an ideal gas mixture confined to a rapidly expanding hemisphere [5, 6]. This approach leads to solutions for the gas velocity and density, which can be used to estimate surface stresses capable of initiating grain saltation. We present the results of some example calculations in Figures 4 & 5.

Ballistic Sedimentation. Low thermal inertia regolith extends to more than ~100 crater radii surrounding cold spot craters [1]. At this distance, primary ejecta are not thick enough to explain this signature. Therefore, we model a cascade of successively higher orders of ejecta particles, each of which influences a volume of material. In this model, de-
compression of the regolith occurs when this volume experiences dilational stress surrounding the impacting particle. Our numerical scheme estimates these stresses and vertical sedimentation velocities, which affect the density of the resulting deposits.

**Discussion:** We investigated the effects of the vapor expansion and ballistic sedimentation models on regolith thermal inertia profiles. Preliminary results indicate that impact vaporization would lead to sufficient surface stresses to mobilize the upper \(-1\) cm to distances of \(-10 - 100\) crater radii. If the pristine lunar surface consists of low-density “fairy castle” structures, they would be disrupted by the vapor, increasing the thermal inertia in this layer sensed by the eclipse thermal measurements.

Ballistic sedimentation may be an important process for decompressing the regolith, and could explain the ray-like morphologies of the cold spots. Our preliminary model results suggest a ballistic cascade could decompress regolith to the required \(-10\) cm depths, although the quantitative agreement with observations is so far unclear. We will present up-to-date model results and supporting observations, and discuss the implications for the impact process and resurfacing of the Moon.


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ASTROBOTIC’S SERVICE: A NEW MODEL FOR LUNAR SCIENCE MISSIONS. D. H. Hendrickson¹, ¹Astrobotic Technology, Inc., 2515 Liberty Ave., Pittsburgh, PA 15222, dan.hendrickson@astrobotic.com

Introduction: This paper describes Astrobotic’s commercial lunar payload delivery service, the company’s progress toward its first mission, and a model for international institutions to utilize Astrobotic’s service to advance science objectives on the Moon.

Commercial Lunar Delivery Service: Astrobotic is a commercial lunar logistics company that specializes in the low-cost delivery of uncrewed science and exploration payloads to lunar orbit and the lunar surface. Historically, planetary missions to destinations like the Moon have been custom built to accommodate a suite of specialized instruments and experiments. Astrobotic’s end-to-end commercial service is a departure from this model, and instead uses a standard lunar lander called Peregrine that can modularly integrate a host of unique payload types on a single mission.

This approach is analogous to a cargo shipping service on Earth, and allows Astrobotic to offer a delivery price of $1.2 million per kilogram to lunar orbit or surface. By taking a shipping model approach, Astrobotic is eliminating the barriers to frequent, low-cost robotic missions to the Moon. Lunar missions no longer require massive, cost-prohibitive infrastructure investments that are typically afforded by only a very select group of governments worldwide. This makes the Moon accessible to institutions around the world, large and small, nascent or mature.

Astrobotic’s first mission. In fact, Astrobotic has 9-signed payload deals toward its first mission from international companies, governments, and nonprofits. One especially notable signed customer is the Mexican Space Agency, Agencia Espacial Mexicana (AEM). Beyond this first mission, Astrobotic has developed a sales pipeline of 110 payload deals that will fill the manifests for the first 5 Peregrine missions to the Moon. Following the first mission, a flight is scheduled to occur at least once every two years. Peregrine will fly as a secondary payload for its first mission with a payload capacity of 35 kilograms. This capacity can be scaled up to 300 kilograms for future missions, with Peregrine flying as a primary payload with additional propellant. Virtually no other configuration changes are needed to scale this capacity.

Astrobotic’s World Class Partners: Astrobotic has put together a team of the world’s best partners to make this service possible. To start, the company has a Space Act Agreement with NASA through the Lunar Cargo Transportation and Landing by Soft Touchdown (CATALYST) Program. The CATALYST program allows NASA to contribute technical expertise, provide access to test facilities, and loan equipment in direct support of developing Astrobotic’s lunar lander. Through CATALYST, Astrobotic is leveraging a half-century of NASA experience for the benefit of its customers.

In addition to NASA, Astrobotic is also partnered with Airbus Defence and Space, the world’s second largest aerospace company. Airbus DS is contributing world-class industry expertise to the Astrobotic team. This was most recently demonstrated by the support Airbus DS provided to Astrobotic’s preliminary design review of the Peregrine lander in the fall of 2016. Airbus DS’s decision to work with Astrobotic followed an assessment that concluded, “Airbus Defence and Space clearly regards Astrobotic as the
front runner in commercial lunar transportation services” [1].

Astrobotic has also partnered with the world’s largest shipping and logistics company, DHL. DHL is the Official Logistics Provider to the Moon, providing key mission support around the world for Astrobotic and its customers. Between major international companies like Airbus and DHL, and a space agency legend like NASA, Astrobotic has built a world-class team to deliver international payloads to the Moon.

**Astrobotic’s First Mission**: Astrobotic’s first mission will be a key demonstration of the service in 2019. The Peregrine Lander will fly as a secondary payload on a commercial launch opportunity to GTO. When the launch vehicle deploys Peregrine at GTO, Peregrine’s onboard propulsion system (built by Aerojet Rocketdyne) carries out a translunar injection burn. The vehicle then coasts to the Moon for 3 to 6 months.

Following this coast, Peregrine carries out propulsive maneuvers to enter a 100 km near-polar orbit around the Moon. In lunar orbit, Peregrine will deploy cubesats via P-Pod deployers bolted to the lander’s deck plates. Peregrine then makes a powered descent to the lunar surface, deploys surface payloads, and then serves as a local utility for payloads by providing power (0.5 watt per kilogram of payload) and communications (2.8 kbps per kilogram). Additional power and communication can be purchased on a per unit basis. Payload data is sent back to Earth through Peregrine’s communication system and a commercially procured ground network. Once received by the ground network, the data is disseminated to customer mission control terminals around the world. The duration for payload operations on the lunar surface is 8 Earth days.

**Model for Advancing Lunar Science**: In addition to demonstrating Peregrine’s technical capability, Astrobotic’s first mission will also pioneer a new model for science and exploration on the Moon. The payload model developed by AEM will serve as a useful precedent for other institutions and organizations to send their first payloads to lunar orbit and the lunar surface. AEM made a reservation of service on Astrobotic’s first mission and then used the parameters of this reservation to inform a request for proposals in Mexico. This forward-thinking model is likely to be repeated by institutions around the world, and is an excellent on-ramp for organizations to send their first instruments and experiments beyond Earth orbit. In doing so, organizations can send small to medium-sized payloads to the Moon at a low-cost, and take on the kind of risk posture that spurs rapid innovation and advancement of the state of the art in science, exploration, and technology demonstration.

Introduction: Straight to curvilinear positive-relief landforms, so-called lobate scarps, occur on all terrestrial bodies [e.g., 1-3]. These scarps are formed by thrust faults that cut through and offset the upper part of the crust. On Earth, these scarps erode rather quickly, even in arid regions [e.g., 4]. Thus, it is difficult to quantify displacements from topographic profiles of terrestrial scarps. Most of these measurements are restricted to well-preserved thrust-fault scarps with ages of at most a few hundred thousand years [e.g., 5,6]. In contrast, because of the absence of a substantial atmosphere results in extremely low erosion rates on Mars, Mercury, and the Moon [e.g., 7-9], fault scarps can be preserved for hundreds of millions or even billions of years. Hence, fault scarps on planetary surfaces provide the opportunity to study the growth of faults under a wide range of environmental conditions (e.g., gravity, temperature, pore pressure) [10].

Results: We investigated four lunar thrust-fault scarps (Simpelius-1, Morozov (S1), Fowler, Racah X-1) ranging in length from 1.3 km to 15.4 km [11] and calculated the vertical displacements along these faults. We find that the maximum total displacements of these thrust faults follow a linear increase with length over one order of magnitude (Fig. 1).

Fig. 1: D/L ratios for the studied faults, together with two additional fault data sets from the Moon [12,13]. A linear regression through our data yields a D/L ratio of 0.023 (or 2.3%). For the calculation of the total displacements for the faults from all three data sets we assumed a fault dip of 30°.

Similar to previous fault displacement interpretations [e.g., 14-18], we interpret this relationship to indicate that during the progressive accumulation of slip, lunar faults propagate laterally and increase in length. For the investigated faults, the maximum displacement to fault length ratio (D/L) has a mean value of ~0.023 (or 2.3%), ranging from 0.017 to 0.028 (Fig. 1). This is an order of magnitude higher than the value derived from theoretical considerations (~0.1%) [10], and about twice as large as the estimates of [12,13], which are ~0.012-0.013. Like recently published findings for other lunar scarps [2,19], our results indicate that the D/L ratios of lunar thrust faults are similar to those of faults on Mercury and Mars (e.g., 1, 20-22). In addition, they are almost as high as the average D/L ratio of ~3% for terrestrial faults [16,23].

On the basis of our analyses of topographic profiles, we find that three of the investigated thrust faults (Simpelius-1, Morozov (S1), Fowler) are uphill-facing scarps. These scarps were formed by slip on faults that dip in the same direction as the local topography. We find that thrust faults with such a geometry are quite common (~60% of 97 studied scarps) on the Moon [e.g., 2,11,13]. To explain these scarps, we propose that surface topography plays an important role in the formation of uphill-facing fault scarps by controlling the vertical load on a fault plane. To test this hypothesis, we simulated thrust faulting and its relation to topography with two-dimensional finite-element models using the commercial code ABAQUS (version 6.14). In our models, an elastic crust is shortened by a velocity boundary condition acting at both model sides to simulate horizontal shortening induced by long-term cooling of the lunar interior (Fig. 2). According to our 200-km-long models, the onset of faulting is a function of surface topography (Fig. 2b) [11]. Thrust fault 1, which dips in the same general direction as the topography, forming an uphill-facing scarp, starts to slip 4.2 Ma after the onset of shortening and reaches a total slip (i.e., the vector sum of the throw and the heave) of 5.8 m after 70 Ma (Fig. 2b). Slip on fault 2, resulting in the formation of a downhill-facing scarp, starts much later (i.e., after 20 Ma of elapsed model time) and produces a total slip of only 1.8 m in 70 Ma (Fig. 2b). In the case of a horizontal surface, our model predicts faulting on both structures to start after 4.4 Ma. In this case, faulting proceeds at a lower rate than for fault 1, which generated the uphill-facing scarp. We emphasize that the absolute ages for fault initiation (as well as the total fault slip) depend on the arbitrarily chosen shortening rate (as well as on the size of the model and the elastic parameters). However, the relative timing of fault activation was consistently observed, irrespective of the chosen shortening rate. Thus, all other factors being equal, the model results indicate that the different
weight of the hanging wall above the two modeled faults is responsible for the different timing of fault initiation, as well as the difference in total slip.

![Figure 2: Model setup and results of our finite-element analysis.](image1)

According to our model results, uphill-facing scarps preferentially form in areas where the topography is not flat. To further support our model results, we present a Mohr circle analysis of the state of stress that controls the initiation of faulting for different topographic slopes (Fig. 3). To initiate faulting on a potential failure plane, the Mohr circle (i.e., the differential stress) needs to be large enough to touch the Mohr-Coulomb failure envelope (Fig. 3). For this study we assume identical mechanical properties of rocks throughout the model. We consider a point, P, located on a potential thrust fault below a horizontal (Fig. 3a) and two dipping surfaces (Fig. 3b and c), respectively. For thrust faulting to occur, σ₁ must be horizontal and σ₃ vertical [e.g., 11,24]. In the first case (Fig. 3a), no failure occurs because the differential stress at point P beneath a horizontal surface is not high enough. In the second case, i.e., a surface that dips in the same direction as the potential fault plane, the overburden and hence the vertical principal stress σ₃ at point P is reduced. This increases the Mohr circle diameter, possibly to the point of fault initiation (Fig. 3b). Beneath a surface that dips in the opposite direction as the potential fault plane, the minimum principal stress σ₁ is larger. Thus, the Mohr circle is smaller and moves away from the failure envelope, which suppresses faulting (Fig. 3c). This analysis provides a dynamical basis for how thrust faults with uphill-facing scarps form on the Moon.

![Figure 3: Schematic sketches and Mohr diagrams illustrating the state of stress at point P on a potential thrust-fault plane beneath horizontal (a) and dipping (b, c) surfaces. σ₁ and σ₃ are the maximum and minimum principal stresses, respectively. (a) thrust fault beneath a horizontal surface. (b) fault plane that dips in the same direction as the surface. (c) fault plane that dips in the opposite direction as the surface.](image2)

**Conclusions:** On the basis of LRO NAC-derived terrain models of unprecedented spatial resolution, we studied four thrust-fault scarps on the Moon and quantified their maximum displacement with a series of topographic profiles, from which we evaluated the along-strike variations in fault slip. Such measurements were not possible prior to the LRO mission. We find that the ratio of maximum displacement to fault length of the studied lunar scarps is ~0.023, and is thus similar to terrestrial faults. This result needs to be taken into account in lunar tectonic studies including, for example, when attempting to quantify the magnitude of the Moon’s global contraction using fault scaling relations. The formation of uphill-facing scarps requires less energy than do downhill-facing scarps. Our numerical model indicates that uphill-facing scarps form earlier and grow faster than downhill-facing scarps under otherwise similar conditions.

**References:**

2. Williams et al., 2013, J. Geophys. Res. 118;
4. Yeats et al., 1997, The geology of earthquakes, 568 pp.;
5. González et al., 2006, Tectonics 25;
6. Cordingley et al., 2014, Quat. Res. 81;
8. Hauck et al., 2004, Earth Planet. Sci. Lett. 222;
9. Grott et al., 2007, Icarus 186;
10. Schultz et al., 2006, J. Struct. Geol. 28;
15. Dawers et al., 1993, Geology 21;
16. Schlische et al., 1996, Geology 24;
17. Hetzel et al., 2004, Terra Nova 16;
18. Kim and Sanderson, 2005, Earth-Science Rev. 68;
19. Banks et al., 2013, LPSC 44, 3042;
21. Hauber et al., 2013, EPSC2013-987;
22. Byrne et al., 2014, Nature Geosci. 7;
23. Torabi and Berg, 2011, Marine Petrol. Geol. 28;
In November 2016 the ESA Council at ministerial level agreed to unify ESA’s exploration activities into a single envelope programme, the European Exploration Envelope Programme (E3P). This programme brings together human and robotic activities in Low Earth, Orbit Moon and Mars. The programme will implement:

- The continued operation and exploitation of the International Space Station until 2024
- Deliver and operate the Exomars 2020 rover mission
- Develop ESA’s contributions to the Russian led Luna missions, in particular the PROSPECT and PILOT systems on the Luna-27 lander planned for 2021
- Deliver the ESA provided service model for NASA’s Orion human deep space transportation system for the unmanned flight around the Moon of Exploration Mission 1 and the crewed flight of Exploration Mission 2.

In addition to delivering these missions E3P will look forwards to the future, preparing the required technologies and performing studies into future missions. These future activities will include the establishment of European contributions to the first human missions beyond Low Earth Orbit since Apollo, and the utilisation of these missions to prepare for later human missions to the lunar surface. Other key elements of the programme will be preparing for future exploitation of Low Earth Orbit post ISS and establishment of European roles in a sample return mission.

A key element of this work will be the establishment of new international partnerships and the consolidation of existing ones, with a view to a long term exploration future based on international cooperation. In addition work is on-going to establish new partnerships with the private sector; capitalising on and supporting new commercial initiatives in space exploration.

In this presentation we will describe the status of lunar exploration in the context of the new E3P programme, describe the elements which are being implemented and provide an insight in to the opportunities for lunar exploration that may be on the horizon.
METEORITIC WATER ON THE MOON. D. M. Hurley¹ and M. Benna², ¹Johns Hopkins University Applied Physics Laboratory (Laurel, MD 20723 USA; dana.hurley@jhuapl.edu), ²NASA Goddard Space Flight Center (Greenbelt, MD 20771 USA).

Introduction: The lunar water cycle is a system of great significance for understanding volatile inventories, gas-surface interactions, and thermal stability. In addition, water is a useful resource for planetary exploration because it can be converted into propellant and life support for astronauts. Enhancements of water and other volatiles exist in permanently shadowed regions (PSR) in lunar polar regions (e.g. [1]). However, it is still unknown when and how those volatiles were emplaced. Potential sources include episodic delivery by comets and other large impactors, continual delivery by meteoroids or solar wind, or an ancient remnant of endogenous lunar water. There is evidence to support each hypothesis, and nothing precludes contributions from multiple sources throughout the history of the Moon.

This work focuses on the contribution of meteoroids to the lunar volatile inventory. We model the expected signatures of meteoroid impacts on the Moon. We make predictions about the evolution of water vapor emanating from the impact and how vapor plumes would appear to remote sensing data. We compare the predictions to Lunar Atmosphere and Dust Environment Explorer (LADEE) Neutral Mass Spectrometer (NMS) data to extract the source rate of water to the Moon from meteoroids.

Meteoroids: The population of interplanetary dust and larger debris that cross paths with the Earth to make meteors and meteorites on Earth also encounter the Moon. They impact the Moon at high speeds a produce a small plume of vapor stemming from both the target lunar regolith and the meteoroids themselves. These meteoroids, partially composed of volatile-bearing species [2], are an exogenous source of water to the Moon.

Meteoroids encountering the Moon can be described by a distribution function of mass. Many more small mass objects hit the Moon than large mass objects. The meteoritic flux by mass presented in [3] has a distribution that is fit by a power law with an exponent of -1.34.

Data: The Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft was equipped with a Neutral Mass Spectrometer (NMS) [4]. The mission’s operations plan involved alternating between operating the NMS, the Ultraviolet Spectrometer, and the LaserComm technology demonstration. While the NMS was not operating, the high voltage to the source was powered down and the temperature of the instrument cooled. During this time, the NMS accumulated water inside the chamber. When the source was powered on again, the count rate in the mass 18 channel results from the balance of the integrated flux into the instrument and the loss function of particles out of the instrument.

LADEE NMS data for water are presented in Figure 1. Sporadic, short-lived spikes of water are observed during LADEE’s 5-month mission at the Moon. They are generally associated with known meteoroid streams. The stochastic nature and the distribution of density measurements fit by a power law suggest that meteoroids are responsible for the water observed by NMS.

Model: The model is a particle tracer that propagates plume vapor along the equation of motion under gravity [5]. We run a set of 1e7 test particles released from a single location. Each test particle is assigned an initial velocity from a Maxwell-Boltzmann distribution at T=5000 K [6].

At 1-s time steps, the test particles are binned into a grid with 10 km altitude bins and 0.25° bins in angular distance from the impact location. Density is calculated by counting the number of test particles in the bin, dividing by the volume of the bin, and scaling to represent a given mass of water molecules. Assuming 1 g water release, the temporal and spatial evolution of the plume at 50 km altitude is shown in Figure 2.

Because meteoroid impacts are stochastic, the relative position and timing of the observation to the
impact cannot be predicted. Therefore we calculate the probability of observing a density by analysing every possible geometry and timing of the spacecraft trajectory relative to the impact. We integrate the density encountered for a 2 hr time period while applying the decay rate of water within the instrument. The probability distribution for density measured by LADEE for a 1 g water release is shown in Figure 3.

![Figure 3. Probability of detecting a given density by NMS during a two-hour integration is shown for a 1 g water release. The probability is shown as a cumulative distribution function, meaning each point represents the integrated probability of detecting that density or higher.](image)

Next we fold in the expected distribution of meteoroid impact mass to produce a simulated density measurement histogram for the LADEE mission. Stepping through meteoroid mass ranges, the probability of a meteoroid impact is computed. The density probability function is scaled to match the mass of water released by an impactor of that mass. These are compiled to produce a probability function that NMS would measure a given density.

**Discussion:** Converting the impactor mass to a mass of water released involves making an assumption about the water content of the meteoroid and of the target material. Because LADEE orbit was at low latitude, we assume the target material is dry. For assumed meteoroid water content of 5%, 10%, and 15%, we present the expected density distribution for LADEE. The model matches the data well.

**Conclusion:** Our data-model comparison indicates that water vapour plumes released from meteoroid impacts is consistent with the LADEE NMS water vapour measurements. The coincidence between the spikes and known meteoroid streams further supports the interpretation.

Given an assumed mass distribution and impact rate of meteoroids to the Moon, we calculate expected frequency of observing a given density by LADEE NMS. Comparison between simulated data for different assumed water content of the meteoroids, the modelling suggests that the weight fraction of water released by meteoroids. Although that fraction could be derived from either the meteoroid or the lunar regolith, the low latitude of the LADEE orbit traverses mainly low water content regions of the Moon. This suggests most of the water is derived from the meteoroids.

**Introduction:** The lunar cratering chronology is used to derive absolute model ages (AMAs) for the geological units of the Moon and has been modified for use on many other bodies in the Solar System [e.g.,1-6]. Modern data from recent missions allow us to test and improve the lunar cratering chronology [5-9]. Using Lunar Reconnaissance Orbiter Camera (LROC) images, we measured new crater size-frequency distributions (CSFDs) for the Apollo 11 and 12 landing sites, which are important calibration points for the lunar chronology.

Both the Apollo 11 landing site in Mare Tranquillitatis and Apollo 12 landing site in Oceanus Procellarum are partially covered with the rays of the ejecta from nearby craters. These rays expose materials from the deeper layers [5,6,10,11]. The samples collected from these landing sites have been studied thoroughly for radiometric ages.

Using the radiometric ages and petrology of the Apollo samples, Stöffler et al. (2006) [6] proposed four groups of basalts for each site on base of chemical differences. Samples collected from Apollo 11 site were divided as follows: Group A (3.58 Ga) is a high potassium basalt, Group B1-B3 (3.70 Ga) is a complex group, and the two oldest groups Group B2 (3.80 Ga) and D (3.85 Ga) are relatively less abundant. However, all types of basalts are varieties with high titanium [6,11,12,13]. The Apollo 12 samples were divided into groups of four basalt types as well: olivine basalt (3.22 Ga), pigeonite basalt (3.15 Ga), ilmenite basalt (3.17 Gyr), and feldspathic basalt (3.20 Ga) [6]. New and ongoing detailed geological mapping of the landing sites will hopefully reveal the positions of the different varieties of mare basalt units surrounding the landing sites, and allow more precise selection of corresponding count areas for CSFD analyses.

**Methods:** CSFDs were measured at the landing sites and surroundings on Lunar Reconnaissance Orbiter Wide Angle (WAC) and Narrow Angle Camera (NAC) data, obtained from PDS node [12]. The images have a pixel resolution of 1.17-100 m/pixel and incidence angles of 60-82°. The calibration and map-projection of images were done in ISIS 3 [13], and then imported into ArcGIS. CraterTools [14] was used for measuring the area and crater diameters. The CSFDs were plotted with Craterstats [15], using the lunar production and chronology functions of Neukum et al. (2001) [4]. The PF is only valid in the diameter interval of 10 m to 100 km [3,4], hence only craters larger than 10 m were fit in cumulative and relative fits [3,4]. The technique to measure CSFDs has been widely described [1, 2, 3, 4, 7,16].

**Figure 1.** (a) Count areas at the Apollo 11 landing site. The blue area is the same as that defined by Neukum (1983) for the initial calibration of the lunar chronology. We recounted this area using LRO WAC data. The red areas are newly defined and measured using NAC data. The NAC count areas show a wider range of ages consistent with the range of radiometric sample ages. (b) New CSFD measurements of the original Apollo 11 count area using WAC data (blue) and a combined CSFD distribution for four new NAC-scale count areas (red) in cumulative form with cumulative fits for determination of absolute model ages. The randomness analysis of the WAC count area shows no obvious secondary crater contamination (panel above).
The geological map is being prepared using data sets including Clementine spectral data, LRO satellite images, and LOLA digital elevation models. The data are assembled and analyzed within ArcMap. We will associate new CSFDs, and the geological map with the well-measured radiometric ages of the returned samples [6, 10, 12, 13].

Results and discussion: Apollo 11. The new CSFD measurements of the Apollo 11 landing site show an average age of 3.59 ± 0.02 Ga. The separate NAC count areas give AMAs that range from 3.45 to 3.61 Ga (Fig. 1, a, b). The previously measured N(1) values of 9×10^3 and 6.4×10^3 were determined by Neukum et al. (1983) and assigned to samples described in Stößler et al. (2006) as Apollo 11 ‘old flows’ and ‘young flows’ respectively [2,3,4,6]. Our new values of N(1) are 6.55×10^3 for the WAC count area and 6.47×10^3 for the combined NAC count areas. Hiesinger et al. (2000) [7] measured an N(1) value of 7.60×10^3 for the much larger mare basalt unit (T17) surrounding the Apollo 11 landing site and determined AMA of 3.63 Ga. The newly obtained ages via CSFD measurements are consistent with the radiometric ages of the Group A, High-K basalts [6, 17]. These basalts show a radiometric age of 3.58 Gyr [6, 17].

Apollo 12. The Apollo 12 landing site shows a resurfacing age of 3.32 Ga (N(1)=3.65×10^3) and 3.58 Ga (N(1)=7.1×10^3) for the underlying surface on the basis of newly measured CSFDs on LRO NAC and WAC data, respectively. These ages are consistent with previously measured ages [3,18]. Hiesinger et al. (2003) defines the site to be within the Mare Cognitum (C5) unit. Calculated AMAs of the unit are 3.65 Ga with a resurfacing age of 3.32 Ga and N(1) values of 8.38×10^3 and 3.30×10^3, respectively [18]. Neukum et al. (1983) measured an N(1) value for this area of 3.6×10^3 representing an age of 3.15 Ga for the resurfaced area [3]. In further studies of the site, high-resolution CSFDs will be measured on LRO NAC data to determine ages of the surrounding areas and other geological units.

Our ongoing project will complete an updated geological map of each landing site to investigate whether sample locations and corresponding count areas can be revised [6, 12, and 13], and will evaluate whether the lunar chronology function can be improved. We are in the process of applying the same method to other landing sites.

COMMERCIAL PARTNERSHIPS FOR EXPLORATION – THE LUNAR COMMUNICATIONS PATHFINDER MISSIONS.
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s.jason@sstl.co.uk, lunar@sstl.co.uk.

Introduction: The successful commercialisation of space Telecoms and Earth Observation has catalysed a growing movement to release similar latent benefits for science and exploration. There are large numbers of planned lunar and interplanetary small satellites and CubeSats with high utility and value for furthering science, innovation, education and economic ambitions as part of national and international plans for exploration [1].

The European Space Agency (ESA) commercial partnerships for exploration initiative [2] aims to stimulate and support innovative, marketable solutions for delivering the ESA exploration strategy. A key objective is to strengthen the economic dimension and thereby the sustainability of space exploration. Based on private sector capabilities and ambitions, the commercial partnerships intiative will lead to new services and products that can be exploited by ESA and its international partners to support delivery of the global exploration roadmap. These ESA partnerships for exploration enable new market creation and stimulation with ESA as a business partner and potential anchor customer.

Lunar Communications Pathfinder (LCP) is one of the ESA commercial partnerships for exploration currently in its pilot phase. The LCP is a private sector provided Lunar data relay and CubeSat delivery service and is the first in a series of missions led by Surrey Satellite Technology Ltd (SSTL) and Goonhilly Earth Station (GES). The Lunar Communications Pathfinder mission starts up affordable core services for lunar exploration and is part of a longer term roadmap for providing commercial communications and navigation services for solar system exploration.

For small augmentable missions, affordable transport of space assets to lunar and interplanetary orbits and communications of these assets with Earth are a common barrier [1]. The Lunar Pathfinder missions will provide enabling support infrastructure allowing customers to focus on the science and business aspects of their missions. The low entry level costs enables new players and increased participation into Lunar and Interplanetary business.

Services:
The Lunar Communications Pathfinder missions comprise a Mothership which delivers customer small satellite and CubeSat missions into Lunar Orbit. In addition to deployment into lunar orbit, there are opportunities for payloads to remain on the Mothership as hosted payloads. The Mothership then provides communications data relay services with Earth. Provision of orbit determination for Lunar assets is also being assessed as a pilot service for the first mission. The initial services are therefore summarised as:

- Delivery of small satellites and CubeSats to Lunar Orbit
- Hosted payload slots on Mothership
- Data relay services with Earth
- Orbit determination for Lunar assets

Subsequent missions will look at continuing to augment services via increasing coverage, capacity (data throughput) plus improved navigation precision and other performance enhancements.

Financing:
The LCP mission is to be financed by ticket sales. Customers can purchase a ticket for their small missions and payloads. The standard ticket price target ed at €1.2 million per kg and includes:

- Delivery to lunar orbit
- 6 months data relay services

Following a call for expressions of interest [3], a significant percentage customer interest has been established for the first and second missions. The next phase is to establish firm commitments prior to go ahead.

Mission Delivery
SSTL are providing the Mothership, building upon the extensive heritage of small satellite design techniques and operational missions, platforms and payloads in Low Earth orbit and Medium Earth orbit. Experience developed on lunar and interplanetary mission designs with ESA, UKSA and NASA such
as ExoMars, ESMO, MoonLite and Magnolia will be exploited, alongside the payload communications and navigation expertise on Galileo FOC and Eutelsat Quantum.

GES are upgrading the 32m antenna (GHY-6) at the Goonhilly site in Cornwall, UK, into a deep space ground asset, which will be the first element in a commercial deep space network. In addition, GES will provide a dedicated mission operations centre situated in Cornwall to control the Mothership as well as to provide facilities for customers to control their own spacecraft. GHY-6 will typically have continuous visibility of the Mothership for an average of 8 hours per day. ESTRACK ground stations, as possible ESA contribution to the partnership, could be used to provide additional support during LEOP, time critical operations, additional coverage and ranging.

![Left: GHY-6 32 m antenna. Image Credit: GES
Right: Mothership for transporting cubesats & data relay](image)

ESA operates as a business partner and potential anchor customer. In addition to this ESA will provide access to its state-of-the-art facilities and extensive expertise. Other activities include technology transfer and regulatory support to the mission as well as supporting coordination of international participation.

This partnership aims to deliver the best balance between performance, cost and tempo required to service small satellite exploration ambitions. Key mission characteristics are summarised in the table below.

**Benefits:**
LEC and its successors will build up core support infrastructure for exploration allowing customers to focus on the science and business aspects of their missions.

The relatively low capital expenditure per customer mission brings exploration within the reach of a wider range national space agencies as well as private and university budgets. Benefits include in-country technical, knowledge and economic capacity building, servicing of national and international space and numerous downstream applications. Essentially offering increased opportunities and increased tempo for:
- Science and Exploration
- Technology and industrial proving
- Education, inspiration and outreach
- Commercial exploitation/in-situ activities
- Global cooperation and coordination

**Summary:**
The Lunar Communications Pathfinder mission is the first in a series of missions to put in place commercial infrastructure to enable affordable and frequent small satellite and CubeSats for exploration. This first mission comprises a single spacecraft to deliver around 60kg of customer payload into lunar orbit and provide them with data relay and navigation services. Details of the delivery are being developed under a Commercial Partnership for Exploration pilot phase between ESA, SSTL and GES. Subsequent missions will continue to deliver step-wise increases in coverage, capacity and performance. The longer term vision is to support sustained human presence on the Moon, Mars and beyond via data relay service provision and ultimately lunar and planetary surface internet, mobile communications and navigation services.

**References:**

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>DESCRIPTION</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transfer Phase</td>
<td>Orbit raising to boost GTO epageto lunar residence, capture into elliptical lunar polar orbit</td>
<td>Bi-propellant chemical propulsion. Duration ~ 1 month.</td>
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<tr>
<td>Passenger deployment phase</td>
<td>2000km x 5000km</td>
<td>Customer tailorable, currently assumes apoluna over lunar south pole.</td>
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<tr>
<td>Data relay orbit</td>
<td>6000km x 8000km</td>
<td>Offers good stability &amp; coverage.</td>
</tr>
<tr>
<td>Total payload mass to lunar orbit</td>
<td>60 kg</td>
<td>Assuming reference mission architecture</td>
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<tr>
<td>Data Relay to MotherShip</td>
<td>CCSDS UHF Proximity-1</td>
<td>Allows cross-support</td>
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<tr>
<td>MotherShip to Earth Data Relay</td>
<td>X-band for Earth link</td>
<td>Supports ~180 Gbites per day to Goonhilly</td>
</tr>
<tr>
<td>Estimated data throughput</td>
<td>~1 Gbit per user, per day</td>
<td>Based on relay through MotherShip</td>
</tr>
<tr>
<td>Design lifetime</td>
<td>6 months lunar operations, Goal 1-2 years</td>
<td>Dependency on customer-selected orbits</td>
</tr>
<tr>
<td>Schedule</td>
<td>36 months</td>
<td>First mission 2020 timeframe</td>
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<tr>
<td>Target Ticket Price</td>
<td>£1.2 Million / kg</td>
<td>Launch fees &amp; transfer to lunar orbit: Plus first 6 months data relay services</td>
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Introduction: Science objectives of the Moon-Rise sample return mission include: (1) determine the South Pole-Aitken basin impact chronology and thereby test the cataclysm hypothesis for the late heavy bombardment (LHB) of the inner Solar System; (2) elucidate the effects of a giant impact basin on a differentiated body such as the Moon; (3) investigate the lower crust and upper mantle through impact melt rocks and breccias generated by the SPA impact; (4) illuminate sources of thorium and other heat-producing elements in SPA and test models for thermal evolution; (5) determine compositions and ages of farside SPA basalts to learn how mantle sources differ from regions sampled by Apollo and Luna; and (6) assess the origin of H$_2$O and other volatile elements and species in SPA surface samples to help constrain the delivery of water to the Earth-Moon system. The mission would scoop and sieve regolith at a landing site in the interior of the SPA basin to concentrate rock fragments in the 3-20 mm size range in addition to sampling unsorted regolith. From Apollo experience, we expect a diversity of rock fragments that represent well the surrounding region. By sampling at a landing site in the deep interior of the SPA basin, we expect rock materials to contain a substantial amount of SPA indigenous materials.

Impact Mixing and Lithologic Variability: A key premise of this approach is that the regolith is the product of impacts at many different scales, but dominated by local to regional source materials. This premise is amply supported by our experience with Apollo regolith samples. Rock fragments in Apollo 11 regolith are predominantly basaltic, but include 28% nonmare materials from the highlands [1]. Apollo 12 regolith contains rock fragments of 4 different varieties of local basalts, but also includes ejecta from Copernicus and other nonmare sources in the Procellarum region [2]. All of the Apollo 17 soils contain rock fragments of local mare and pyroclastic origins, as well as representative materials from the nearby highland massifs, regardless of whether the soils are located in the mare or on the massif slopes [3]. We can confidently anticipate that regolith in the central portions of SPA basin will contain rock fragments of the SPA impact-melt complex, impactites from other local large impacts and basins that lie within SPA, and local volcanic rocks, both buried and exposed. The SPA basin still retains a compositional signature (FeO and Th) revealed by LP-GRS data [4] that is spatially associated with the basin interior and thus reflects the dominant signature of the SPA basin substrate (Fig. 1).

Provenance: Studies that have focused on the effects of impact ejecta and ballistic sedimentation, coupled with mass balance of ejected material [5,6] support the idea that SPA basin interior deposits contain a significant proportion of original SPA substrate, i.e., impact melt and melt breccia, or possibly differentiates of the thick impact-melt complex [7-9]. Haskan et al. [5] and Petro and Pieters [6] showed that considering the major possible contributing impacts to the SPA interior, the interior impact ejecta deposits from impacts subsequent to SPA formation would still consist largely of original SPA substrate (Fig. 2). These models include mass-balance constraints, and the results are consistent with the preservation of the SPA compositional signature.

Figure 1. FeO signature of SPA basin interior, Lunar Prospector Gamma Ray Spectrometer [4] overlain on LROC Wide Angle Camera mosaic. Dashed yellow line is the topographic rim of SPA basin.

Mineralogical data from the Moon Mineralogy Mapper (M$^3$) provides additional indicators of specific provenance of the compositional signature, including SPA substrate and volcanic rocks in the interior of the basin [10,11].

Accordingly, in addition to impact-melt products, we expect to find volcanic rock fragments in any SPA regolith sample. Although not filled with basalt to the extent of some nearside basins, volcanism did occur in the interior of SPA and evidence exists for both obvious (exposed) basaltic volcanism as well as older buried deposits or cryptomare. As was found even in Apollo 16 regolith [12], basaltic fragments will have been delivered by impact processes to regolith in every SPA basin location.
Figure 2. Ballistic emplacement of crater ejecta causes mixing and homogenization of deposits. Large impacts and basins within SPA such as Apollo, Leibnitz, Von Kármán, Zeeman, and Poincaré would contribute substantial amounts of material, but that material would mostly be SPA substrate, excavated and redistributed. Graphic from [5].

**Breccia Components:** In addition to rocks representing a diversity of lithologies, we anticipate that many of the impactites will be breccias bearing clasts of originally deep-seated crustal and even mantle materials, and impact-melted materials. Geochemical and microanalytical methods will be used to characterize these materials and mixing models will be used to deconvolve impact-melt and bulk compositions to determine source components. Coupled age and compositional analyses will discriminate lithologic groups.

**Rock Fragment Size Distribution:** Data from Apollo samples also yield a good understanding of the expected size distribution of rock fragments in SPA regolith. Tabulating data for all Apollo soil samples yields the average rock particle size distribution shown in Figure 3. In 900 g of returned sieved rock fragments, we expect over 7000 rocklets in the 3-20 mm size range, including over 200 rocklets greater than 8 mm diameter, and ~600 in the range 6-8 mm. All of these sizes are easily large enough for consortium study and integrated geochemistry, geochronology, petrography, and petrology. Currently available microanalysis methods make all of the sieved rocklets and even many in the <3 mm size fraction suitable for studies that address the science objectives.

**Expected Science Results:** The most significant result of the analysis of samples returned from SPA basin will be determining the age of the SPA event and the compositions of materials that represent the impact melt and its possible differentiates. We anticipate that a range of ages will be recorded, representing mainly the chronology of SPA and subsequent large craters and basin-sized impacts that would reflect the Moon’s heavy bombardment. Comparing that chronology to the “Apollo basin chronology” will provide a firm constraint for models that attempt to account for the Moon’s heavy bombardment, and resolve whether or not the SPA event itself was part of the LHB. Knowing the age and composition of SPA materials from ground truth will lead to a new or greatly improved understanding of remote sensing data for the entire region, and a new understanding of the conditions and effects that this huge impact had on the Moon, including whether some of the ancient ages recorded in Apollo sample chronometers, and possibly associated with enhanced magmatic activity, correspond to the SPA event. SPA samples will also tell us which, if any, of the lunar meteorites come from the SPA region of the Moon, thus greatly enhancing the value of information contained in those meteorites. MoonRise samples would be available to the scientific community for allocation according to the same procedures as for Apollo samples.


Figure 3. Grain size distribution in lunar regolith used to estimate numbers of rock fragments expected in SPA regolith, bounded by the extremes of Apollo soil samples. MoonRise further increases the percentage of coarse rock fragments by digging beneath the surface to as deep as 0.5 m.

![Figure 3](image-url)
OUTCOME OF THE 1st SILICON VALLEY WORKSHOP ON LUNAR COMMERCIALIZATION TO SUPPORT A PERMANENT HUMAN SETTLEMENT ON THE SURFACE OF THE MOON. Angeliki Kapoglou¹, Moon Village Association (kapoglou.angeliki@gmail.com).

Introduction: On July 19, 2016, fifty (50) Silicon Valley innovators including founders and CEOs of Newspace startups; key personnel from prime contractors and the Google Lunar XPRIZE; NASA and ESA officials; Venture Capitalists, Wall Street and infrastructure finance experts and Stanford University researchers gathered at the Rainbow Mansion in Cupertino, California, to discuss the future of lunar commercialization and start a Moon Village Leaders Consortium with very concrete proposals and clear plans addressing finance, technology and organizational strategies. Through the dynamic “unconference,” attendees self-organized into breakout groups and used creative exercises to encourage discussion and gain experts’ insights. Unlikely groupings of diversely skilled participants from inside and outside of the aerospace sector and other career paths worked together for more than ten hours to define strategies and provide valuable recommendations, summarizing challenges and opportunities, that would advance both the Moon Village vision and lunar commercialization in the near and mid-term.

Results: The Workshop consensus saw private funding that might fill a portion of a Low-Cost approach to the Moon Village. However, the timing is mismatched for technology investment and returns, where the economics of profitable Lunar Operation are decades away. Venture capitalists (VCs) interested in allocating parts of their 7-10 year funds to space technology indicated that there is an urgent need to focus discussions on realistic near-term payoffs (2 - 5 years) to attract commercial interest to invest now enabling technologies with credible terrestrial returns in the near term, that also pave the way for a private lunar activity in the future. Additionally, there was broad consensus regarding the need to cut through red tape bureaucracy and to increase the speed of commercially enforceable arrangements that require government permission, cooperation, contract or enforcement support. Therefore, a new Framework for Participation of Private, Public, Investors, and Philanthropists to the Moon Village should be articulated to prepare for novel, low-cost and agile programs for space settlement and allow for space agencies, donors, and commercial space to create an integrated, mutually reinforcing strategy.

Efforts will be made to raise awareness among relevant angel investor networks/ VC groups of the Moon Village vision, its benefits, and how to utilize it for applied commercial research. Efforts will also be made to demonstrate credibility and start a dialogue between Newspace and ISECG taking advantage of the already existing mechanisms for cooperation between ISECG and external entities.

The group suggested setting clearly the objective of a Self-Sustainable Settlement on the Moon which will also drive long-term, financial sustainability. Importance was also given to facilitate explaining how Lunar Commercialization could benefit Earth’s citizens, regions, and the environment in the near-term. The scope of our efforts to bring the Moon Village vision to life should be designed to include—and care about—systems beyond our corporate or governmental needs.

Finally, the group unanimously agreed to have a bias towards action and focus efforts on building real change for the space sector. We cannot any longer just create policy papers and exploration roadmaps. Instead, we need to design policy-consistent legal instruments and financial transaction vehicles that shift established behaviors and exploration roadmap recommendations. The private commercialization of Lunar Exploration will accelerate if policymakers gain the trust of real actions and investments, taken by established and new organizations. The Moon Village is a pivotal setting for demonstrating human, technology, institutional and financial cooperation for doing things not only on the Moon, but as precedent for other destinations on Earth and in space.

Over the next year, we aim to host a series of follow-up, invitation-only workshops made up of leading thinkers, who come together to provide interdisciplinary expertise, stimulate dialogue, as a means to drive a near to mid-term commercial lunar development movement with tangible next steps.

Taken as a whole, our approach enables us to generate action and inclusion of established and new government, corporate and NGO stakeholders. By connecting to and deriving our solutions from real people, we are tapping into the forcing function of a shared vision, the tangible goal of a Self-Sustainable Settlement on the Moon, which is likely to bring new, more agile business models and methods into the space sector. It is our hope that we may serve to spark the excitement and curiosity of entrepreneurs, decision makers, economic researchers, investors and all others interested in a sustainable lunar development and human space exploration.
The Lunar Reconnaissance Orbiter mission (LRO) is in the first year of a two-year extension, through September 2018, to study fundamental processes recorded on the Moon. LRO’s instruments are measuring processes that operate not only at the Moon but also generally throughout the Solar System, especially on bodies without a significant atmosphere. This “Cornerstone Mission” (CM) employs all seven LRO instruments (including the return of Mini-RF to operational status) to constrain new science questions. This synergistic approach allows processes to be constrained at distinct spatial (both lateral and vertical) and temporal scales. These processes are divided into three distinct eras of lunar history (Figure 1).

Contemporary Processes (2009–today): LRO has been at the Moon for nearly 8 years, making it NASA’s longest duration lunar and airless body orbital mission. This unprecedented baseline of observations enables fundamentally new science, especially in observations of subtle changes to the lunar surface and its environment [e.g., 1].

Evolutionary Processes (~<1 Ga): LRO will look to the recent geologic past to study processes taking place within the interior and their reflection on the surface, such as those that provide evidence of the Moon’s recent volcanism, and the evolution of the regolith [2, 3].

Fundamental Processes (~<4.0 Ga): Reaching farther back in time, LRO will employ new observations to determine the relative timing and duration of basin-forming impacts during the proposed period of Late Heavy Bombardment [4], the formation and evolution of the early crust, and the styles of early volcanism.

Science Focus During the CM: The LRO science teams identified three science themes for the CM, which build on Decadal-relevant science questions: 1) Volatiles and the Space Environment, 2) Volcanism and Interior Processes, and Impacts and 3) Regolith Evolution. A few examples of the science questions we address during the CM are illustrated in Figure 1.

LRO’s Orbit Enables Fundamental New Science: LRO has maximized its science return by employing a quasi-stable orbit for more than 5 years, which has minimized fuel consumption. In this configuration, which has LRO with a low periapsis over the southern hemisphere (Figure 2), enables focused investigations on the region surrounding the South Pole [e.g., 5, 6]. Going forward, the LRO mission team is evaluating options for future orbits that will maximize science collection capability for the remainder of the CM and future potential extended missions.
unique observations that improve the value of the surface measurements.

Requests for landing site assessments by international partners should be made via NASA Headquarters and the Planetary Science Division. At that point, data may be collected, processed, and delivered to the Planetary Data System for use by any interested party. For example, the LROC team can collect multiple views of a possible landing site, and prepare a Digital Terrain Model (DTM) of the potential site (Figure 3).

Figure 3. Example of a DTM produced from LROC NAC images [7] for a possible ISRO landing site at the Malapert Massif [10].

Scientific Productivity: The LRO instrument teams remain highly productive, publishing over 240 peer-reviewed manuscripts since launch. Recently, a three volume special issue of Icarus has been published featuring manuscripts from each of the instruments as well as from outside the LRO teams [11-13]. These special issues are the largest produced by Icarus, and illustrate the continuing contributions to lunar and planetary science by the LRO teams.

Conclusions: LRO remains a highly productive, scientifically compelling mission [13]. During its Cornerstone Mission LRO will continue to advance the leading edge of lunar and Solar System science (Figure 3). The LRO mission looks forward to many more years of providing critical data for the revolution in our understanding of the Moon, and by association the Solar System.

References:

THERMAL SIMULATION OF A ROVER TRAVERSE AT THE LUNAR SOUTH POLE. M. Killian¹, ¹Chair of Astronautics, Technical University of Munich, Boltzmannstr. 15, 85748 Garching, Germany (m.killian@tum.de).

Introduction: The Lunar Volatiles Prospector (LVP) mission study funded by ESA investigates the feasibility of a mission to the Lunar Poles in search of volatiles. A mobile rover is intended to be carried to the lunar surface. The work presented here provides information about the dynamic thermal environment of a potential traverse between Shoemaker and Faustini craters, identified by Flauhaut et al. [1]. The centre of the corresponding digital elevation model (DEM) in the region of interest (RoI), derived from LOLA data and depicted in Figure 1, lies at 87.695 °S and 65.512 °E. An estimated date of such a mission is anytime between the years 2022 and 2025. Previous investigations focused on illumination conditions and direct communication possibilities to Earth throughout that period. Here a traverse is optimized with respect to encountered slopes along the waypoints from [1], avoiding slope angles higher than 15 °. The resulting total length is about 24 km. Subsequently, a thermal simulation of this scenario with an arbitrary date of May 2022 provides information about heat fluxes for the rover that can be used to assess the feasibility of the traverse or inform the thermal design of the rover.

Figure 1: High resolution DEM of RoI, traverse highlighted

Simulation: The thermal software ESATAN-TMS is used for the radiative calculations as well as for solving the entire thermal model. Because of the long duration of such a traverse (about 24 days constant driving), the elevation and azimuth angles of the sun have to be modelled dynamically as well. Our in-house tool TherMoS [2] provides this capability to calculate the sun position with respect to the centre position of the DEM by using an orbit propagator. The varying sun angles cause high temperature changes, which the implemented thermal model of the lunar surface can reproduce. TherMoS includes a simplified surface model that is based on the two-layer model of Vasavada [3,4]. Every surface triangle consists of four thermal nodes in depth in the reduced version used for this analysis.

The original DEM of the region of interest (RoI) has a resolution of 20 m per pixel, which is too detailed for the computation of radiative interactions within a reasonable time. Hence, only the traverse optimization along the waypoints makes use of this high resolution DEM, whereas radiative calculations rely on a reduced DEM with a resolution of about 400 m per pixel. The modelled rover has dimensions of 1.4 m x 1.4 m x 1.0 m in width, length, and height and is assumed as a black body with a constant temperature of -20 °C. For the first iteration of thermal calculations, which are presented here, the rover drives continuously with a constant speed of 40 m/h, not stopping at the waypoints.

The traverse, shown in Figure 1, has a total length of about 24 km. In the simulation, the rover starts driving on May 1st 2022 and reaches its destination at the end of May 24th 2022. During that time, the sun elevation varies between -1.66° and +9.56°, and the sun azimuth angle covers slightly more than 300° with the solar constant set to 1347 W/m². The resulting temperatures for the lunar surface lie between -183.5°C and +65.0 °C.

Results and Discussion:

Heat fluxes. Figure 2 depicts heat fluxes through radiation (infrared and solar) of the rover summed up over all rover surfaces. The graphs show that at the start of the mission sun light reaches the rover and the surface underneath for a period of about 11 days. During that time, the average solar heat flux amounts to roughly 300 W/m² with peaks of 700 W/m².

Figure 2: Heat fluxes of rover, starting date May 1st 2022

The peaks of the solar heat flux are interesting because at certain positions with the corresponding orientation of the rover, the solar heat flux can be maximized. Thus, for example a solar panel might need a mechanism for accurate pointing in order to achieve receiving the highest solar heat flux possible.
The total heat flux stays positive in the sunlit phase meaning that the rover would heat up. However, the rover always has a negative infrared heat flux, mainly because the top panel sees deep space with a temperature at about 3 K. On top of that the lunar surface temperatures along the traverse are colder than -20°C (the rover temperature) for most of the time.

After a sunlit phase of nearly 11 days, the traverse of the rover stays in a shadowed area until the final target point is reached. During that period the total heat flux is negative with about –225 W/m².

Communication link. The direct communication link to Earth along the traverse can also be calculated by ray tracing, using the aforementioned tool TherMoS. If a direct line between the rover position and the Earth does not intersect with the terrain, a communication link is possible. In May 2022, the rover always has direct view to the Earth.

Discussion. The results show that May 2022 is not a favourable month for that kind of mission in the chosen RoI. The biggest challenge to overcome for a thermal design is the change in heat fluxes. During sun-lit phases, the total heat flux increases to 200 W/m² but in shadowed phases, it decreases to –225 W/m². It is much easier to find technical solutions for constant conditions. Additionally, the rover has to cope with prolonged periods of extreme cold temperatures, which probably are only survivable when using nuclear heat sources.

Conclusion: With the presented simulation, dynamic thermal requirements can be derived for a lunar rover. Traverse planning should be combined with simulations of the thermal environment to account for thermal problems and feed into the thermal design [6,7]. In the simulations presented here, a continuous traverse was assumed, neglecting stations where the rover stops and performs scientific tasks. As such tasks will prolong the mission duration to an estimated five months, the thermal environment has even greater impact on the rover. Future work will therefore attempt to find periods and paths with more favorable thermal conditions throughout the entire year 2022.

Speyerer et al. [5] already provide a sophisticated baseline traverse optimized for solar illumination and slopes. Further thermal simulations will be performed to analyze this baseline in terms of heat fluxes and give suggestions for improvements regarding the thermal aspects.


Introduction: We present the Netherlands-China Low-frequency Explorer (NCLE), a low-frequency radio instrument selected for the 2018 Chinese Chang’e 4 mission to the Moon. NCLE consists of 3 5-meter long monopoles antennas that will be mounted on the Chang’e 4 relay satellite, and will be sensitive in the 80 kHz - 80 MHz frequency range (see also Figure 1). The instrument is designed to address a multitude of high-profile science cases, but predominantly NCLE will open up the low-frequency regime for radio astronomy and will prepare for the ground-breaking observations of the 21-cm line emission from the Dark Ages and the Cosmic Dawn, considered to be the holy grail of cosmology.

The Chang’e 4 mission will consist of a relay satellite placed in a halo orbit at the Earth-Moon second Lagragian point (L2, ~64000 km behind the Moon), for which the launch is planned for May 2018. This will be followed by a Lunar Lander and a Rover which will land on the Lunar Farside in the 2019-2020 timeframe. The NCLE instrument will be placed on the Chang’e 4 relay satellite and is expected to have a nominal mission lifetime of at least 3 years. During this period only for the 6 months Chang’e 4 mission on the lunar surface, NCLE will have to share resources with the Lander experiments and operations.

The NCLE instrument is designed and build in the Netherlands by a team consisting of scientist and engineers from the Radboud Radio Lab (RLL) of the University of Nijmegen (PI Prof. Falcke), the Dutch institute for radio astronomy ASTRON and Innovative Solutions In Space (ISIS, Delft). The RRL has the PI role and is responsible for the digital receiver system (DRS), ASTRON is responsible for the antenna and analog electronic systems and ISIS the the industrial system integrator and responsible for the interface to the Chang’e 4 platform.

Low-frequency radio science: Low-frequency radio astronomy, i.e. below ~30 MHz, can only be done well from space due to the cut-off in the Earth’s ionosphere, the man-made Radio Frequency Interference (RFI) and the Earth’s Aroral Kilometric Radiation (AKR) and Quasi-Thermal Noise (QTN) that make sensitive measurement from ground-based facilities impossible [1]. At the Earth-Moon L2 point NCLE will be outside the Earth’s ionosphere and relatively far away from terrestrial interference, which, however, will still be detectable. As the Earth will always be in sight we can measure and quantify the RFI emission for the first time since 50 years and with unprecedented quality. This is required for any future moon-based low frequency interferometer that targets the detection of the weak 21-cm line emission from the Dark Ages, making NCLE a true prototype mission. NCLE targets a number of objectives, the first being to qualify the technology in the low frequency domain that can be used for future space missions. It will do this by qualifying the different sub-systems (analog and digital) and calibration and measurement techniques (e.g. Very-Large Baseline Interferometry (VLBI), goniopolarimetry) over the entire 80kHz to 80 MHz regime. Secondly, NCLE will characterise the RFI at the lunar location, determine the galactic background 80kHz—80MHz radio spectrum, measure the radio emission from the Sun and space weather, and the auroral emission from the large planets in our solar system, and create a low-frequency sky map (over the course of its mission lifetime). Finally, NCLE will attempt to constrain the 21-cm Hydrogen line emission from the Dark Ages and the Cosmic Dawn ([1],[2],[3]). NCLE will be a first step towards opening up the virtually unexplored low frequency domain for astronomy, which will potentially lead to new discoveries.

Design specifications: The NLCE payload will have to be delivered by the end of 2017. Given this short lead time the design is based on commercial off the shelf- and space qualified- components as much as possible, and the design and model philosophy as is common for small- and nano-satellites is adapted.

![Figure 1: The Chang’e 4 satellite and the 3 NCLE monopole antennas.](image-url)
Three co-located, 5 m monopole antenna elements mounted on the spacecraft wall, see Figure 1. These antennas are configured as dipoles to minimize common mode interference. NCLE will have its optimal sensitivity in the frequency range between 1 and 80 MHz where the highest priority science signals are expected, but will extend down to the kHz regime, albeit with reduced sensitivity. The analog signals are digitized in a DRS system on which dedicated science modes are implemented in a flexible software-defined radio system. These modes for instance perform fast Fourier transforms to create average radio spectra, allow triggering on transient radio events, or allow to retrieve direction of arrival information using beam-forming or goniopolarimetry techniques. Raw time traces can be stored for ground-based post processing and VLBI.

In addition to the aggressive time line, the Electromagnetic Interference (EMI) as introduced by the satellite platform subsystems is considered the major technical risk. As mentioned above, a common-mode rejection method will be implemented to reduce EMI levels, and a number of EMI measurement campaigns are planned. These will allow for small modifications to the Chang’e 4 platform to reduce the EMI levels, and will be used as input for the calibration plan.

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**References:**


GEological AND SPECTRAL ANALYSIS OF LOW-CALCIUM PYROXENES AROUND THE IMbRIum BAsIN ON THE MOON. Rachel L. Klima (Rachel.Klima@jhuapl.edu), Debra L. Buczkowski, Carolyn M. Ernst, and Benjamin T. Greenhagen. 1Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA.

Introduction: As an early crystallizing mineral, orthopyroxene provides important clues for understanding the evolution of the lunar surface, from the earliest magma ocean cumulates, through the anorthositic flotation crust, to later stage intrusive magmatism. Using data from the Moon Mineralogy Mapper (M3) to search for Mg-suite norites, concentrations of low-Ca, high-Mg pyroxene have been located around the Imbrium and Apollo Basins [1]. These deposits may be exposures of Mg-suite plutons, may represent excavated material from deeper within the primary lower crust or mantle, or may be remnants of melt sheets (differentiated or undifferentiated). Iron-rich orthopyroxenes have been identified elsewhere, in smaller craters and specific types of terrain? (3) Is there an association between orthopyroxene modal abundance, cooling rate, and specific types of terrain? (3) Is there an association between the cooling rate of orthopyroxenes and their depth of origin in the lunar crust? We focus here on deposits located in the Montes Alpes and Montes Apenninus, surrounding the Imbrium Basin.

Imbrium Basin: The Imbrium basin has been extensively studied for many years [e.g., 2-3]. Though the bulk of the basin is flooded by mare basalts, massifs consisting of more generally feldspathic material surround the edges of Mare Imbrium in the northwest, northeast, and southeast (Fig. 1). Telescopic measurements of Apennine mountains revealed regions spectrally dominated by orthopyroxene or pigeonite [3]. Later radiative transfer modeling of Clementine data suggested that Mg-suite-like norites may surround much of the Imbrium basin [4]. In the initial global survey of norites using M3 data, the norites modeled to have the highest Mg# were found in the Montes Alpes region near Vallis Alpes [1].

The Imbrium basin is large enough to have excavated between 60-85 km into the Moon [3], deep enough to penetrate through the crust and into the mantle. It is also associated with the strongest thorium detections by Lunar Prospector [5], and is likely to be rich in KREEP [6].

Fig. 1. M3 standard color composite (R=integrated 1 μm band depth, G=integrated 2 μm band depth, B=1.58 μm reflectance). Orthopyroxene-rich regions appear as cyan. The highest concentration of Mg-rich orthopyroxene is in the massifs of Montes Alpes (outlined in yellow). The center of Imbrium basin is located at 32.8°N 15.6°W and the scale bar is 100 km across.

Geological Occurrence of Orthopyroxene-Rich Deposits: Orthopyroxenes around the boundary of the Imbrium basin are primarily associated with material mapped as crater slope material or undifferentiated terra material [eg. 7-8]. This material occurs throughout the Alpes formation, which has been interpreted as deformed pre-Imbrium material, and Fra Mauro formation, which is defined as thick basin ejecta. The massifs in which the orthopyroxenes are found are primarily distinguished from the surrounding formations by their occurrence on steep slopes and their medium to high albedo, and their origin, as currently mapped, may be either uplifted material or crater ejecta. We have identified dozens of LROC narrow-angle camera images covering the most prominent orthopyroxene exposures in the Montes Alpes region. These images are currently being correlated with the M3 data to refine the boundaries of the deposits, and to begin to investigate their specific origin with respect to the impact that formed the Imbrium Basin.

Spectral Properties of Orthopyroxene-Rich Deposits: In parallel with the geological investigation of the orthopyroxene-rich deposits, we are examining the spectral properties of different blocks within the mountains and valley. Shown in Figure 2
are example spectra from outcrops around Vallis Alpes in the Montes Alpes. Compositionally, the orthopyroxenes are generally quite consistent with one another, as evidenced by the positions of the strong absorption bands near 900 and 1900 nm. However, the overall albedo varies among exposures, with the reflectance near 750 nm varying from just below 15% to almost 40%. The observed brightness levels may be due to slight differences in the exposure ages of these deposits, physical mixtures with darker local mare material, or the actual modal mineralogy of the orthopyroxene-bearing (likely noritic) rocks.

Fig. 2. Example spectra from different geological environments in the Vallis Alpes focus region.

The specific mineralogy and exposure age of the deposits is being investigated by a combination of spectral modeling and by incorporating measurements taken by the Diviner thermal infrared spectrometer. Building on the laboratory work described in [9], we are performing spectral modeling of high-quality orthopyroxene-dominated spectra using the Modified Gaussian Model (MGM) to try to assess the cooling history of the orthopyroxene-rich deposits. The MGM is used to deconvolve a spectrum into a continuum slope and a series of bands that can be directly linked to the crystal field absorptions that produce them [10-11]. The MGM also outputs a wavelength-dependent RMS error, allowing the user to analyze whether additional absorptions are not being accounted for in a given fit. The relationship between the continuum-removed intensity of the absorption band near 1200 nm and that near 2000 nm has been shown to relate to the site occupancy, and thereby the cooling rate, of pyroxenes. An example MGM fit to a laboratory pyroxene is shown in Fig. 3.

To complement our NIR analysis, we will present an initial analysis using Diviner data to analyze the position of the Christiansen feature (CF). The CF shifts in wavelength depending on the silicate polymerization of the bulk rock being measured, and is thus extremely effective at distinguishing relative proportions of minerals in a two-component mixture of a highly polymerized silicate such as anorthite and a less polymerized silicate such as pyroxene. Though fine-grained materials in the NIR and in the vibrational Reststrahlen bands are nonlinear, mixing at the CF have been shown to be essentially linear [12]. The assumption of linear mixing of endmember CFs may cause uncertainties in absolute mineral abundances of up to ~10% but will not affect relative abundances between sites [e.g. 13].

Fig. 3. Example of model fit for M³ spectrum extracted from Vallis Alpes.


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ANALOGUE SIMULATION OF LUNAR ENVIRONMENT - LESSONS LEARNED FROM THE FIRST LUNAR CAMPAIGN IN POLAND. Kołodziejczyk A.K.1,2, Ambroszkiewicz G.1, Budziń D.1, Davidova L.1,4, Foing B.2,3 Gawlak M.1, Goetty M.1, Harasymczuk M.1,2, Harasimiuk F.B., Nędzarek A.1, Konorski P.1, Lawrynowicz A.1, Nisztuk T.1, Noga T.1, Percz M.1, Ptak P.1, Rudolf A.1, Salteri E.1, Słonina M.1, Takla M.1, Traple M.1, Wojciechowska M.1, Zagórski P.1 Modular Analog Research Station Team (ficbio@gmail.com), 2ESA/ESTEC Postbus 299, 2200 AG Noordwijk, NL, 3 ILEWG, 3Vrije Universiteit Amsterdam, 4Charles University Prague, 5University of Warsaw

Introduction:
Human exploration of the Moon has become one of the main space priorities and challenges in the world. Soon we will be back on the Silver Globe trying to inhabit it as the next continent for living. In order to reach readiness for this goal, multiple developmental pathfinders have been enabled including lunar analogue simulations on Earth. This paper discusses operational lessons learnt from the 2016 testing lunar simulation campaign for future habitat operations on the Moon. The one-week campaign named Lunar Expedition 0 was conducted in the area of Astronomical Observatory of Queen Jadwiga in Rzepiennik Biskupi in Poland. A series of technological, operational, medical, biological, geological and human factors experiments toward the goals of the future lunar analogue missions were tested. The results from this mission provide recommendations for future manned expeditions to increase the quality of simulation. Additionally we put focus on optimization of procedures and scheduling methods as well as science return based on improved resource allocation and crew habitation.

Lunar Simulation in Poland:
During 15th-21st of August 2016 a testing lunar simulation campaign was performed at the Astronomical Observatory of Queen Jadwiga (Figure 1). The simulation was organized by Astronomia Nova Association (www.astronomianiova.org), M.A.R.S. (Modular Analog Research Station) Team and with significant support of Space Garden Company. A group of more than 20 people managed to run testing lunar campaign, to prepare all necessary procedures, test operations and perform critical for the mission training for astronauts and mission control crew. Astronaut selection was based on psychological evaluation in order to reduce the risk of pathological behaviors occurrence, which could jeopardize safety of the mission. A series of thorough questions was prepared and the data gathered through analysis of the answers led to successful selection of candidates who presented possibly optimal behavioral patterns to make a good team member in an extreme environment condition. Twelve people: six analogue astronauts and six backup crew astronauts, were finally chosen among 50 candidates. The whole recruitment process took 3 months including analysis of applications, psychological tests, personal interviews and medical examinations.

Lunar habitat:
Confined space for astronaut’s crew - isolated from natural light habitat, consisted of two 5m Ø astronomical domes connected with 8x4m tent (Figure 2). The domes simulated rockets landed on the lunar surface, while the tent was a simulation of deployable structure.

Figure 2. The scheme of functional organization of the habitat’s interior.

Mission structure:
23 people were continuously engaged during the lunar simulation campaign (Figure 3).

Project manager coordinated and designed habitat interior, astronaut and mission control crew trainings, mission documentation, post-mission publishing and conference presentations. Scientific program of the mission was designed in collaboration with professional experts called Principal Investigators working at universities and in European Centre of Science and Technology (ESTEC) in Netherlands. Astronauts were divided into two EVA Teams to facilitate scheduling. Astronauts were supported by dedicated staff at Mission Control Centres (MCCs). For safety reasons Mission Control was divided into three locations: the local Rzepiennik Flight Centre (RFC) 5 km from the habitat, the main mission control in ESTEC distanced 1200 km and emergency backup - remote mission control.

Due to the time-limited and dynamically changing environment of space missions, it is important to communicate with the crew and to provide them with crucial technical/medical information. The data could be in the form of regular status updates between MCC members and astronauts or instructional technical/medical data for experiment procedures. When humans are in the loop, the safety of the crew and their ability to solve critical problems and deal with many unknowns are the main concerns of ground controllers, i.e. MCC team. And so, the idea of a ground control team was conceived to supplement, augment, and assist the crew on board in the harsh space conditions. The idea of a ground control team, i.e. MCC team, was also created to support the joint problem solving and decision making by both mission controllers and the crew, providing crewmembers with less technical or medical knowledge/expertise with support on the experiment procedures/ EVA operations.

Additionally, it is desirable that astronauts report the status of their tasks more frequently. To make this possible, communication tools need further development; a platform that enables MCC team to communicate with one another and with the crew through different loops to clearly and efficiently communicate with the crew from virtually anywhere is currently in development.

**References:**


The Lunar Electric Rover (LER) is primarily designed to provide astronauts with mobility on the lunar surface. This design was improved in a series of trade studies involving field trials that mimicked 3-, 14-, and 28-day-long missions on the lunar surface. These mission simulations were invaluable, in part because they taught us several unanticipated lessons. Here I focus on one of those lessons: that the LER is not just a mobility platform, but also a valuable geological tool for exploring a planetary surface. What is an important insight when discussing the implementation of a mission scenario that involves two LER at five human landing sites on the Moon, as recently proposed by the International Space Exploration Coordination Group (ISECG) [1] as part of the Global Exploration Roadmap (GER) [2].

Introduction: The Lunar Electric Rover (LER) was designed to provide astronauts with mobility on the lunar surface. This design was improved in a series of trade studies involving field trials that mimicked 3-, 14-, and 28-day-long missions on the lunar surface. These mission simulations were invaluable, in part because they taught us several unanticipated lessons. Here I focus on one of those lessons: that the LER is not just a mobility platform, but also a valuable geological tool for exploring a planetary surface.

Proof of concept and major trade studies: The initial concept for a new generation rover was Charriot [3]. This was an unpressurized rover (UPR) designed for a crew of two, with a contingency capacity of four. The chassis had six wheel modules with independent suspension, drive, and steering systems. The vehicle was tested at the Moses Lake sand dune region (Washington) and Black Point Lava Flow (Arizona), showing the concept sound.

A cabin was then mounted on the chassis to simulate a small pressurized rover (SPR) and tested along with the UPR at Black Point in mission simulations that included realistic tasking, accurate traverse timelines, and an in-loop science CAPCOM. It was quickly realized that the SPR was a superior mission element. Traveling within the SPR was easier on crew than spending an entire day in a spacesuit. Crew had more energy at stations when traveling in the SPR and were, thus, more productive. The SPR, renamed LER (and, later, the Space Exploration Vehicle (SEV); Fig. 1), could also provide shelter during any suit malfunction, radiation event, or medical emergency [4]. To reduce time-line, mass, and volumetric overhead, rapid egress and ingress was envisioned, requiring lower cabin pressure (8 psi within the LER vs. 14.7 psi on the International Space Station) and suit ports on the aft cabin wall [4] rather than an airlock. A nominal speed of 10 km/hr is expected for lunar surface operations [5], although the Charriot had a 20 km/hr top speed as a design specification [3]. During mission simulations at Black Point, the LER had an average speed of ~5 km/hr.

Intravehicular activity (IVA) capabilities: Descriptions and photo-documentation of distant features are possible from within the LER during drives between stations. Likewise, descriptions and photo-documentation of features in the near-field, directly in front of the LER, are possible from within the vehicle. The vehicle can rotate 360° without any lateral movement, providing views in all directions.

The LER can function like a geologist, approaching outcrops while photo-documenting them (Fig. 1). It has high-visibility windows, a ForeCam, AftCam, port and starboard cameras, docking cameras, and a GigaPan camera (Fig. 2).

The view from within the SPR is very good. To evaluate the quality of that view, I conducted a test at Black Point: After examining the geologic details of a shale and siltstone region like that in Fig. 1 on foot, I re-examined it from within the LER and was able to conduct 90% of the geology from within the vehicle. While that value will vary depending on geological and topographical complexity, the test demonstrated the value of IVA from within the LER.

Extravehicular activity (EVA) capabilities: When needed for closer inspection and sample collecting, crew can quickly egress in about 10 minutes through suit ports. Crew use SuitCams for additional photo-documentation, transmit mobile observations verbally, and sample surface materials. We learned that a structural element, like the aft deck, which is akin to a table, is also a useful external surface on the LER, because it allows crew to re-describe samples if needed prior to storage on the vehicle. Typical simulations involved 3 to 4 EVA stations/day and 2 to 3 hrs/day of boots on the ground. This allowed crew to explore a far larger territory, with more complex geological and ISRU features, than would a single, longer-duration EVA at one location, while also minimizing crew time in a spacesuit. During EVA, crew utilized hammers, scoops, tongs, and sample bags...
available on an aft tool rack adjacent to a sample storage compartment. Voice and video from crew were streamed through the LER to mission control.

Other scientific instrumentation: Ground-penetrating radar (GPR) was installed on the UPR Chariot during the Moses Lake test and successfully detected subsurface water. A more advanced unit was installed beneath the aft deck of the LER (Fig. 2) for an extended 14-day mission simulation at Black Point, demonstrating its application in rugged field conditions. A neutron spectrometer is another ISRU-related survey tool for volatiles that could be installed on future LER.

Exploration potential: The LER was designed to carry 14 days of consumable supplies, so crew do not need to return to the lander each day, providing a capability for extended traverses. A single 14-day-long LER traverse was simulated with a crew of two at Black Point. In addition, a 28-day-long, dual rover mission was tested with two crews of two. A dual LER operational mode may extend the ~6 mile Apollo-era walk-back limit on distance from a lander to 150 mi (~240 km) [5], which would exceed that needed to traverse the 100 km-radius exploration zones being examined [6] for the ISECG five-mission scenario.

Crew landing sites: Potential capabilities of the LER were previously evaluated for missions to the Schrödinger basin [7] and Kepler crater [8]. Based on a global landing site survey for locations that address the largest number of lunar science and exploration objectives [9], the Schrödinger basin was found to be the highest-priority target [10]. As part of the ISECG study of human missions to the lunar surface [1], a sequential series of five landing sites that included the Schrödinger basin was identified for crew: Malapert massif, South Pole, Schrödinger basin, Antoniadi crater, and the center of the South Pole-Aitken basin. At each of those sites, four crew would use dual LER to explore regions up to 100 km radius with two 14-day-long loops during 28- or 42-day-long missions. An initial assessment of those landing sites has been completed [6] and demonstrates that a large fraction of the science objectives for the Moon [9] can be addressed at those sites.

Tele-robotic capabilities: In the ISECG five-mission scenario [1], the LER are tele-robotically driven from one landing site to another during year-long intervals between crew landings. A recent study of those traverses [11] revealed that a tremendous amount of science and exploration can be conducted along those traverses. For example, with on-board GPR and a neutron spectrometer, the LER can survey the floors of Cabeus and Anumnsen craters for subsurface volatile deposits that could be mined for important ISRU constituents needed for a sustainable exploration program. Thus, while crew can provide detailed studies of the 100-km-radius regions around landing sites, the rovers can extend that exploration potential to the entire 2,570 km length between the five landing sites along a 3,718 km-long route optimized for science and exploration purposes [11].

Conclusions: The LER provides mobility, visibility, accessibility, surface documentation, and surface sampling, making it a valuable geologic tool. It potentially extends the distance travelled from the lander by a factor of 25 compared to the limit of the Apollo Lunar Roving Vehicle (LRV) and, thus, an area 625 times larger. It also greatly reduces daily spacesuit time for crew, while extending their exploration potential.

Acknowledgements: The lessons captured here are a product of NASA Desert Research and Technology Studies in 2008 through 2011 and would not have been possible without the input of vehicle crews and the science, mobility, communication, health and safety, human factors, and mission operational teams that supported them. The JSC mobility team built an incredibly capable vehicle.

European Engagement in Human Lunar Exploration: Near-Term Technical Challenges and Scientific Opportunities. M. Landgraf and S. Hosseini1, 2Markus.Landgraf@esa.int, ESA/ESTEC, Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands, 1ISAE/Supaero, 10, avenue Édouard-Belin, BP 54032 - 31055 Toulouse CEDEX 4, France

Introduction:

There is growing consensus that the next steps in human spaceflight beyond Earth orbit will be the implementation of a staging post in the lunar vicinity. Key questions to be addressed are: What are the technical challenges of such an undertaking, and what are the respective opportunities for scientific investigations offered by it?

The common goals and objectives of space exploration are constantly coordinated and evolved by participating agencies of the International Space Exploration Coordination Group (ISECG) – a forum representing 15 agencies. A high-level roadmap of exploration missions and capabilities is one of the products of ISECG. This global exploration roadmap (GER), in its current version [1], reflects a common long-range human exploration strategy. Building on International Space Station (ISS), it calls for discovery-driven missions that evolve capabilities and techniques needed to go further.

The international community recognises that – while the staging post commonly referred to as the evolvable Deep Space Habitat (eDSH) is a multi-destination capability – lunar surface exploration represents a significant utilisation case thereof. The eDSH will likely be placed on one of the family of libration orbits in the Earth-Moon system [e.g. 2]. It will support preparations for deep space missions by providing power, habitation, robotic manipulation, docking, and communication. Due to its strategic location, access and communication to the polar and far side locations on the Moon’s surface will become available.

For the lunar surface, the GER foresees a step-wise approach of increasing capability starting with automated missions aiming to close strategic knowledge gaps by the end of this decade, advancing to human assisted sample return in the mid-2020s, and culminating in the return of human explorers to the lunar surface towards the end of the 2020s. The main subject of the present paper is a description of the two latter mission scenarios, attempting to engage in an open exchange with the community on the technical challenges and scientific opportunities posed by them.

Human Assisted Sample Return:

Recognising the significant challenges of human lunar return, the ISECG has devised an affordable and feasible approach to flight-demonstrate critical components of a human lunar exploration architecture. The ISECG study “Human Lunar Exploration Precursor Programme” (HLEPP) has conceptualised a mission using a sub-scale landing vehicle and rover [3]: The lander operates for two and a half lunar cycles (day-night-day-night-day) while the rover demonstrates mobility collecting samples. The ascender returns the samples to the eDSH – much as the human-rated ascender will return humans to the same location. Recognising the capabilities of human operators [4], it is planned to enable tele-operations of the rover on the surface by crew from the eDSH. After approximately 10 kg of samples will have returned to the Earth inside the crew vehicle the rover continues its demonstration of long-duration and long-distance planetary surface mobility tele-operated from the ground and relying on time-tagged commands. A tentative definition of a one-year surface traverse in given in [5].

Results of the HLEPP study indicate a high efficiency of this approach in reducing the development and operational risk for human lunar exploration.

Human Lunar Exploration:

A concept of human lunar exploration that addresses the objectives of scientific knowledge gain, advancement of in-situ resource utilisation, and preparing human missions to Mars has been advanced by ISECG based on strategic principles of affordability, exploration value, international cooperation, capability evolution, human-robotic partnership, and robustness. In its current version the human lunar architecture calls for five mobility-based missions allowing exploration of far side and polar locations within an exploration zone of approximately 100 km radius each.

Technical Challenges:

Lunar surface exploration benefits from the availability of data and experience from the Apollo programme [6]. However, increased mission duration, mobility requirements, and a changed level of risk acceptance by stakeholders lead to a number of technical challenges. The lunar surface environment requires mechanisms to be resilient against dust, withstanding temperature fluctuations and hard vacuum. Radiation poses challenging conditions for complex data handling equipment and humans. However, on the Moon it is with $<1$ mSv/$0.3$ mGy per day more benign by a factor $\sim 3$ than on the martian surface.

Operational risk is dominated by space transportation, i.e. reliability of the propulsion system and its associated control system. There are mission phases in orbit insertion, descent, ascent, and rendezvous that require flight-demonstrated systems before humans are accepted on board. On the surface, the crew
will critically rely on the functioning of their habitat and surface mobility, both of which have seen only short-term demonstration in the frame of the historic Apollo missions. There are a number of technologies and components that are considered in the frame of human lunar exploration and thus require flight proving in the frame of a demonstrator mission: main engines, guidance, navigation, and control (GNC), hazard detection and avoidance (HDA), attitude and orbit control system (AOCS), generation of electrical and thermal power for life support, and drive trains for locomotion.

**Scientific Opportunities:**

In space exploration, scientific investigations address strategic knowledge gaps and provide enabling information for future missions, but also benefit from the opportunities of new capabilities. The ongoing process of regular review and update of scientific goals and objectives has the motivation to make maximum use of opportunities if and when they arise.

For the case of lunar exploration, prominent, internationally recognised reference documents have been released by the National Research Council [7], the Lunar Exploration Analysis Group [8], and the ISECG [9].

Mastering the technical and operational challenges of lunar exploration requires capabilities that naturally open opportunities for sample return and in-situ investigations that potentially address many of the top-priority investigations [7,8,9]. The need to reduce the risk of operating in the less known locations in the lunar polar regions and on the far side means that new, previously unexplored regions will become available for science [6]. In particular, the one-year traverse of the tele-operated demonstration rover will provide imaging data, (limited) opportunities for in-situ payloads. The samples taken during the lander mission represent the most significant opportunity for laboratory analyses after the return of more than 380 kg of lunar samples in the frame of the Apollo programme. While the missions are primarily for demonstration purposes, scientific objectives will be developed for each mission with input from the scientific community, and scientifically-informed operations activities for selection of samples will be developed in order to address these objectives.

In the human exploration phase, the capabilities of a scientifically-trained crew to intuitively characterise and document a geologic context and to make serendipitous discoveries as proven in the Apollo programme will create potential of scientific discovery beyond current capabilities. It is expected that hundreds of kilogrammes of samples are returned in the frame of the five missions currently conceptualised. Also, deployment of in-situ instrumentation with an accumulated mass in the same order will become available. Investigations in the frame of in-situ resources will create opportunities for understanding the evolution and origin of volatile materials in the Solar System.

**Summary:**

The communities addressing lunar geology, solar system physics, astrophysics, life sciences, and technology research are called to contribute ideas for instrument payloads, sample analysis, and technology demonstration in the frame of mission scenarios conceptualised in the frame of the GER. Opportunities exist in the near term to shape possible programmatic implementation of these concepts by international space agencies.

**References:**

LUNAR SURFACE MG# DISTRIBUTION AND MAGMA OCEAN CRYSTALLIZATION. M. Laneuville¹, D. Breuer², A.-C. Plesu², S. Schwinger² and K. Miljković³. ¹Earth Life Science Institute (ELSI), Tokyo Institute of Technology, Tokyo, Japan. ²German Aerospace Center (DLR), Berlin, Germany. ³Department of Applied Geology, Curtin University, Perth, Australia.

Abstract. Recent results from the Japanese Kaguya (SELENE) mission [1], and analysis of lunar meteorites [2,3] suggest that the lunar highlands are much more heterogeneous than previously thought. Specifically, there is a longitudinal gradient in magnesium number (Mg#) that needs to be explained.

During magma ocean crystallization, the Mg# of anorthosite varies with time as iron and magnesium fractionate between liquid and solid phase. Understanding the observed hemispherical Mg# trend is thus linked to the problem of understanding the time evolution of near- and farside crustal thickness.

In this presentation, we review the petrological character of the Mg# variation trend and report possible scenarios to explain its existence.

Introduction. The lunar nearside and farside differ in terms of volcanic activity, crustal thickness, elemental abundances, but the highlands have long been thought to be homogeneous on both hemispheres.

Recent analysis using Kaguya (SELENE) spectral profiler showed that there is a significant difference in magnesium content relative to iron (Mg#) between the two hemispheres, as can be seen in Fig. 1 [1]. Iron is more incompatible than magnesium (i.e., stays preferentially in the melt), therefore a higher Mg# implies crystallization from a less evolved magma ocean. However, such an observation could be explained by different scenarios: (1) a homogeneous primordial magma ocean followed by an asymmetric crustal crystallization, (2) a poorly mixed magma ocean followed by a uniform crust formation, or (3) a symmetric crust composition, but an asymmetric mixing process that resurfaced different portions of the crust on each hemisphere.

We approach this problem from two perspectives. From petrological considerations, we study the link between magma ocean properties and anorthosite composition. On the other hand, we also consider an energy balance approach to understand which environmental conditions could produce a thermal evolution consistent with observations.

Magma ocean crystallization sequence. The sequence of crystallizing phases in a lunar magma ocean has been studied both through direct experiments and thermodynamic considerations. Here we use the software package MELTS to understand how the Mg# content of anorthosite evolves with magma ocean crystallization. Figure 2 (top) shows the anorthosite Mg# as a function of magma ocean crystallization state (in “percent solid”, PCS, vol%) for different relative plagioclase fractions, defining anorthosite as a pure mixture of plagioclase and clinopyroxene. From these curves, it is possible to compute what PCS distribution is required to reproduce a given Mg# distribution (Fig. 2, bottom). We do this by inverting the functions in Fig. 2 (top) and asking which range of PCS would produce the Mg# distribution of Fig 1.

This result depends on a minimal amount of assumptions, namely a given crystallization sequence. We can therefore use this to get an insight into the timing of crystallization and depth of origin of the crust. It is important to stress here that we can only make statements about the part of the crust that is sampled by remote sensing. For example, the nearside Mg# distribution can be best explained by a narrow range of PCS, while the farside is explained by a broader, almost uniform distribution.

In this study, we focus on scenario (1), which can be explained either by asymmetric crystallization, where the early crust is formed first on the farside [3], or formed everywhere but transported preferentially to the farside [e.g., 4]. A scenario where the crust is formed symmetrically, but partly removed on the nearside is possible but not studied here. We now investigate models that can explain a crystallization sequence such as that in Fig. 2 (bottom).
We run simple energy balance calculations in the magma ocean to track the evolution of the crustal thickness and composition. The thermal model is similar to [5], but we do not model orbital evolution:

\[ E - Q = (Q_L + Q_s) \frac{dr}{dt} \]

Where \( E \) is the surface heat flow, \( Q \) heating due to radioactive decay, \( Q_L \) and \( Q_s \) the latent heat and secular cooling contribution terms, respectively, \( r \) the thickness of the crust and \( t \) is time. The surface heat flow is parameterized as \( F_0 + (F_0 - F_1) \exp(-t/\tau) \), to take into account a possible asymmetry between near- and farside cooling rate, where \( F_0 \) and \( F_1 \) are the initial surface heat flows on the far- and nearside.

For a given crystallization sequence (as parameterized in Fig. 2, top), the free model parameters to generate Mg# distribution on both hemispheres are the different cooling rates between hemispheres (including potential delay), and the effective depth sampled by remote sensing (impact induced crustal mixing) which can be different between hemispheres. We use results from a shock physics hydrocode to assess this.

Fig 3 shows an example of Mg# profile with depth in the crust on both hemispheres. The gradient is shallower on the farside, which crystallized from lower PCS than the nearside. Fig 2 (top) indeed shows that at low PCS, a given volume of crystallization leads to a smaller decrease in Mg# than at higher PCS values. Note that those curves can change depending on the crystallization model (i.e. trapped liquid at depth, melting by decompression...). This will be investigated in the future.

**Conclusion:** The crustal profile shown in Fig. 3 does not fit the observed Mg# distribution, as both hemispheres have a similar largest Mg# value. We plan to sample the model phase space through Monte-Carlo algorithm to find which type of evolution can best reproduce the data (i.e. observed nearside comes from a much smaller range of PCS than the observed farside). A critical point will be to understand which property of the distribution observed in Fig. 1 informs us most about the crust formation process.

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Introduction: This presentation will introduce Moon Trek, a new name accompanying a major new release of NASA’s Lunar Mapping and Modeling Portal (LMMP). Upgrading to the new Trek interface provides greatly improved navigation, 3D visualization, performance, and reliability. The new Moon Trek interface also provides compatibility with the other portals developed by NASA’s Lunar and Planetary Mapping and Modeling Project. Behind the scenes, this release also entails upgrades to the portal’s back end infrastructure and services. These will significantly facilitate the implementation of exciting new features and capabilities in the months to come, some of which will be previewed in this presentation.

An Integrated Suite of Interactive Tools: Originally designed to support site selection and analysis for the Constellation program, Moon Trek evolved from LMMP to meet the needs of mission planners in a new era of lunar exploration. The portal integrates a suite of interactive tools that incorporate observations from past and current lunar missions, creating a comprehensive lunar research Web portal. The online Web portal allows anyone with access to a computer to search and view a vast number of lunar images and other digital products. As a web-based application, Moon Trek does not require users to purchase or install any software beyond current web browsers. The portal provides easy-to-use tools for browsing, data layering and feature search, including detailed information on the source of each assembled data product. Using Moon Trek, many hundreds of lunar data products can be both visualized and downloaded. Detailed metadata for each data product is also made available to the user. While emphasizing mission planning, Moon Trek also addresses the lunar science community, the lunar commercial community, education and public outreach (E/PO), and anyone else interested in accessing or utilizing lunar data. Its visualization and analysis tools allow users to measure distances, generate elevation profiles, conduct lighting analyses, and generate slope maps.

Moon Trek’s generalized suite of tools facilitates a wide range of exploration activities including the planning, design, development, test and operations associated with lunar sortie missions; robotic (and potentially crewed) operations on the surface; planning tasks in the areas of landing site evaluation and selection; design and placement of landers and other stationary assets; design of rovers and other mobile assets; developing terrain-relative navigation (TRN) capabilities; deorbit/impact site visualization; and assessment and planning of science traverses.

Current data products include image mosaics, digital elevation models, local hazard assessment tools (such as maps of slope, surface roughness and crater/boulder distribution), lighting assessment tools, gravity models, and resource maps such as soil maturity and hydrogen abundance.

In addition, Moon Trek fosters outreach, education, and exploration of the Moon by educators, students, amateur astronomers, and the general public. It has been designated by NASA as a component of its Science Education Infrastructure. While great utility is provided by Moon Trek’s interface and tools, it also provides particular value through its ability to serve data to a variety of other applications. In the outreach realm, this has been demonstrated with data served to planetariums and NASA’s Eyes on the Solar System.

New Features and Coming Enhancements: The most notable enhancement in the new release is the greatly improved visualization and navigation capabilities provided by the new Moon Trek interface. Users can also now draw a bounding box around any surface feature and generate an STL or OBJ file for use with 3D printers. New enhancements are also being made to hazard analysis tools, including local hazard assessments such as surface roughness and crater/boulder distribution. Looking further ahead, we are working on automated traverse planning tools, developing plans to facilitate examining surface temperatures as a function of time, and are collaborating with Bill Farrell and the DREAM2 SSERVI team on a Surface Potential Analysis Tool. We will collaborate with the NASA Astromaterials Acquisition and Curation Office to integrate with their Lunar Apollo Sample database in order to help better visualize the geographic contexts from which samples were retrieved. Additional clients in the works include a gesture-controlled touch table and virtual reality/augmented reality capabilities.

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Redox transition and compatibility of Mo during partial melting in the lunar mantle, F. P. Leitzke, R. O. C. Fonseca, G. Mallmann, P. Sprung, M. Lagos, L. T. Michely, and C. Münker. Steinmann Institut, Universität Bonn, Poppelsdorfer Schloss (Mineralogisches Museum), 53115 Bonn, Germany (felipe.leitzke@uni-bonn.de), Research School of Earth Sciences, Australian National University, ACT 2601 Canberra, Australia, Institut für Geologie und Mineralogie, Universität zu Köln, 50674 Köln, Germany.

Introduction: Molybdenum is a transition metal that exists in at least four known oxidation states in basaltic melts, ranging from Mo$^{6+}$ above AFMQ +2 to Mo$^{5+}$ below ΔIW-2 [e.g., 1,2,3]. Most of the planetary sciences' interest in Mo stems from its moderately siderophile character and its refractory behavior during evaporation or condensation, a fact that facilitates the determination of its natural isotope abundances in the solar nebula and comparison with what is observed in the terrestrial planets [4, 5]. A great amount of effort has been allocated to studying the partitioning behavior of Mo between metal and silicate liquids [e.g., 6,7] due to its importance constraining core formation processes. However, there is no systematic study on the redox transition of Mo based on the changes observed on crystal/silicate melt partitioning. Here, we present results from a series of experiments aimed at investigating changes in the partitioning behavior of Mo between silicate crystals (pyroxene and olivine) and melts as a function of composition and oxygen fugacity. Experimental redox conditions cover a broad range of fO$_2$, ranging from the average expected for terrestrial mantle reservoirs (FMQ -0.6 to FMQ +1.6) [e.g., 8,9], to the extremely reduced conditions expected for the lunar mantle, at IW -0.5 and below [10,11,12].

Experimental and analytical methods: Five compositions in the CaO-MgO-Al$_2$O$_3$-SiO$_2$ system were prepared in order to obtain at each time IV-Al-poor and IV-Al-rich clinopyroxene, orthopyroxene, olivine and plagioclase in equilibrium with silicate melt. Trace elements (P, Sc, Ti, V, Cr, Sr, Y, Zr, Nb, Ba, La, Nd, Sm, Eu, Hf, Ta, Mo, W, Th and U) were added to the powders, in amounts of 500 to 1000 µg/g. The only simplification from natural systems to our starting compositions is the small amount of Fe. We avoided large amounts of Fe to reduce loss to Pt wire. Nevertheless, it is considered reasonable to deal with an Fe-free composition when analysing the behavior of trace elements during mantle melting, since both primitive or depleted mantle reservoirs have molar Mg# higher than 80 % [12].

Experiments were carried out using Pt or Re wire loops. The metal loops and slurry (powder + glue + water) were hung inside a one-atmosphere vertical tube furnace and the temperature raised to 1350 and 1400 °C, i.e., around 50 to 100 °C above the liquidus of each composition and under redox conditions imposed by a gas mixture of CO-CO$_2$. Each sample remained at supra-liquidus conditions for 3 hours to ensure that powders were completely molten and homogenized. Cooling ramps were chosen for ideal crystal growth (at least 100 µm) for LA-ICP-MS analysis and temperature was lowered to the target run value (1220 to 1300 °C), in which it remained for 48 to 96 hours to ensure that chemical equilibrium was reached. The effective values of fO$_2$ inside the furnaces were checked and calibrated using a CaO-Y$_2$O$_3$-stabilized ZrO$_2$ electrolyte cell [see 13]. Temperature was monitored during the experiments using an internal type B (Pt70Rh30 – Pt94Rh6) thermocouple. Quenching of the samples was in air by removing the sample holder from the top of the furnace or in water. Quenched loops were recovered, mounted in epoxy resin and polished for chemical analysis. Major and minor elements (CaO, MgO, Al$_2$O$_3$, SiO$_2$, TiO$_2$, MnO and FeO) were analysed by a JEOL JXA 8900 electron microprobe at Wavelength Dispersive mode (WDS), with 15 kV acceleration voltage, 15 nA beam current and a focused beam. Trace element concentrations were analysed by a Resonetics Resolution M50-E 193 nm Excimer Laser Ablation apparatus coupled to a Thermo Scientific XSeries II Q-ICP-MS. Laser spot sizes ranged between 58 to 100 µm, and were picked depending on crystal size and/or prevalence of melt inclusions.

At lower fO$_2$ the presence of metallic micro or nano-nuggets is known to affect ICP-MS measurements of silicate phases. To mitigate this problem, only analyses where the presence of these nuggets could be filtered out from the time-resolved spectra were used. This approach has proven successful in determining true solubility and partitioning of siderophile elements in silicate systems [e.g., 14]. At oxygen fugacities exceeding the FMQ mineral redox buffer, Mo is partially lost due its volatile behavior, while at lower oxygen fugacities it starts to diffuse into the metallic Pt wire, turning the LA-ICP-MS analysis of crystals and silicate glasses difficult due to its low concentration (0.1 - 1 ppm). Nevertheless, the lack of any obvious isobaric interference, as well as the agreement between crystal/silicate melt Mo partitioning values under similar fO$_2$ but with different Mo contents from experiments done with Pt and Re-wire strongly suggests that such issues did not impact on Mo data quality in this study. Results and Discussion: Results show that Mo is volatile above FMQ and that its compatibility into pyroxene and olivine increases three orders of magnitude within the range of oxygen fugacities covered in this study. At FMQ -4, Mo$^{6+}$ is the dominant valence state, while at values above FMQ, Mo$^{6+}$ is prevalent. This indicates that during partial melting...
in the mantle of the Earth, Mo will be exclusively 6+ and highly incompatible in silicate phases.

![Diagram showing partitioning of Mo as a function of fO2 (given in Δ relative to the FMQ redox buffer) between clinopyroxene (a), orthopyroxene (b), olivine (c) and haplobasaltic melt. Lines represent best fits of the partitioning data considering a two-electron redox transition. Error bars are 1σ standard deviation. Literature partitioning data for Mo is from various studies [15,16,17,18], Data from previous studies at unconstrained fO2: This parameter was estimated based on crystal/silicate melt partitioning of V [19] or the approximated buffer assembly mentioned in the text.](image)

For the lunar mantle, however, which is equilibrated at lower oxygen fugacities, Mo is present exclusively as 4+ and is less incompatible in olivine and pyroxene (Fig. 1), due to its ionic radius being close to the ideal substitution into these crystals’ octahedral sites (0.65 Å). Molybdenum, and to a lesser extent its geochemical twin W, show similar values of crystal/silicate melt partition coefficients between cpx, opx and olivine, while HFSE and REE crystal/silicate melt partition coefficients follow the trend cpx > opx > olivine, in agreement with previous findings under similar experimental conditions [e.g., 19]. This is a result of the tetravalent species of Mo and W being close to the t0 value in all crystals, and the substitution in cpx is probably as Ca-Mo4+Al2O6, i.e., similar to the expected substitution mechanism of other tetravalent cations, such as Ti4+ and Re4+ [e.g., 18,20]. For opx and olivine the substitution mechanism appears to be direct exchange between 2Mg2+ and Mo4+. The stiffness of the M1 site, represented by the Young’s modulus (E) in GPa follows the expected increase from cpx to opx and olivine. It is important to point out that no evidence regarding the presence of Mo6+ was found in our experiments. This was expected, because the transition to this oxidation state probably takes place at conditions more reduced than IW-3 [2].

**Concluding remarks:** Our results show that molybdenum behaves as a relatively compatible trace element in silicates at extremely reducing conditions, such as those pertinent to the lunar mantle. This indicates that at least some Mo may have been retained in the silicate portion of the lunar mantle during core formation and/or genesis of the lunar mare basalts. This is in agreement with the depletion in Mo in lunar samples relative to the observed concentration in chondrites and terrestrial basalts [21]. There is still a great need for studying the behavior of Mo between phases like ilmenite, garnet, and plagioclase, which would help to better constrain the Mo budget in lunar mantle reservoirs.

MOON ADVANCED RESOURCE UTILIZATION VIABILITY INVESTIGATION STUDY. S. Lentz, J. Bolz, T. Diedrich and J. Weppler, Airbus Defence and Space GmbH, Airbus-Allee 1, 28199 Bremen, Germany, Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Königswinterer Str. 522-524, 53227 Bonn, Germany (stefan.s.lentz@airbus.com).

**Introduction:**
This presentation presents the activities performed in the frame of the Moon Advanced Resource Utilization Viability Investigation (MARVIN) phase 0 study. MARVIN was initiated by the DLR Space Administration, with the purpose to develop a lander mission which shall perform extraction and utilization of resources on the moon as a technology demonstration for the usage within future exploration missions.

In-Situ Resource Utilization (ISRU) is seen as a key element to expand the capabilities for lunar exploration by breaking up the reliance on earth supplied resources for structures, power, propellant, life support etc and thereby to lower overall launch mass of lunar exploration missions and associated cost for transportation of infrastructure and consumables from earth.

Within the field of possible ISRU applications, MARVIN focuses on the utilization of consumables and in particular on the extraction of oxygen from lunar regolith as a useful product for human exploration life support, as well as an element for propellant or fuel cell production.

Several processes for oxygen production from lunar regolith have been proposed and discussed within the last 30 years [1] and some have been matured up to a Technology Readiness Level of analog site testing [2] [3]. The missing step still is the prove of oxygen production on the lunar surface under lunar environmental conditions.

The main objective of MARVIN is to close this gap and to demonstrate repeatable oxygen production on the moon as a technology demonstration that can be scaled pending on the needs of future missions. In order to achieve this objective the study overall includes not only the design of an oxygen reactor, but also the mission concept, a lunar landing spacecraft and robotic elements for the lunar regolith excavation and processing within the ISRU feed and disposal system.

The study was performed by Airbus Defence and Space On-Orbit Services and Exploration in close cooperation with the German aerospace centre DLR institutes of Space Operations and Astronaut Training, Robotics and Mechatronics Centre and the Institute of Planetary Research and the Technical University of Munich (TUM).

This presentation will provide status of the work performed. It will briefly describe the results of the trade-offs and assessments, outline the selected mission elements and the follow-up roadmap up to the targeted launch in 2025.

**References:**
A LUNAR HYGROMETER BASED ON PLAGIOCLASE-MELT PARTITIONING OF WATER. Y. H. Lin1*, H. J. Hui2, Y. Li3, Y. J. Hsu3, W. Chen1, E. S. Steenstra1 and W. van Westrenen1, 2Faculty of Earth and Life Sciences, Vrije Universiteit Amsterdam, The Netherlands (y.lin@vu.nl); 3State Key Laboratory for Mineral Deposits Research, School of Earth Sciences and Engineering, Nanjing University, China; 4Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, China.

Introduction: The classic view of a dry lunar interior has been challenged by recent discoveries of hydrogen (H, often reported as equivalent amounts of OH or H2O) in lunar samples [1-4]. Sample-based inferences about water in the Moon are complemented by experimental studies of lunar magma ocean crystallization, that suggest the presence of water in the early Moon is required to explain the observed thickness of the lunar crust [5]. Converting measured hydrogen abundances in samples or experiments to quantitative estimates of the abundance of water in the Moon and its temporal and spatial evolution is, however, far from straightforward [6]. As a result, estimates of lunar interior water contents vary by several orders of magnitude from <10 ppm to >1000 ppm.

This study focuses on improving constraints on the water content in the Moon specifically during the lunar magma ocean (LMO) stage. Nominally anhydrous plagioclase is thought to have crystallized and floated to the surface during the later stages of LMO cooling, forming the primary lunar crust [5,7,8]. This indicates that lunar plagioclase from ferroan anorthosite, a direct product of the LMO [9], could be our best candidate for estimating the water content of the LMO [10].

To link plagioclase water contents to the water contents in the LMO from which these crystals grew, plagioclase-melt partitioning coefficients for hydrogen are required, with \( D_{\text{pl-ag}} = \frac{C_{\text{pl}}}{C_{\text{ag}}}/\frac{C_{\text{pl}}}{C_{\text{ag}}} \).

Unfortunately, to date, no plagioclase-melt partitioning data for water are available under lunar conditions. In this study, \( D_{\text{pl-ag}} \) was measured for the first time at lunar-relevant pressure-temperature-composition-oxygen fugacity conditions using high-pressure and high-temperature experiments and Fourier-transform infrared (FTIR) spectroscopy. The main purpose of this study is to offer further constraints on the LMO content of the Moon at the time of plagioclase formation.

Experimental: The composition of our starting material and the experimental pressure-temperature conditions were based on our recent experimental study of lunar magma ocean crystallization [5]. High-pressure, high-temperature experiments were performed in a piston cylinder press using a half-inch diameter talc-pyrex cell assembly. For these experiments a hand-machined graphite bucket was filled with starting material, closed with a graphite lid and inserted in a gold-palladium (Au90Pd10) capsule. Experiments were pressurized cold and then heated to a superliquidus temperature of 1280 °C in 20 mins.

Subsequently, samples were cooled to the temperature of interest at a rate of 10 °C per hour while maintaining target pressure, followed by 14–22 hours at target temperature. Pressure was 0.4 GPa in all experiments performed to date, and final target temperatures ranged from 1160 to 1200 °C. At completion of an experiment, runs were quenched by cutting power to the heater and the temperature typically dropped below the glass transition in < 10 s.

Analytical: Experimental run products were mounted in epoxy and polished for back-scattered electron (BSE) imagery (Fig. 1) to assess texture and mineralogy, and then carbon coated for electron microprobe analysis (EMPA). After EMPA analysis, hydrogen concentrations in minerals and coexisting glass in our samples were analyzed at the State Key Laboratory for Mineral Deposits Research, Nanjing University, using a Nicolet IS50 Fourier Transform Infrared Spectrometer equipped with Continuum microscope, liquid nitrogen cooled MCT/A detector and KBr beam splitter.

Results: Experiments produced plagioclase crystals in equilibrium with quenched melt (Figure 1).

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Figure 1: Back scattered electron (BSE) image of a representative experimental run product (LBS7H, 0.4 GPa – 1200 °C). Px = pyroxene; Plag = plagioclase.

The hydrogen concentrations of our samples range from 58±18 to 99±36 ppm OH in plagioclase and from 0.24±0.09 to 1.03±0.16 wt.% OH in glass. The corresponding partition coefficients range between 0.006±0.002 and 0.04±0.01. Water partitioning values decrease with increasing abundance of water in coexisting glass. The lowest D value in our experiments is still higher than almost all previously published data (\( D_{\text{pl-ag}} = 0.001–0.006 \) based on Hamada et al. [11]). Our highest partition coefficient is ~10 times higher than previously reported values. The possible reason for this major difference is likely...
oxygen fugacity, consistent with previous observations about the dependence of H solubility in feldspars on oxygen fugacity [12].

Discussion and Conclusions: The only study published to date of the water content of lunar plagioclase reported 6.4 ppm water (H$_2$O equivalent) in ferroan anorthosite sample 60015 [10], thought to be a primary crystallization product of the LMO [9,13]. Our experiments constrains $D_{\text{water}}^\text{plag}$ to 0.006–0.04 under lunar conditions. Based on the above constraints, the amounts of water (in terms of equivalent H$_2$O) in the residual LMO after ~75% solidification of the initial magma ocean is calculated to be 160–1130 ppm. We previously showed that the minimum amount of water in the initial LMO was 500–1800 ppm (with the lower minimum linked to a shallow (400 km) initial magma ocean and the higher minimum linked to a deep (1000 km) initial magma ocean) [5]. If no H degassing from the LMO had occurred until sample 60015 was formed, the water content of the LMO at the time of plagioclase formation should have been 0.2–0.72 wt.%. The much lower estimates of the amount of water remaining in the LMO by the time of formation of 60015, derived from our plagioclase-based hygrometer, indicate that the early Moon experienced extensive degassing during the LMO stage, with ~45–98 percent of the initial water lost during the first three quarters of LMO crystallisation.

References:


Introduction: Impact events have been the primary mechanism for modification of the lunar surface since the formation of the lunar crust[1]. Impacts produce varying amounts of melt, which may be identified and radiometrically dated in surface samples. Existing melt can be redistributed by the ejection process of subsequent impacts.

It is possible to evaluate the amount of the impact melts, but the cumulative effect of the impact gardening process (i.e. excavating, burying, and re-excavating) has not been systematically studied. Michael et al. 2014 simulated such long-term process by using the Monte Carlo method[2]. Nevertheless, the corresponding results are in an average sense, where the impact melt is considered to be evenly distributed over the entire lunar surface.

The purpose of this work is to refine the average model into two-dimensions where the lateral distribution of impact melt is recorded, and the age of melts within the evolving mixture is tracked.

Method: The essence of the model is the following:

1. The nominal starting age, $t_0$, is taken as 4.5 Ga, and the minimum crater diameter considered, $D_{min}$, is chosen as 30 km based on the performance of computers.
2. By using the Monte Carlo method, the diameter of the formed craters is generated to conform with the production function larger than $D_{min}$ [3].
3. The impact rate is calculated for the current model time, $t$, on the basis of the lunar chronology function, which describes the cumulative number of craters larger than 1 km in diameter at age $t$[3]. Using the production function the formation rate of craters larger than $D_{min}$ is found.
4. The average time to the next impact event can be obtained based on the impact rate.
5. For each crater, the excavation depth is taken as $D/10$[4], where $D$ is the corresponding crater diameter.
6. The ejecta blanket thickness is related to the distance from crater center, $r$: $\delta = aR^b(r/R)^c$ for $r>R$, where $R$ is the crater radius, and $a$, $b$, and $c$ are taken as 0.14, 0.74 and -3.0, respectively[4].
7. The distribution of impact melt both inside and outside the crater has not been fully understood limited by the laboratory conditions or/and computer performance in the previous researches[5]. Such issue is under study in collaboration with the group guided by Kai Wünnemann.

Expected Results: The following figure shows the expected results after the lunar surface experiencing two impact events in this model.

During the first impact process, the old materials with age of $t_0$ are excavated, a fraction of which is melted because of the high temperature (Figure a)[4]. The thickness of ejecta blanket decreases, whereas the portion of the impact melts increase, with increasing distance from the crater center (Figure b)[4, 5]. By dividing the surface into cells, the lateral distribution of ejecta blanket and the portion of unheated and melted materials are recorded, tracking the age of impact melts as $t_1$ (Figure c).

The subsequent impact process penetrates the previous ejecta blanket and excavates materials from both the previous layer and beneath, melting a fraction of both (Figure d). A fraction of the ejecta materials overlay the previous deposition. The distal ejecta material consists of the higher portion of impact melt (Figure e)[5]. The three components (i.e. impact melt with age of $t_1$ and $t_2$, and the oldest materials with age of $t_0$) of the newly-formed ejecta deposit are stored in this model (Figure e).

Significance: Using the observed distribution of melt age in lunar samples and meteorites, the possible scenarios of the lunar impact history can be discriminated[2].

The record of lateral distribution of the impact melt with different ages is also helpful for the future lunar sampling, guiding the choice of site to obtain samples from different impact basins, and to understand the mixture of melt ages observed at any one site.

There has long been a dispute over the cause of the high percent of lunar samples with age of ~3.9 Ga[6]. Some believe that it results from the impact cataclysm[7]. Others argue that it might be due to the origin of the collected samples, most of which might be the ejecta materials from Imbrium crater[6].

Where do the ejecta go? Our model will present a general explanation of this issue, which aids the analysis of the lunar samples.

Figure. Schematic of the simulations. (a) Impact event causing ejecta of both unheated and melted material when time is $t_1$. (b) The deposition of ejecta with a mixed layer of unheated (white) and melted (red) material. (c) The expected lateral distribution of (b) in this model tracking the percent of unheated and melted material, the age of impact melt and the thickness of ejecta. (d) A subsequent impact event when time is $t_2$, penetrating the previous ejecta blanket, excavating material from both the previous layer and beneath, and melting a fraction of both (blue). (e) The deposition of a new layer containing both new melt and a component of re-excavated melt from the previous event. A fraction of ejecta materials overlay the previous deposition. (f) The expected lateral distribution of (e) in this model tracking the percent of unheated, melted material, the age of each fraction and the thickness of ejecta.
THE LUNAR REFORMATION: A REFORMED PLAN FOR RETURNING TO THE MOON

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**Introduction:** The Moon has long been a focal point in our collective human spaceflight aspirations and imaginations. Since the 1640s, when John Wilkins first seriously discussed the technical aspects – at least as they were understood at the time – of travel to the ‘World in the Moone’ revealed by the recently invented telescope, visions of missions to the Moon have been core to the idea and ideal of space exploration. The Moon has also been central in space policy discussion, both internationally and at NASA. Although Mars and other destinations in the solar system have had, at times, equal or even greater political prominence, there is no doubt that the Moon is a central node in planning for the future of space exploration and space development.

As a result of the Moon’s natural importance for the space community, and indeed for human culture in general, a subset of the space community has recognized this importance and focused on realizing the most rapid and extensive set of lunar exploration and development activities possible. The result has been the emergence of a set of dominant beliefs regarding the appropriate motivations and methods for a return to the Moon within parts of the international space community; that humans should build permanent habitable bases on the surface of the Moon for a wide variety of purposes - whether public, private or a combination of both – and that moving towards this goal starting with government-led human surface landings at the present time represents a logical focus for both near and long-term space policy.

This approach to lunar surface missions and development, although understandable and laudable as a driver for particular groups within the broader space community, is a potentially destabilizing trap from the perspective of overall space policy. There are a number of legitimate reasons to think about expanded and intensified lunar activities at this time. However, the financial and opportunity costs associated with adhering fully to the approach described above are far too high and threaten the viability of human missions beyond the Earth-Moon system for a generation or more. The lunar surface remains a compelling destination, but the prevailing dogma regarding how to realize that future – return humans to the lunar surface as soon as possible with the long-run goal of building up a permanent base to enable the provision of lunar-derived propellant – is damaging. We must reform our thinking if we to realize a course that allows for both interplanetary human spaceflight missions and returns to the lunar surface in the next few decades.

This paper will lay out the arguments against the prevailing approach to lunar surface return and for a reformed approach to a lunar return that also meaningfully enables interplanetary spaceflight. The core elements of this ‘lunar reformation’ are: 1) human lunar fly-by and orbit missions with SLS and Orion; 2) purchases of data from commercial lunar landers; 3) robotic polar landers for assaying lunar ice; 4) public-private partnerships for encouraging the development of autonomous robotic mining capabilities development; 5) the coordination and support of private-sector and/or international human lunar landers; and 6) an international interplanetary-class spaceship operating in the vicinity of the Moon to validate and test the long-duration deep space habitation and transportation operations and capabilities required for interplanetary spaceflight.
**Introduction:** A crater population is considered to be at equilibrium at a particular diameter when craters of that diameter (and smaller) are being produced at the same rate at which they are being destroyed [1-4]. Large-scale, short-timed events, can readily produce a degraded crater population (e.g. ejecta emplacement, lava flows or tectonic activity) in addition to the (comparatively slower) erosion of craters due to meteoritic bombardment and advective surface processes. In addition, small lunar craters (SLCs; <300 m) are susceptible to target-specific effects, such as strength dependent degradation rates [5]. Accelerated degradation is expected for less-cohesive (weaker) targets [6,7] and target strength is controlled by material properties [8,9]. Effusive and/or explosive volcanism can add discontinuous strength boundaries in the target layers that accelerate or slow the pace of degradation. Seismic and impact events can also weaken existing targets, either instantly or progressively [4]. The effect of accelerated degradation can be observed from the morphology of the affected SLC population. In the worst case scenario, accelerated degradation can manifest as removal of parts of SLC population, modifying the size frequency distribution (complete/partial resurfacing [16-18]).

Identifying the equilibrium onset diameter, D_{eq}, is complicated for a modified SFD, and recent work shows that a blanket (valid globally for the Moon) D_{eq} value cannot be assigned for specific surface ages [10], although smaller values of D_{eq} are more probable than larger values. In this work, we analyse and compare morphological statistics for equilibrium populations of SLCs obtained at the Apollo 14 and 16 sites to identify and investigate effects of target properties and associated past events.

**Methods:** SLCs were first identified manually from NAC ortho-photo mosaics, the digital terrain model (DTM), and a derived slope map for the two sites: Flat geologic units were then chosen (Figure 1) with slopes (<3°) to minimize slope effects on the longterm impact-related degradation process. Crater size-frequency distributions (CSFD) were then used to identify a common size range exhibiting equilibrium. Corresponding R-plots were used to identify the D_{eq} and then a subset of the common size range (40 m - 80 m) was used for our analysis.

Depth (d) and diameter (D) measurements for this size range were extracted automatically [11] followed by computation of d/D (Table 1). The fractional evolution time (P_0) is obtained from d/D. The d/D decreases as the crater population evolves with time and at d/D < 0.04, the crater is not recognizable and considered erased - the total number of craters with d/D ≥ 0.04 is proportional to a first-order approximation of the total evolution time [12].

![Figure 1: Crater size range selection for study](image)

**Table 1: SLC at equilibrium (Apollo 14 and 16 sites)**

<table>
<thead>
<tr>
<th>Region</th>
<th>Apollo 14</th>
<th>Apollo 16</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of craters</td>
<td>788</td>
<td>1791</td>
</tr>
<tr>
<td>Area</td>
<td>43</td>
<td>140</td>
</tr>
<tr>
<td>Median Crater Depth</td>
<td>2.5</td>
<td>6.6(fresh)</td>
</tr>
<tr>
<td></td>
<td>7.6(fresh)</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td>7.1(fresh)</td>
<td></td>
</tr>
<tr>
<td>Median Regolith Depth</td>
<td>6-8</td>
<td>12</td>
</tr>
<tr>
<td>D_e</td>
<td>230</td>
<td>170</td>
</tr>
<tr>
<td>Equilibrium Range</td>
<td>36 - 230</td>
<td>38 - 170</td>
</tr>
<tr>
<td>Median d/D</td>
<td>0.06</td>
<td>0.08</td>
</tr>
<tr>
<td>Median wall slope</td>
<td>10°</td>
<td>14°</td>
</tr>
<tr>
<td>P_0 ([d/D]_e = 0.1)</td>
<td>7</td>
<td>30</td>
</tr>
</tbody>
</table>
number of craters with \(d/D \geq [d/D]_0\) (a particular value) and the total number of craters \((d/D \geq 0.04)\) represents the fractional evolution time up to \([d/D]_0\).

Slope values were extracted for each crater (6 m baseline) on each crater wall midpoint.

**Results & Discussions:** The Cayley Plains and Fra Mauro regions are both highlands, where SLCs form within a deeper regolith layer than in mare regions. Imbrium ejecta underlies both areas, and the regolith layer consists of the existing Imbrium ejecta modified over extended impact bombardment in which impact melts and rock debris were mixed in varying proportions[15]. Thus, similarity is expected for the formation and subsequent degradation of SLCs due to similarity in the (strength) nature of the regolith target.

![Figure 2: Morphological difference for Apollo 14 and 16 small crater populations](image)

However, the \(d/D\) and slope histograms (Figure 2) show that the morphology of SLCs is distinctly different between the two regions, indicating that different target properties (and possibly seismic events) are responsible, assuming a similar crater production rate. A larger part of the SLC population at Apollo 14 is degraded \((d/D < 0.1)\) and this is true even for craters of sizes larger than investigated here \((>80\) m), contrasting only smaller sizes at other landing sites [13].

On an average an Apollo 14 crater spends only 7% \((P_0, \text{Table 1})\) of the total evolution time as a relatively fresh crater \((d/D > 0.1)\). In contrast, A16 SLCs spend an average of 30% time as fresh crater and after each interval of equal evolution time, A14 SLCs are more degraded (Figure 3). By computing absolute age estimates by an empirical expression: Age = 2.5 D ± 30% My [12], the freshest crater \((d/D ~ 0.16, D ~ 55\) m, \(P_0 < 1\%\)) has a maximum age of 2 Ma and the largest crater \((d/D ~ 0.1, D ~ 80\) m, \(P_0 < 10\%\)) has a maximum age of 26 Ma. It is possible that the few fresher SLCs formed after a major seismic event, e.g. the formation of Cone crater, which erased or strongly degraded existing craters, aided by the layered fragmental rocky nature of the regolith [14] at Fra Mauro.

![Figure 3: Comparing evolution of populations](image)

**Conclusion:** The Apollo landing sites with known radiometric ages and different targets provide interesting locations to analyze the effect of target properties on small crater degradation. SLCs at Apollo 14 are more degraded than at Apollo 16 and possible reasons include earlier (e.g. formation of Cone crater) and perhaps ongoing impact-related seismic degradation and/or the presence of a thick unconsolidated layer (loose friable Imbrium ejecta). Conversely, slower degradation at Apollo 16 might be caused by a larger mixing proportion of impact melt (into the regolith), making it more consolidated. Inclusion of secondary impact can also affect our statistics and future work will further investigate the above possibilities.

**References:**

CHARACTERIZATION OF LUNAR HIGHLANDS REGOLITH SIMULANTS IN PREPARATION FOR DRILLING AND SAMPLING INTO THE POLAR REGOLITH BY ESA’s PROSPECT PACKAGE. D. J. P. Martin\(^1\), K. L. Donaldson Hanna\(^2\), K. H. Joy\(^3\), J. D. Carpenter\(^4\), N. E. Bowles\(^5\), and PROSPECT User Group\(^6\), \(^1\)School of Earth and Environmental Sciences, University of Manchester, Manchester, UK, (dayl.martin@manchester.ac.uk), \(^2\)Atmospheric, Oceanic and Planetary Physics, University of Oxford, Oxford, UK, and \(^3\)ESA ESTEC, Keplerlaan 1, Noordwijk, The Netherlands.

**Introduction:** The Package for Resource Observation and in-Situ Prospecting for Exploration, Commercial exploitation and Transportation (PROSPECT) is in development by ESA for application at the lunar surface as part of international lunar exploration missions in the coming decade, including the Russian Luna-27 mission planned for 2021. PROSPECT will search for and characterize volatiles in the lunar polar regions to answer science questions and investigate the viability of these volatiles as resources.

Here we present the characterization of two lunar highlands regolith simulants: NU-LHT-2M produced by the United States Geological Survey (USGS) and NU-LHT-2M produced by Zybek Advanced Products. We use a range of complementary analytical and laboratory techniques at the University of Manchester and the University of Oxford to assess the similarities and differences in the two simulants including their particle size distributions, physical properties including texture and cohesiveness, and mineralogical make-up. Characterizations of regolith simulants like these are needed to assess their utility for testing drilling, imaging, and sampling packages like those on the ESA PROSPECT experiment [1].

**Regolith Simulants:** The USGS and Zybek NU-LHT-2M simulants were provided to the PROSPECT User Group (PUG) by Leonardo-Finmeccanica for the purpose of laboratory characterization. NU-LHT-2M is a lunar highlands simulant that was originally developed by the USGS to simulate the lunar highlands feldspathic regolith and has the chemical composition of the average of all Apollo 16 soils [2]. The bulk of the simulant material originated from the Stillwater Complex in Montana and included crystalline (65%) and glass (agglutinate 30% and ‘good’ glass 5%) components in proportions similar to the typical Apollo surface regolith value [2]. The particle size distribution of NU-LHT-2M was based on the average of 19 Apollo 16 surface soil samples and consists of particles from dust size to 1 mm [2]. As the USGS and Zybek simulants are derived from rocks of the same deposit and subject to the same milling and plasma-melting processes used to achieve the required grain size and glass component, they would be expected to have similar physical and spectral properties.

**Analytical and Laboratory Techniques:** The bulk properties of the provided USGS and Zybek NU-LHT-2M simulants were characterized using complementary analytical and laboratory techniques.

**University of Manchester.** The grain shapes, sizes and interactions at the sub-millimeter scale as well as the composition were analyzed using a FEI XL30 Environmental Scanning Electron Microscope (SEM) using secondary electron images (SEI) and Energy Dispersive Spectroscopy (EDS). In order to perform the SEM and EDS analyses, the regolith simulants were mounted onto SEM sample stubs via an adhesive carbon sticky pad and then carbon coated. Six mounts per sample were created in order to investigate grain interactions: two heavily pressed grain mounts, two lightly pressed grains mounts, and two that were sprinkled directly onto the pad from a height of approximately 2 cm. In addition, to characterize the bulk spectral properties reflectance spectra were collected across the 4000 to 750 cm\(^{-1}\) spectral range using a Perkin-
Elmer Spotlight 400 Fourier Transform Infrared (FTIR) spectrometer.

University of Oxford. The bulk composition, dominant particle size, and thermal properties were analyzed using thermal infrared (TIR) spectroscopy. TIR emissivity measurements were made under Earth-like (ambient) and simulated lunar environment (SLE) conditions in the Simulated Lunar Environment Chamber (SLEC). The experimental setup and calibration of SLEC have been previously described by Thomas et al. [3]. TIR spectra were collected using a Bruker IFS66v FTIR spectrometer at a resolution of 4 cm\(^{-1}\) from ~2400 to 400 cm\(^{-1}\) (~4 to 25 \(\mu m\)).

**Results:** The USGS simulant has a greater proportion of fine material compared to the Zybek simulant (Figure 1). While the bulk mineral compositions of the simulants are similar, Manchester EDS and FTIR spectra show the mineral proportions of the finest size fraction in each are different. The finest fraction of the USGS simulant is plagioclase-rich in nature, while the finest fraction of the Zybek simulant is a mixture of plagioclase, olivine, and pyroxene similar to the average composition of Stillwater anorthosite.

The USGS and Zybek simulants we have studied also differ in their physical properties, in particular their cohesive nature. As seen in Figure 1, the finest size fraction (< 30 \(\mu m\)) in the USGS simulant is highly cohesive in contrast to the more loose sediment nature of the Zybek simulant. This may be due to the largely mono-mineralic nature of the fine fraction, or it may be due to the smallest minerals (<1 \(\mu m\) in length) being more fibrous in shape (i.e. having 1 long and 2 short axes) and having a greater surface area, allowing for more cohesion between grains. The Zybek sample behaves more like a loose sediment with a low cohesive strength because its finest size fraction is not cohesive either due to its poly-mineralic nature or the absence of a fibrous component.

As seen in Figure 2, both simulants are of similar bulk composition to Apollo 16 soils as their Christianen Features (CF), an emissivity maximum indicative of composition [4], are at similar frequencies as are other diagnostic features in the ambient emissivity spectra. Under SLE conditions, the emissivity spectra of the simulants show a larger shift to higher frequencies of the CF and a larger increase in the spectral contrast between the CF and the fundamental vibration bands than the Apollo 16 soils. These results suggest the thermal properties of the simulants differ from the actual Apollo 16 soils. In addition, reflectance and emissivity spectra of the USGS and Zybek simulants corroborate the SEM analysis that both are spectrally dominated by the finest particle size fraction as demonstrated by: (1) the appearance of a transparency feature near 800 cm\(^{-1}\) and (2) the increase in depth of the feature at higher frequencies than the CF. The spectra also show that the Zybek simulant is of a coarser particle size fraction than the USGS simulant, and both NU-LHT-2M simulants are of coarser particle size fractions than Apollo 16 soil 66031 and 67701.

**Future Work:** Further analysis is needed to better constrain the differences observed in the USGS NU-LHT-2M and Zybek NU-LHT-2M simulants including: (1) repeat SEM and spectral measurements of the simulants; (2) constrain the particle size distribution of each simulant using multiple techniques; (3) further EDS analyses of the finest size fractions; and (4) compositional analyses of the fibrous material in the USGS simulant.

**Acknowledgement:** This work was supported by ESA in the context of the PROSPECT lunar volatiles package. In addition we would like to thank the UK Space Agency, UK Science and Technology Facilities Council, and the Royal Society for funding this work.

Introduction: The composition and stratigraphy of the lunar crust provide insight into the understanding of the thermal and magmatic evolution of the Moon e.g., [1]. Spectroscopy can be used to survey the lunar surface mineralogy and constrain the composition of the crust. Some authors proposed that the mafic content of the crust increases with depth, [ e.g., 2], while others suggest that the crust becomes more plagioclase-rich as it thickens, and more mafic-rich as it thins [3]. This study aims at characterising the mineralogy of the crust-mantle transition zone with spectroscopic data from the Moon Mineralogy Mapper (Mappers) and imagery from the Lunar Reconnaissance Orbiter and Kaguya cameras available over the central uplift of selected craters in the Humboldt region of the Moon.

Datasets: Mineralogical information is provided by the Mappers spectroscopic data. Mappers is a visible to near-infrared hyperspectral imager, with 85 spectral channels spanning from 430 to 3000 nm [4] and a spatial resolution of 140 to 280 m/pixel. High-resolution images of the craters are provided by the Lunar Reconnaissance Orbiter Wide Angle Camera (WAC, resolution of 100 m/pixel) and Kaguya Terrain Camera (TC, resolution of 10 m/pixel) mosaics.

Crustal thickness values are estimated from the Gravity Recovery and Interior Laboratory (GRAIL) crustal thickness model 1, derived from gravimetric data of the GRAIL mission [5]. Combined with cratering equations, pre-impact crustal thickness estimates are used to calculate the proximity to the mantle for numerous craters. The depth of origin of the material emplaced in the craters central uplift is calculated using the melting depth as a minimum depth of origin of craters central uplift material [6]. The proximity value to the crust-mantle transition zone (P, or distance to the mantle) is calculated by subtracting the melting depth to the crustal thickness. If the proximity value is positive, then the crater central uplift sampled crustal material; if the proximity value is negative, mantle material may be uplifted in the central uplift [7].

The choice of Humboldt crater: [8] performed a study of the global distribution of pure crystalline plagioclase in the lunar crust. The proximity value of the craters displaying plagioclase in their central uplift is shown in Figure 1 [8]. Most craters have a positive proximity value, except Humboldt and Zeeman craters, displaying a negative proximity value. Plagioclase-rich rocks are uplifted in their central uplift, whereas they should have uplifted material from below the crust-mantle transition zone.

Zeeman crater is a 184 km diameter crater located within the South Pole Aitken (SPA) basin, which is believed to have differentiated after formation [9]. Zeeman crater is discarded from further study, because the interpretation of its central uplift mineralogy would be contaminated by the SPA impact melt sheet differentiation. Humboldt crater, selected for further analysis, is a 205 km diameter complex crater located in the highlands.

Surveying the Humboldt crater region: Humboldt crater has been described as a floor-fractured crater, displaying concentric and radial fractures on its floor [10]. Four pyroclastic deposits are observed on the Humboldt crater floor, two of which are associated with a mare pond [11]. The volcanic deposits are highlighted in yellow and green in the colour composite presented in Figure 2. The yellow stars show the detections of pure crystalline plagioclase described by [8]. Humboldt crater central uplift is largely dominated by plagioclase, which is compatible with a crustal signature. Interestingly, several occurrences of spinel and olivine are detected in Humboldt crater’s walls, suggesting they originate at a shallow depth.

Two additional craters’ central uplift are studied in the region of Humboldt crater in order to determine if the plagioclase signature observed in the Humboldt crater central uplift is a regional trend. Petavius crater is a 188 km floor-fractured crater located on the nearside of the Moon. Its proximity value is small but positive (+1.63 km). [8] described...
pure crystalline plagioclase occurrences on Petavius crater central uplift (Figure 3.a), compatible with a crustal signature. Milne basin is a 272 km diameter peak ring basin located on the lunar farside. Milne basin proximity value is negative (−12.15 km). [8] described several occurrences of pure crystalline plagioclase on the peak ring basin floor (Figure 3.b). The colour composite Figure 3.b highlights pyroxenes in yellow, green and reddish patches according to the respective size of the absorption bands area. Pyroxene occurrences are detected on Milne peak ring, which might be compatible with a lower crust or mantle signature [12].

**Conclusions:** Both Humboldt and Petavius craters have small proximity values (−1.23 km and +1.63 km, respectively), meaning that their central uplift could have excavated mantle material during the impact cratering event. However, their central uplift display a strong plagioclase signature, compatible with a crustal signature. The proximity value of Milne basin peak ring is lower (−12.15 km), and a more mafic signature is observed on its peak ring. This signature might be compatible with a lower crust to mantle signature. It is interesting to note that the proximity value of Humboldt and Petavius are small, and that their central uplift displays a strong plagioclase signature. This could mean that the crust in the Humboldt region is thicker than predicted by the GRAIL model 1. Alternatively, Humboldt and Petavius craters central uplift might sample a plagioclase-rich pluton emplaced in the lower crust.

TELE-OPERATED TRAVERSE ASSESSMENT FOR PHASE 2 OF EDSH-ENABLED LUNAR MISSION BEING EXAMINED AS AN ISECG-GER MISSION SCENARIO. S. Mazrouei¹ (sara.mazrouei.seidani@mail.utoronto.ca), E. J. Allender², N. V. Almeida¹, J. Cook⁵, J. J. Ende°, O. M. Kamps⁷, C. Orgel⁴, T. Sleza⁵, A. J. Soini¹⁰, D. A. Kringle¹¹; ¹University of Toronto, ²University of Cincinnati, ³Natural History Museum, London, ⁴Birkbeck College, London, ⁵University of Houston, ⁶University of Tennessee, ⁷University of Twente, ⁸Freie Universität Berlin, ⁹Brigham Young University, ¹⁰University of Helsinki, ¹¹USRA-Lunar and Planetary Institute.

Introduction: The International Space Exploration Coordination Group (ISECG) has been examining mission scenarios that are consistent with its Global Exploration Roadmap (GER) [1]. Hufenbach et al. (2015) outlined a Design Reference Mission (DRM) architecture for humans to the lunar surface, beginning in 2028. In this concept, there are five human landing sites. At the first landing site, the crew utilizes two Lunar Electric Rovers (LERs), which are then tele-operatively driven to each of the next four landing sites. The five proposed human landing sites of potential scientific interests are: Malapert Massif (85.9°S, 2.9°W), South Pole/ Shackleton Crater (89.3°S, 130.0°W), Schrödinger Basin (75.4°S, 159.9°W), Antoniadi Crater (69.7°S, 172.0°W), and South Pole-Aitken (SPA) Basin center (69.7°S, 172.0°W) [2]. Here, we evaluate the feasibility of a traverse between the above landing sites and optimize it such that it addresses lunar science and exploration objectives [3]. We compare an efficient traverse versus an alternative that increases the scientific value of the mission.

Traverse Conditions: The time constraint for the traverse between these human landing sites is 365 Earth days. It is assumed that the LERs can only be driven during lunar daylight and with Earth communications relayed through the eDSH during the tele-operated traverse. A speed of 0.36km/h (0.1m/s) is assumed, based on the planned driving speed of the Resource Prospector rover, which is consistent with the bandwidth of the Deep Space Network and the speed where a neutron detector and a ground penetrating radar (GPR) can survey the surface. We also assign a 30% contingency margin to that speed. The maximum accessible slope is restricted to 25°, with a preferred slope of less than 15° [4].

Accessibility: The maximum driving distance is calculated with the following constraints: We assume that the surface is illuminated half of the year due to the day and night transition. Communication coverage via an asset in a large halo orbit around the Earth-Moon Lagrange point 2 (EM-L2), based on an unpublished study shared with us by the Lockheed Martin Corporation, changes from 84.5% of the time per orbital period of 10.6 days between Malapert Massif and South Pole/Shackleton Crater to 86% between Antoniadi Crater and SPA Basin Center. We calculate the maximum drivable distance based on a 0.36 km/h speed and a 30% contingency margin (Table 1). The most efficient tele-operated traverses between the human landing sites are designed using slope maps from the highest resolution LOLA Digital Elevation Model (DEM) available at each landing site. The resolution of the DEMs change from 5 m/px near the South Pole to 100 m/px at lower latitudes. In areas with steep slopes and low resolution DEMs, we use Narrow Angle Camera (NAC) images (1 m/px) to provide a better assessment of the terrain. This analysis revealed that there is sufficient time to conduct a more complex science traverse to address more National Research Council (NRC) goals [3] and evaluate the potential for in-situ resource utilization (ISRU). The resulting efficient and science traverses, and their lengths are provided in Figure 1 and Table 1, respectively.

![Figure 1](image-url)
**Discussion:** To conduct science during the traverses in this study, we assume the LERs have a GPR, a neutron detector, and cameras onboard. To increase scientific productivity, one or more tools for in-situ chemical analyses could also be installed. It would also be useful to have the ability to tele-robotically collect samples.

*Malapert Massif to South Pole/Shackleton Crater Traverse:* Two highlights in this traverse are the ability to better understand early Solar System bombardment and the distribution of volatile resource deposits. The science traverse visits some of the largest craters in the SPA Basin, including Drygalski and Ashbrook craters, where impact melt can be sampled for radiometric analyses. Additionally, it is possible to conduct a thorough sub-surface survey of ice deposits in Cabeus Crater and nearby regions. Temperature maps indicate the maximum temperatures in Cabeus Crater are low enough to host stable CO₂ ice [5], where the Lunar Prospector Neutron Detector (LPND) reported high concentration of hydrogen [6]. An oscillating survey pattern across Cabeus Crater will provide a better spatial understanding of the volatiles in Permanently Shadowed Regions (PSRs).

*South Pole/Shackleton Crater to Schrödinger Basin Traverse:* Here, the science traverse visits Amundsen Crater, which is one of the best locations to study volatiles [7,8]. Amundsen Crater has a relatively flat floor, making it possible to perform a search pattern along the edge of a PSR where the maximum temperature does not exceed the sublimation temperature for water and CO₂ (Figure 1).

Entering and leaving Schrödinger Basin with the LERs is possible at two locations based on an analysis of the 30 m/pix LOLA DEM, in which the slope does not exceed the 15°. NAC imagery of the proposed traverse were used to study potential obstacles smaller than the LOLA DEM resolution.

*Schrödinger Basin to Antoniadi Crater Traverse:* The science traverse to Antoniadi Crater focuses on the crater walls, which have the potential to expose the SPA impact melt sheet. Close to Schrödinger Basin, a secondary impact field originated from the emplacement of Antoniadi Crater along with impact melt ponds from Schrödinger Basin [9].

There is only one possible way to access the floor of Antoniadi Crater, with a maximum slope of 17°, based on a slope map from a 60 m/pix LOLA DEM.

*Antoniadi Crater to SPA Basin Center Traverse:* Due to the large distance between these two human landing sites, the science and efficient traverses differ only slightly. The science traverse visits a different side of the Mafic Mound that is not accessible to the crew. Additionally, more mare and cryptomare basalt in the vicinity of the human landing site can be studied.

**Conclusion:** Based on this feasibility study and given the time, communication, illumination, and speed constraints, the five human landing sites proposed in [2] are all accessible with the tele-operated LERs. The proposed science traverse in this study affords valuable opportunities to address NRC (2007) goals [3]. In particular, the science traverse provides an opportunity to study complex impact craters and conduct a comprehensive survey of volatiles suitable for ISRU in two locations. To accommodate trafficability of those shadowed, potentially volatile-rich areas, the LERs will need to have the capability of accessing PSRs for short periods of time.

**Acknowledgment:** This work is a part of the 2016 Exploration Science Summer Intern Program and was funded by The Lunar and Planetary Institute and the NASA Ames Solar System Exploration Virtual Institute (SSERVI) program.

**References:**


**Table 1:** Calculated maximum drivable distances and topographic lengths of efficient and science for each tele-operated traverse

<table>
<thead>
<tr>
<th>From</th>
<th>To</th>
<th>Maximum drivable distance (km)</th>
<th>Efficient Traverse (km)</th>
<th>Science Traverse (km)</th>
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<tbody>
<tr>
<td>Malapert Massif</td>
<td>South Pole/ Shackleton Crater</td>
<td>932.7</td>
<td>208.4</td>
<td>911.4</td>
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<td>Schrödinger Basin</td>
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<td>949.2</td>
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<td>946.9</td>
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</table>
HYDROGEN DISTRIBUTIONS IN THE MOON’S LARGE SOUTH POLAR PERMANENTLY SHADOWED REGIONS. T. P. McClanahan¹ (timothy.p.mcclanahan@nasa.gov), I. Mitrofanov², W. V. Boynton³, G. Chin¹, M. Litvak², T. Livengood⁴, A. Sanín², R. D. Starr⁴, J. Su⁴, D. Hamara³, K. Harshman³, ¹NASA Goddard Space Flight Center, Bldg. 34 Room W218, Greenbelt, MD 20771 USA, ²Institute for Space Research, Moscow, Russia, ³Lunar and Planet. Lab., Univ. Ariz., Tucson AZ USA, ⁴The Catholic Univ. Wash. D.C. USA, ⁵Univ. of Mary., College Park MD USA.

Introduction: For the past eight years the Moon’s south pole has been intensely studied by scientific instruments onboard the Lunar Reconnaissance Orbiter (LRO) [1]. LRO’s continuous low altitude mission over the south pole, varying between 25-70 km has allowed unparalleled high-resolution regional coverage and in particular detailed coverage of its PSR’s, thought to contain high concentrations of hydrogen [2]. LRO’s Lunar Exploration Neutron Detector (LEND) and its collimated neutron detector (CSETN), with a nominal spatial resolution of 10 km FWHM at 50 km altitude is tasked with deriving the spatial distribution of hydrogen for the mission and has provided new insights into the Moon’s PSR’s and extend that record in this presentation [3-5].

In this study we test the hypothesis that H is distributed uniformly within the PSR’s. Results show that the maximum hydrogen (H) concentrations are distributed heterogeneously in each of the Moon’s four largest south polar permanently shadowed regions (PSR). In particular, H concentrations are biased towards the break in slope on the poleward facing side of the PSR’s. The bias in the H distributions within the PSR’s is an indication that H is heterogeneously distributed. A systematic analysis of the PSR’s at Cabeus, Haworth, Shoemaker and Faustini craters is reviewed in the presentation, though only Shoemaker is reviewed here. A high-resolution hydrogen map derived from the Lunar Exploration Neutron Detector (LEND) onboard the Lunar Reconnaissance Orbiter (LRO) is reviewed and correlated with maps of topography, illumination and maximum temperature from LRO’s Lunar Observing Laser Altimeter (LOLA) and Diviner Radiometer [6-8]. Maps and corresponding transects from the co-registered maps provide an upper-bounds of 13.2 km full-width and half-maximum.

Background and Methods: LEND’s collimated sensor for epithermal neutrons (CSETN) is designed for high resolution studies of the Moon’s epithermal neutron emission flux. Neutrons are produced in regolith by spallation from galactic cosmic-ray in the surface upper meter. In the presence of H, neutron energies are attenuated quickly, causing a deficit in the orbit detectable neutron emission flux. Neutrons of epithermal energy are particularly sensitive to H in the regolith.

CSETN’s design includes a ¹⁰B/polyethylene collimator to restrict detected neutrons to a 5.6° half-angle about the instrument boresight. The collimator surrounds four nadir-pointing ³He detectors that integrate at a 1-Hz rate. Hydrogen values were derived from a model-dependent measure of the neutron-flux suppression as compared to the average neutron flux measured between 55°S to 60°S [14]. Units are in weight percent water-equivalent hydrogen (WEH %)

Corresponding topography and temperature maps were derived from instrument archives in NASA’s Planetary Data System.

Results: Figure 1 reviews an excellent example of heterogeneously distributed hydrogen concentrations within the PSR at Shoemaker crater at 88.1°S 44.9°E. Shoemaker crater is an ideal study of H distributions within the PSR’s as the diameter of the crater of 46 km and PSR of 35 km can fully contain the field of view of LEND’s collimated sensor, so that a determination can be made as to whether H is distributed uniformly or heterogeneously within the PSR.

Corresponding profiles of the Shoemaker PSR’s pixel are taken from the maps of LOLA topography (top), Diviner maximum temperature (middle) and LEND CSETN weight-percent water-equivalent-hydrogen WEH %. Pixels in each profile are sorted as a function of their distance (km) from the south pole to illustrate variation between equator-facing and pole-facing slopes. Dashed lines (black) show the 3rd order polynomial fit of pixels in each profile. Results show that the maximum H concentrations 0.63 WEH % occurs near the break in the poleward-facing slope between 60 and 68 km from the pole, approximately 3-5 km from the break in the poleward-facing slope. Maximum H concentrations correlate well with the minimum maximum temperature in the same region.

Conclusions: Within the largest PSR’s the minimum maximum temperature is well correlated with maximum H concentrations. Similar results will be shown for Cabeus, Haworth, and Faustini. However, results reviewed in this presentation make the case that not all PSR’s contain high H concentrations, even though they may have similar temperature distributions. So, maximum temperature is an incon-
sistent predictor of high H concentrations, suggesting 
H depositional processes may vary.


Figure 1: Corresponding profiles of pixel distributions from LOLA topography (top), Diviner maximum temperature (middle) and LEND CSETN weight percent water equivalent hydrogen WEH %. Pixels in each case are sorted as a function of distance from the pole. Equator-facing slopes are on the left and pole-facing slopes on the right. Results show that H concentrations are biased towards the break in the pole-ward facing slope.
THE HALOGEN BUDGET OF MARE BASALTS: INSIGHTS TO THE VOLATILE INVENTORY OF THE NEARSIDE LUNAR MANTLE. F. E. McDonald¹, P. L. Clay¹ K. H. Joy¹, and R. Burgess¹. ¹School of Earth and Environmental Sciences, University of Manchester, Williamson Building, Oxford Road, Manchester, M13 9PL, UK. Email: francesca.mcdonald@manchester.ac.uk.

Introduction: Volatile elements play a key role in terrestrial planetary processes including influencing melt viscosity, solidus temperatures, and rheology [1]. The halogens are an important group of volatile elements that are controlled by melt mobility, but are not strongly affected by fractional crystallisation or partial melting processes. This makes the halogens a useful tool for tracing other volatile elements, magma source regions, degassing processes and the movement of hydrous fluids [2]. Therefore, the determination and comparison of halogen compositions (Cl, Br and I) of the primitive lunar mantle provides an understanding of the behaviour and distribution of halogens (and other volatiles) during the formation and evolution of the Moon.

Lunar Volatiles: The purported giant impact is widely believed to be the Moon forming event [3]. Such an impact can explain the close similarity of the terrestrial and lunar oxygen isotope composition [4], light element isotopic fractionation [5, 6], and the current angular momentum of the Earth-Moon system [7, 8]. After the giant impact, the Moon differentiated from a lunar magma ocean (LMO) [9, 10], giving rise to a mafic mantle and a feldspathic crust.

The Moon, and other inner Solar System rocky bodies, are considered to have accumulated volatiles during the main planetary early accretion phase from solar and chondritic material [11, 12]. How the giant impact event and planetary differentiation affected the evolution of volatile elements within the Moon is not currently well understood. Chlorine isotope studies imply that the lunar mantle is anhydrous [13]. This is consistent with the giant Earth-Moon forming impact causing major degassing by hydrodynamic escape of lunar volatiles [5, 6]. Previous SIMS analysis of lunar glass beads and apatites suggest, however, that the lunar mantle may contain water in abundances comparable to present day MORB [14-17]. This favours retention of volatiles after the purported impact, or volatiles being acquired as a “late veneer” of chondritic material subsequent to degassing during planetary formation and pre-dating closure of the LMO [18-19].

We aim to measure the heavy halogen abundance of Apollo lunar mare basalts to constrain a halogen budget for the lunar mantle. Such an inventory can provide insights into lunar primitive volatiles.

Samples: Seven olivine-rich mare volcanic basalts (Fig. 1) from a range of Apollo missions (11, 12, 14 and 15) aged between ~4.2 and 3.2 Ga have been selected as representative of partial melts of the lunar mantle across 1 billion years of lunar history. Several samples have reportedly preserved olivine-hosted melt inclusions [20] (Fig. 2). These melt inclusions (MI) provide access to halogen compositions representing the least degassed, primitive mantle compositions. Variation in sample texture and chemistry (e.g., bulk rock Ti and Al composition) between Apollo sites reflects differences in their respective mantle source regions and melting depths. The full sample suite will, therefore, provide a global insight into lunar mantle halogen composition.

Figure 1. Apollo 15 - sample 15598.26 exemplifying the typical mineralogy of olivine-rich mare basalts.

Figure 2. BSE image of olivine-hosted melt inclusion in 15555.1052. Melt inclusion (MI) has shrinkage bubble and pyroxene growth.

Halogen Analysis: Bulk rock chips (~5 to 8 mg) and olivine mineral separates (~3 to 5 mg) of each sample underwent neutron irradiation to convert the constituent heavy halogens Cl, Br and I into their respective noble gas isotopes Ar, Kr and Xe. Scapolite, Shallowater aubrite, and Hb3Gr hornblend standards monitored the neutron flux and interference reactions in the reactor. A CO₂ laser was used to heat the irradiated samples (and standards) liberating the noble gases for measurement by Noble Gas Mass Spectrometry (NGMS), using an Argus VI. Halogen concentrations and ratios are then calculated from the noble gas measurements, using parameters defined by the standards [21]. This analysis method is particularly sensitive and able to detect the least abundant halogen, iodine. Iodine is typically present as few ppb within igneous rocks and, therefore, below the detection level.
of many conventional analytical techniques (e.g. INAA, EPMA).

**Lunar Halogens:** The lunar samples are affected by the presence of trapped noble gas components including air contamination and solar wind. In addition, during the samples’ residence close to the lunar surface environment, in situ cosmogenic isotopes are formed from several target elements, and fission-derived Kr and Xe from uranium and plutonium. A technique is being developed to correct the halogen-derived noble gases formed during irradiation for the trapped and in situ components (Fig. 3). Preliminary results indicate that $^{38}$Ar (Cl-derived) appears to be dominated by cosmogenic input (Fig. 3a). However, a measurable amount of $^{128}$Xe (I-derived) and $^{80}$Kr (Br-derived) is found within the samples (Fig. 3b and 3c).


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**Figure 3.** Isotope ratio plots indicating a) chlorine-derived argon, b) iodine-derived xenon and c) bromine-derived krypton. Presented data has not been corrected for nuclear reactor interference or cosmogenic input. SW is solar wind. Errors are 1 sigma.
EVIOLUITION OF THE PRESENCE OF IMPACT MELT AT THE NEAR-SURFACE OF THE MOON
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Introduction: We aim to understand the cumulative effect of the impact gardening process on the presence of impact melt of different ages at the near-surface of the Moon. Estimating the amount of melt produced by impact events of differing scales together with the depth of excavation and quantity of unheated material which is redistributed at the surface, we reconstruct the effect of a sequence of impacts representing the observable history of the Moon. We aim to compare the model’s predictions for the ages of near-surface melt components with what is found in real samples.

Methods: The essence of the model is the following:
1. An initial volume, with a surface area equivalent to that of the Moon is denoted with a nominal starting age of $T_0$ (typically 4.5 Ga), and a minimum crater size for the simulation is chosen, $D_{\text{min}}$.
2. From the lunar chronology function [3], an impact rate is found for the current model time, $T$, which corresponds to craters of 1 km in diameter. By means of the crater production function (PF), the equivalent rate for craters of size $D_{\text{min}}$ is found.
3. The rate gives the average time to the next impact event producing a crater larger than $D_{\text{min}}$. With a Monte Carlo approach, we can use a Poisson function to find realistically distributed time intervals, although for the large number of events being simulated, it can be sufficient to employ an averaged interval.
4. The diameter of the crater formed is generated using the Monte Carlo method in such a way that the size-frequency distribution statistically conforms to the portion of the production function larger than $D_{\text{min}}$.
5. For each crater produced, the penetration depth is taken as $D/10$ [1,2] and the volume of excavated material is approximated as the volume of the transient crater.
6. A portion of this excavated volume is considered to have been melted (or heated above the point required to reset the Ar-Ar clock): $r_{\text{melt}} = cD_{\text{tc}}^d/V_{\text{tc}}$, where $D_{\text{tc}}$ and $V_{\text{tc}}$ are the diameter and volume of the transient crater, and $c$ and $d$ are taken as $2\times10^{-4}$ and 3.85, respectively (after [2]). The melted material is marked in the simulation with the current clock time, $T$.
7. The excavated material, together with the new melt, is redistributed evenly over the entire surface of the body. This is a simplification of the real situation, but in an average sense—because of the relative frequency of smaller impacts whose ejecta do not travel so far—it provides a reasonable reflection of the amount of ejecta sourced from craters of differing sizes at any point of the surface.

Results: Results for an impact rate scenario as described by [3], with the rate being constant back to 3 Ga, and exponentially increasing before then are shown in Fig. 1, in comparison with those for the same scenario with the addition of a cataclysmic peak in the rate function (Fig. 3).

The near-surface melt is dominated by the most recent impacts; further back in time, it is the largest impacts which dominate: it is notable that they produce sufficient melt to leave a permanent signature in the upper layers. Later impacts of lesser scale either penetrate to the original ejecta layer to bring up more of its melt, or recycle the same aged melt nearer the surface. Eventually the melt from these events becomes present at every depth down to its source ejecta layer.
Figure 2. Simulation using craters of random size larger than 30 km conforming to the size–frequency distribution described by the Neukum (1983) production function over a period of 4.5 Ga using a realistic impact rate function (plotted above) and incorporating basin-forming events. The horizontal axis indicates the age of the melt. Each trace in the plot represents a histogram of the presence of differing melt ages, the baseline of the trace being plotted at the layer's depth below the surface according to the vertical axis scale. The histograms are plotted twice: in black – with all traces using the same normalisation; in grey – with exaggerated small values. The numbers at the left side of each trace show the fraction of material of age $T_0$ that has never been melted during the simulation (this fraction is excluded from the histogram, since it would plot much higher). The four prominent peaks present in both runs represent South-Pole–Aitken at 4.23 Ga, Crisium at 4.08 Ga, Imbrium at 3.88 Ga and Orientale at 3.82 Ga.

Figure 3. Simulation using craters of random size larger than 30 km conforming to the size–frequency distribution described by the Neukum (1983) production function over a period of 4.5 Ga using a hypothetical impact rate function with a cataclysmic peak (plotted above) and incorporating basin-forming events. The four prominent peaks again represent South-Pole–Aitken, Crisium, Imbrium and Orientale, but have been compressed into a cataclysmic peak centred on 3.9 Ga.

**Conclusion:** If there was a lunar cataclysm or late heavy bombardment, we would expect its form to be observable today in the histogram of melt ages from surface samples, both those returned from the Moon by manned and unmanned spacecraft and those delivered to the Earth in the form of meteorites.

**References:**

CHARACTERIZING MARE FLOW UNIT STRATIGRAPHY WITH RADAR: EARTH-BASED AND MINI-RF BISTATIC MEASUREMENTS. G. A. Morgan1, B. A. Campbell1, L. M. Carter2, D. B. Campbell3, G. W. Patterson4. 1Smithsonian Institution, Washington, DC, morganga@si.edu. 2University of Arizona, AZ. 3Cornell University, NY. 4Johns Hopkins University APL, MD.

Introduction: The lunar maria are the product of extensive basaltic volcanism that flooded widespread portions of the Moon’s surface (Fig 1). Constraining mare volcanic history therefore provides a window into the endogenic processes responsible for shaping the Moon. Unfortunately, the majority of mare surface structures are masked and subdued by impact regolith, and consequently topographically distinguishable flow fronts are rare. Subtle individual mare flow morphologies, coupled with spatial limitations in the use of crater size distributions to distinguish surface units close in age, have thus placed restriction on our understanding of mare stratigraphy.

Earth-based 70cm wavelength (P-band) radar can reveal features beneath the regolith and highlight very subtle changes in the ilmenite content of the flows [1] (Fig 1-2). Unlike spectral maps of specific mineral concentrations [e.g. 2], or maps derived from the absorption properties of multiple mafic assemblies [e.g. 3-5], which are only sensitive to the upper few microns of the surface, the penetration depth of the P-band signal (>10m) enables the full vertical column of the regolith to be sampled. As a result, the radar echoes are less influenced by contamination from thin surficial deposits, such as rays and ejecta blankets composed of highlands or basaltic material of a different composition to that of the local area. Therefore, radar provides a unique means to map mare units that is complimentary with that of UV-NIR spectral studies [e.g. 3-5].

A proof of concept study of Mare Serenitatis by [1] demonstrated the influence of TiO₂ content on radar attenuation and permitted the identification of a host of previously unseen volcanic features. These features included the digitate forms of flow-unit boundaries and the identification of channels interpreted to be the collapsed remnants of plumbing systems similar to those of terrestrial basaltic volcanic fields. Another important result was the improved delineation of units, which helped to reconcile inconsistencies between regional stratigraphic relationships [6] and crater count age dating [4].

Applying the methodology of [1], Morgan et al [7] conducted a study of Mare Imbrium in order to further constrain the stratigraphy of the individual mare units. Central Mare Imbrium, unlike the majority of the maria, contains a series of 50 – 100 m thick (Eratosthenian-period) flow lobes that are clearly discernable within image and topographical data [8]. These topographic flows provide a stratigraphic framework with which to test the radar mapping results.

Figure 1. Mare Imbrium: Interpretation of the stratigraphic relationships between the radar map units, showing the development of the current mare surface.
Radar Dataset & Methodology: P-band radar images of the lunar nearside were obtained by transmitting a circular-polarized signal from the Arecibo Observatory and receiving echoes from the Moon in both senses of circular polarization at the Green Bank Telescope [9]. Radar returns in the same sense of circular polarization (SC) as that transmitted are attributed to diffuse scattering by rocks >10 cm in diameter, at the surface and buried within the probing depth of the radar signal (10-15 m in the lowest-loss mare regolith).

The Campbell et al. [1] Serenitatis study was the first to utilize the highest spatial resolution, 200 m/pixel P-band data for the nearside, which represents a two-fold increase in spatial resolution over the previous data product. High resolution P-band data coverage extends over other regions of the nearside and was used in the Morgan et al [7] study (Fig. 2).

Imbrium Map: The P-band coverage of Imbrium reveal a complex distribution of radar backscatter, including the existence of distinct boundaries between regions of differing radar brightness (Fig. 2). Tracing these boundaries enabled us to identify 38 individual units, which based on radar brightness can be subdivided into four “map” units (Fig. 1). Through our mapping, we conclude the following:

1. Thin, elongated (~10km wide) regions of low radar backscatter (several of which are located within the margins of topographically distinct flows) are situated downslope of Euler crater. This supports [8] assertion that the Eratosthenian flows originated from a now-buried vent close to Euler.

2. The presence of kipukas within the high TiO₂ map units 3 and 4 (Fig 1) suggest that although the later phases of activity in Mare Imbrium resulted in spatially extensive flow units, the associated lava flows must have been relatively thin in order not to have completely embayed the preexisting low TiO₂ surfaces.

3. The radar mapping suggests that pre-Eratosthenian, low TiO₂ volcanic emplacement originated from several source regions within the Imbrium basin, including the mare surface north of Monte Carpathus. The radar proved particularly valuable in delineating units within this region because the presence of extensive Copernicus ejecta material prevents effective mapping using visible and UV-NIR spectral data sets.

4. Finally, the radar map places important constraints on the interpretation of the Chang’e-3 lunar penetrating radar measurements [10 – 11] and reveals the locations of regions where a range of mare volcanism could be sampled over small areas by a future lander/rover.

Extending the Radar Mapping Work: High resolution P-band data exists for several other nearside maria including: Mare Frigoris, Mare Crisium and Northern Oceanus Procellarum. We will present the mapping results for these mare deposits including the identification of additional volcanic features such as those identified in Mare Serenitatis by [1].

Mini-RF: We are currently conducting X and S-band bistatic observations of the Nearside using Mini-RF as part of LRO’s Cornerstone extended mission. Previous experiments have shown that unlike certain lunar materials, mare surfaces do not exhibit an opposition effect [12]. Nevertheless, variations in Circular Polarization Ratio (CPR) values were observed between the multiple mare surfaces measured as part of these previous observations and were attributed to the incidence angle/latitude at which they were acquired. Alternatively, the differences in CPR may in part have been influenced by material heterogeneity and/or composition. We are currently using the P-band maps to guide future Mini-RF targeting to identify the role TiO₂ content and unit age play on bistatic measurements.

preparing and characterizing carbonaceous chondrite standards for verification of esa’s ‘prospect’ package. james mortimer1, mahesh anand1,2, sasha verchovsky1, simona nicoara1, richard c. greenwood1, jenny gibson1, ian a. franchi1, farah ahmed2, stanislav strekopytov2, james carpenter3. 1school of physical sciences, the open university, walton hall, milton keynes, buckinghamshire, united kingdom, mk7 6aa, uk. (james.mortimer@open.ac.uk). 2the natural history museum, london sw7 5bd, uk. 3esa estec, keplerlaan 1, 2401 az, noordwijk, the netherlands.

introduction: this work has been carried out in the context of a planned russian mission to the lunar surface, near to the south pole (luna 27/luna-resurs lander), for which the european space agency (esa) are providing a sample acquisition and delivery drill system (proseed) and a miniaturized mass spectrometer sample analysis package (prospa). together, this prospect package aims to drill down up to 2 m below the lunar surface, collect samples of icy regolith, and analyze the samples for water and other volatile species abundances and isotopic compositions. this will provide much-needed ground truth measurements to clarify previous orbital observations and measurements of hydrogen and water ice at the lunar surface and particularly in cold regions at the lunar south pole.

since carbonaceous chondrites (ccs) are thought to be major contributors of volatiles to the moon [e.g. 1-3], it was decided to use cc's to produce a set of well-defined meteorite standards, using an array of high precision/high sensitivity instruments available within a modern laboratory setting to characterize the h, o, c, n, noble gases, bulk geochemistry, and petrological characteristics of the meteorites, all from the same stones. these standards will then be used to test and refine the prospa bench development model (bdm) as it becomes increasingly flight-ready.

samples: ccs are inherently chemically heterogeneous, with coarser-grained objects (chondrules, cais, aoas, mineral fragments) enclosed in a finer-grained matrix. therefore, in order to produce meaningful standards, relatively large amounts of sample were required to provide enough well-homogenized material for multiple analyses. unfortunately, since a fundamental requirement of the mission requires that the materials should be curated in perpetuity following these measurements, samples could not be acquired on a loan basis from the conventional museum and university curated collections. this prompted a decision to purchase instead large hand specimens of two well-studied ccs from a trusted source, thus ensuring authenticity by comparison of new results with published data. as a result, a 57.54 g stone of murchison (cm2) and a 692 g stone of allende (cv3) were acquired in september 2016 (fig. 1). these sample masses are large enough to provide ample material for standard preparation and characterization, with a large amount of material left intact for curation and future processing and scientific analysis.

allende (692 g)

murchison (57.54 g)

figure 1: stones of allende (cv3) and murchison (cm2) as purchased for this work

analytical techniques: a wide range of both non-destructive and destructive techniques have been employed to fully characterize these samples. most of the analyses have been conducted at the open university (milton keynes, uk), with additional work carried out at the natural history museum (london, uk).

space constraints in this abstract mean that only some of the collected data are shown here.

x-ray ct scanning (nhm). this was the first technique used in early october 2016, prior to any processing for other analytical methods. such scans on these large sample masses allow us to build up a much clearer understanding about the internal structure and distribution of chondrules and cais within the meteorites, providing additional context to traditional optical petrography, which is limited to a two-dimensional view of structures and internal relationships. figure 2 is a scan taken from the middle of the mass of murchison, and clearly shows how cracks penetrate the sample, as well as the internal distribution of chondrules.
Fluorination for aliquots of Stein et al., 2016. Both chips and homogenized powders of the samples were analyzed using ‘FINESSE’, a custom-built triple mass spectrometer system to measure C, N, and noble gases in increments of 100 °C from 200-1400 °C.

**Stepped Combustion (OU).** Both chips and homogenized powders of the samples were analyzed using ‘FINESSE’, a custom-built triple mass spectrometer system to measure C, N, and noble gases in increments of 100 °C from 200-1400 °C.

**Elemental Analyzer-isotope ratio mass spectrometry (EA-irms) (OU).** Homogenized powders of the two meteorites were measured for C and N by flash heating in an EA connected to a Thermo MAT253 mass spectrometer. Further measurements for H and O are also planned using the same technique.

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**Table 1: Bulk C and N results for Murchison.**

<table>
<thead>
<tr>
<th></th>
<th>C (wt. %)</th>
<th>δ¹³C (%)</th>
<th>N (wt. %)</th>
<th>δ¹⁵N (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stepped Combustion</td>
<td>1.95 ± 0.02</td>
<td>-4.3 ± 0.5</td>
<td>0.08 ± 0.01</td>
<td>43.4 ± 1</td>
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<tr>
<td>EA-irms</td>
<td>1.73 ± 0.09</td>
<td>-4.59 ± 0.39</td>
<td>0.08 ± 0.007</td>
<td>42.14 ± 1.10</td>
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<tr>
<td>Literature</td>
<td>1.93 ± 0.38</td>
<td>-5.46 ± 3.74</td>
<td>0.07 ± 0.019</td>
<td>41 ± 2.35</td>
</tr>
<tr>
<td>Average</td>
<td></td>
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(Literature average values were calculated from [6-10]).

**Summary:** Results from these new CC standards are both self-consistent between different techniques, and in excellent agreement with previous literature data (Table 1). Having an integrated approach, where multiple isotope systems are measured within the same individual stones means that the results are directly comparable to each other and can be considered together. The large sample masses purchased for these standards means that material can be curated for future use, either as standards for other instrument verification studies, or in their own right as scientific samples.

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**References:**

D/H FRACTIONATION DURING SUBLIMATION OF WATER ICE AT LOW TEMPERATURES INTO A VACUUM. James Mortimer¹, Christophe Lécuyer², François Fourel², and James Carpenter³. ¹School of Physical Sciences, The Open University, Walton Hall, Milton Keynes, Buckinghamshire, United Kingdom, MK7 6AA, UK. (James.Mortimer@open.ac.uk). ²Laboratoire de Géologie de Lyon, CNRS UMR 5276, Université Claude Bernard Lyon 1, 69622 Villeurbanne, France. ³ESA ESTEC, Keplerlaan 1, 2401 AZ, Noordwijk, The Netherlands.

Introduction: The work outlined here was carried out within the framework of ESA’s PROSPECT programme, which will provide both a sample drill and miniaturised mass spectrometer system for flight onboard the planned Russian Luna-27 mission to the lunar south pole. There, it aims to collect samples of regolith, containing water ice and other volatiles, and to make isotopic and abundance measurements to fingerprint the source(s) of these volatile species. However, it is necessary to first consider how any localised temperature increases during sample acquisition activities may result in water ice loss via sublimation and thus isotopic modification of the remaining residual ice. To attempt to address these concerns, a suite of sublimation experiments were conducted at the Laboratoire de Géologie de Lyon during the summer of 2016, where a method for performing such experiments was already established [1]. The results of this work will help to inform modelling which will extrapolate the data down to lunar-relevant conditions.

Experimental Procedure: For all experiments, the same starting water reservoir was used, and its composition remeasured alongside each batch of samples to take into account any isotopic evolution over time within the starting water reservoir. A 0.5 mL aliquot of water was measured out from the reservoir flask of starting water (doubly-distilled Rhône river water, with an initial δD value of -75.69 ‰) using a micropipette, transferred into a small Pyrex™ glass round-bottomed vessel for weighing (using a balance accurate to ± 0.0001 mg), and then introduced into the vacuum system. Before exposing the water aliquot to vacuum, the water inside the round-bottomed vessel was frozen using a bath of liquid nitrogen (LN). Once frozen, the vessel was opened to the vacuum line and pumped down to the appropriate pressure. Then, the vacuum line was isolated from the pumps and the temperature-controlled cryogenic trap (TCCT) was cooled (again with an external bath of LN), ready for the transfer of the water aliquot (see Figure 1 for a schematic diagram of the TCCT set-up). Water transfer into the TCCT was facilitated by the use of a hand-held heat gun. After water transfer was complete (monitored by watching the pressure of the vacuum line fall as water vapour was trapped down into the TCCT), the vacuum line was again opened to the pumps to ensure full removal of all untrapped vapour from the system. After approximately ten minutes, the line was again isolated from the pumps and the system was ready for sublimation to begin.

Figure 1: TCCT Section of Vacuum Line

Temperatures of sublimation were controlled by use of a thermal resistance heating wire coiled around the sample tube inside the TCCT, balancing out the cooling effect of an external bath of liquid nitrogen, and with efficient heat transmission ensured by an envelope of helium gas between the LN bath and the heating coil/sample tube (Fig. 1). Temperatures were monitored in real-time by use of a thermocouple positioned at the lowest point of the TCCT. Once the desired temperature was reached, the temperature was able to be held at this value, accurate to within ± 2 °C of the target temperature.

During sublimation, a separate pre-weighed empty Pyrex™ vessel with a glass valve was cooled using a bath of LN, for trapping of any water vapour released during sublimation (the ‘sublimate’). This process was repeated after sublimation by heating up the TCCT to 30 °C and collecting all of the residual ice as vapour in
a third pre-weighed empty Pyrex™ vessel. Amounts of sublimate and residue were then calculated by re-weighing the now-full valved collection vessels and subtracting their empty weights.

Finally, both sublimate and residue water fractions were transferred into small (1 μL) glass vials using separate syringes, stored in an oven at 60 °C between uses, and sealed with metal caps containing septa, ready for isotopic analysis. Samples were loaded into an autosampler and analysed for D/H using a chromium-based reactor tube installed in a EuroEA3028-HT elemental analyser, connected to an IsoPrime isotope ratio mass spectrometer.

**Results:** Until ~35 % of water ice was lost to the vapour phase, the isotopic composition of both the sublimate and residue samples remained relatively constant; sublimate samples were only slightly enriched in H compared to the initial water ice composition, with residue samples correspondingly enriched in D (Figure 2). For both sublimate and residue samples, measured isotopic values fell within ± 5 ‰ of the initial ice composition. After 35 % sublimation, the fractionation trend reversed, with a significant enrichment in D for sublimate samples and an enrichment in H for residue samples. These results imply that at least around 1/3 of the starting water ice can be lost before any significant fractionation of the residual ice occurs, at both -75 °C and -100 °C.

Further, no significant increase in the rate of sublimation was observed when temperature was kept constant and the pressure of the vacuum system was reduced from $10^{-3}$ to $10^{-5}$ mbar (Figure 3), and thus the fractionation behavior at both pressures was almost identical (Figure 4).

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Background: In this work, a milled sandy silt (EAC-1) from Die Rheinischen Provinzial Basalt- und Lavawerke (RPBL) quarry in Königswinter is evaluated as a potential candidate for a lunar regolith simulant.

The European Astronaut Centre (EAC), Cologne, Germany, is building a lunar analogue facility with an estimated ground area of 900 m², named the European Exploration Lab (LUNA). The planned construction has identified a need for access to large amounts (approx. 600 tonnes) of suitable lunar regolith simulant material at an affordable rate. Consequently, the nearby Volcanic Eifel region was identified as a potential source for material for LUNA.

The RPBL quarry in Königswinter in the northeastern areas of the Eifel region was evaluated as it offers sorted basaltic material of <1 mm grain size in a large production volume; providing sorted material volumes of up to 80 tonnes per day. The material is shown to be a reasonably close match compositionally to published basaltic Apollo samples, and has been determined to be of sufficient practical fidelity for use in LUNA.

Physical and chemical characterisation experiments are currently undertaken. The aim is twofold: to provide users of the facility information about the substrate material, and to determine EAC-1’s suitability as a lunar regolith simulant for further experiments requiring a higher grade of fidelity. Herein, possible use cases are also discussed. Further studies and future evaluation of post-processing methods will identify how EAC-1, or other materials, could function as a low-cost and accessible lunar regolith simulant for Europe.

Figure 1: EAC-1, a basaltic, well-graded sandy silt.
A MULTI-DECADAL SAMPLE RETURN CAMPAIGN WILL ADVANCE LUNAR AND SOLAR SYSTEM SCIENCE AND EXPLORATION. C. R. Neal1 and S. J. Lawrence2. 1Dept. Civil & Env. Eng. & Earth Sciences, University of Notre Dame, Notre Dame, IN 46556, USA (neal.l@nd.edu), 2ARES, NASA-Johnson Space Center, Houston TX 77058, USA (samuel.j.lawrence@nasa.gov).

Introduction: There have been 11 missions to the Moon this century, 10 of which have been orbital, from 5 different space agencies. China became the third country to successfully soft-land on the Moon in 2013, and the second to successfully remotely operate a rover on the lunar surface [1]. We now have significant global datasets that, coupled with the 1990s Clementine and Lunar Prospector missions, show that the sample collection is not representative of the lithologies present on the Moon [2]. The M3 data from the Indian Chandrayaan-1 mission have identified lithologies that are not present/under-represented in the sample collection [3,4]. LRO datasets show that volcanism could be as young as 100 Ma [5] and that significant felsic complexes exist within the lunar crust [6]. A multi-decadal sample return campaign is the next logical step in advancing our understanding of lunar origin and evolution and Solar System processes.

Current Decadal Survey (DS) [7]: South Pole-Aitken (SPA) Basin Sample Return is a named New Frontiers class mission in the last two DSs [7,8]. [7] also states (p. 133) “Other important science to be addressed by future missions include the nature of polar volatiles, the significance of recent lunar activity at potential surface vent sites, and the reconstruction of both the thermal-tectonic-magmatic evolution of the Moon and the impact history of the inner Solar System through the exploration of better characterized and newly revealed lunar terrains. Such missions may include orbiters, landers, and sample return.” It is difficult to conduct a lunar sample return mission under the current Discovery cost cap; international cooperation and/or commercial partnerships are essential in achieving such missions.

Sample Return Targets: Given the wealth of orbital and cartographic information now available for the Moon, we can target sample return missions beyond what is outlined in [7]. Nearside and farside targets are proposed in Fig. 1a,b. Note that these locations are examples of locations for the types of samples that would greatly advance our understanding of the Moon and the inner Solar System. Note that Figure 1 is not meant to be an all-inclusive compilation of potential sample return sites, which will also depend on safety and accessibility. Here, science is the only driver for these locations.

Spinel-, Olivine-, Opx, Plagioclase-rich lithologies were discovered by SELENE [9,10] and M3 [3,4] data. These are not well-represented in the current sample collection (Apollo & Luna, plus lunar meteorites), although a small clast in ALHA81005 is spinel-rich [11]. Such lithologies are vital for understanding the composition of the lunar crust, possibly the upper mantle, and to test the lunar magma ocean (LMO) hypothesis.

Figure 1: Examples of sample return locations: (a) nearside, (b) farside. PAN = Pure ANorthosite. Where >1 sample type can be obtained from a single site, symbols = multiple colors.

The locations for “Impact Melt/Basin” are intended to represent returning impact melts from such basins to constrain the impact history of the inner Solar System. This activity also includes “Young Craters”, which will constrain the impact flux at times older and younger than the 3.8-3.9 Ga ages of impacts that dominate the samples returned by Apollo.

“Felsic” locations are those that have been identified from orbital datasets to be silica-rich (and contain high Th abundances and a distinct peak in the Moon’s ther-
mal emission near 8µm, the Christiansen feature, associated with Si-O stretching vibration [12,13]. Felsic lithologies are present in the sample collection, but are relatively small (a few grams at the most). Orbital data demonstrate the presence of presumably extrusive silicic constructs at the Gruithuisen Domes, Hansteen Alpha, Aristarchus, Lassell, and Compton-Belkovich [6,14]. Sampling these massifs will enable tests of granite/rhyolite petrogenesis through silicate liquid immiscibility [15] and/or LMO processes.

**Young Igneous** samples include young basalts [16], and irregular mare patches [4]. The composition of these samples has important implications for understanding mantle composition as well as the thermal evolution of the Moon. Sampling of Farside Mare Basalts will also help to address these science issues. **Pyroclastic Deposits** are critical for understanding the volatile budget of the deep lunar interior. Experimental petrology on the glasses returned by Apollo suggest they are derived from greater depths than the crystalline mare basalts [17]. The presence of volatiles in the Apollo 17 orange and Apollo 15 green glasses [18,19] make pyroclastic deposits important for science and exploration (i.e., *in situ* resource utilization - ISRU). **Hydrogen (volatile) Deposits** are present in and around some permanently shaded regions (PSRs) (e.g., [20]). We know little about these deposits and landed missions (e.g., Resource Prospector and more capable follow-on missions) are required. Return of such samples could contain ancient materials that address Solar System science questions (building blocks of life, source signature of inner Solar System volatiles, etc.). Understanding the nature, distribution, and accessibility will be important for ISRU and human exploration.

**Deep Crust** and possibly lunar mantle can potentially be sampled around central peaks and deep areas within SPA. Having a sample of the deep crust or even the upper mantle will help constrain the Apollo geophysical data as well as the results from the Lunar Geophysical Network, a named New Frontiers mission for the NF-5 call later this decade. **Farside Crust** (highlands): Comparing farside sample locations (Fig. 1b) with Apollo, Luna and lunar meteorite highlands lithologies is important for understanding crustal heterogeneity and test if ferroan anorthosites are the dominant crustal lithology, as predicted from the LMO hypothesis.

**Outcrop Sampling**: None of the current returned samples were collected from unequivocal in situ outcrops. Properly oriented samples are required from various terrains and of different ages to truly test the whether the Moon ever established a core dynamo [21].

**Technology Development**. Sample return is the next step for studying many planetary bodies (Moon, Mars, asteroids). Little technology development is needed for rock and regolith, but cryogenic sampling, return, and curation require investment.

**Human vs. Robotic Sample Return**: The United States has not yet robotically returned a sample from a planetary surface, but has returned samples successfully six times from the Moon with humans. The Soviet Union is the only country to have achieved robotic sample return; the three successful Luna sample return missions brought back a total of 0.3 kg of regolith. The Apollo missions returned 382 kg of rocks, regolith, and core tubes. The trained human eye on the surface allows significant discoveries to be made (e.g., *Genesis Rock* (15415) and *Seatbelt Rock* (15016) from Apollo 15; the *Orange Glass* (74220) from Apollo 17). Human involvement in sample collection is critical for maximizing the return mass and sample types (Fig. 2). Although we assume in the future a permanent human presence on the Moon that will facilitate extensive sample return possibilities, near-term robotic sample returns will advance both lunar and Solar System science and exploration.

![Figure 2: Human returned sample mass is positively correlated with EVA hours][22]

Introduction: The rate of modification of the lunar regolith remains one of the central questions in the evolution of the Moon. We focus here on the smallest scales of roughness accessible to the LOLA instrument [1] on the Lunar Reconnaissance Orbiter (LRO) spacecraft, whose simultaneous topographic measurements on five closely-spaced spots provides an isotropic measure of the surface topographic variance that is decoupled from the influence of surface slope. The LOLA topographic variance on decameter baselines probes surface properties independent of latitude, illumination conditions, dielectric and thermal properties in a manner complementary to the Diviner rock abundance [2] and radar [3,4], and thus may be used as an independent measure of lunar impact degradation and chronology. Given the uncertainties in dating lunar terrain, an independent gauge bears on the overall assessment of surface age derived from Crater Size-Frequency Distributions (CSFDs).

The Copernican System [5] is characterized by “the brightest rays, most highly contrasting albedos of other crater materials, highest thermal anomalies, freshest morphologies, most coherent ejecta blocks, deepest floors, and fewest superposed craters.” The age of rayed craters is anchored by the 797±50 Ma model age of Copernicus derived from radiometric dating of Apollo 12 samples believed to be crater ejecta. Many possess radar-dark halos interpreted as ejecta facies depleted in blocks to depth of several meters [6]. Studies also show that hectometer-scale roughness is controlled by regolith accumulation and modification processes, primarily, geologically recent (1–2 Ga) meteoritic impacts [7].

Figure 1. Binned topographic standard deviation normalized to a footprint spacing of 25 m after removal of slope, as the 95th percentile. Circles denote the crater rim, proximal ejecta (dashes), and area outside the smoother distal ejecta halo (dots).

Aristarchus crater (Fig. 1) is one such rayed crater, whose complex volcanic and melt pool features have led to a wide range of estimates, of which the most recent [9] is given here. The 40-km-diameter crater is surrounded by a proximal region of blocky ejecta and an extensive region of bright rays. We analyze ~750 million laser shots from the LRO Commissioning, Nominal, and Science mission phases, excluding those from elliptical orbits too high to produce full 5-spot returns, to estimate topographic roughness.

Methods: Each LOLA laser pulse can produce up to 5 returns. With 5 returns on a uniformly-spaced pattern, the surface height may be modeled as a sloping plane. The sum of the squared differences between plane-fit and measured height, divided by \( 2^5 - 3 \) degrees of freedom, yields an estimate \( \sigma_h \) of the surface height variance on a baseline determined by the footprint spacing, which is proportional to the spacecraft altitude of between 30 and 70 km over the nominal and science LRO mission phases. The root variance (minus the ~10 cm measurement noise)[1] is, on average, almost proportional to the length of the baseline. The variance of individual measurements is thereby empirically normalized to an equivalent spacecraft altitude of 50 km. While some additional coverage results from the use of four spots or adjacent shots, the baseline variation is less predictable. As a refinement of earlier techniques [9], we apply an empirically-determined time-varying adjustment for centimeter-level residual curvature in the 5-spot altitude resulting from system bias on an orbit-to-orbit basis, providing better accuracy for averaged decameter-scale roughness (Fig. 2). The distribution of \( \sigma_h \) is long-tailed, and globally, 95% of the \( \sigma_h \) values are < 1 m. A similar distribution was found for rock abundance fractions determined by the Diviner team [2]. For impact cratering analysis, the resulting distribution of standard deviations was binned at 16x16 pixels per degree (~2 km) or finer and the 95th percentile value determined on each pixel.

Figure 2. Latitudinal variation of mean \( \sigma_h \) for nearside (red, blue) and farside (green, orange) sectors.
Global variation: The farside highlands are 50% rougher than the nearside, as shown in Fig. 2 (averaged over 1 degree latitude bins in sectors). Overall there is a fairly uniform distribution of roughness with little variation arising from latitude-dependent effects inherent in e.g., thermal measurements. Thanks to our isotropic slope measure, we also avoid the tendency for altimetric roughness at longer baselines to be strongly correlated with slope due to the leakage of impact-produced slope and curvature into the roughness measurement. Material differences between highlands and lowlands, including the nearside mare plains and the South Pole-Aitken basin floor, are likely responsible for the bulk of the pole-to-pole variation. Poleward of 85°N/S, an increase in average roughness suggests a possible lessening of thermally-induced breakdown of large boulders, although this may also result from poorer signal-to-noise due to LOLA thermal sensitivity.

Impact cratering and regolith breakdown: The binned 95th percentile of $\sigma_h$ was averaged within a circle of 1.25 times the crater radius (Fig. 1), encompassing the crater floor and proximal ejecta. To account for regional material variations and to avoid the smooth continuous ejecta region, interpreted as a several-meter-thick layer of fine-grained material [10] a baseline average was taken from values outside of a circle of 2.5 times the crater radius out to a distance of 200 km, and subtracted to obtain a residual roughness $\sigma_{95}$.

The nine Copernican-aged craters studied in [6], ranging in diameter from ~20 to 100 km, provide a test of this measure against their imputed CSFD ages [11], the oldest being King crater at 992±90 Ma. We also included less-certain ages for Eratosthenian craters and several other prominent rayed craters. LOLA data are too sparse to include the small, young (~7 to 80 Ma) North Ray and South Ray craters at the Apollo 16 landing site, but our test otherwise spans three logarithmic decades of age. The correlation with age, which does not encompass the youngest age and is not as close to a -0.5 power law as one might expect on theoretical grounds [12, 13], extends beyond King, and with a baseline larger than thermal methods, appears to be more sensitive in a logarithmic scale at older model ages. For the dozens of relatively fresh craters with and without rays, but uncertain ages, such a roughness measure with suitable refinement could provide additional age constraints.


![Figure 3](image.png)

Figure 3. Logarithmic plot of residual decameter-scale roughness $\sigma_{95}$ values from this study, vs. model ages from the literature, out to the nominal 3200-Ma Eratosthenian age. Symbols highlighted in red were recently studied for Diviner rock abundance [11]. A negative 0.5-slope power-law is shown for reference.
ANCIENT BOMBARDMENT OF THE INNER SOLAR SYSTEM – REINVESTIGATION OF THE KEY LUNAR BASINS WITH A NEW CRATER COUNTING APPROACH; THE BUFFERED NON-SPARSENESS CORRECTION. C. Orgel (orgel.csilla@fu-berlin.de), Michael, G. G., Kneissl, T. Freie Universität Berlin, Department of Planetary Sciences, 12249 Berlin, Malteserstrasse 74-100, Building D, Germany.

Introduction: The lunar cratering record provides valuable information about the late accretion history of the inner solar system. To learn more about the impacted projectiles, we can examine the crater size–frequency distributions (CSFDs) on the Moon. CSFDs are used to help us to define the so-called lunar “production function” (PF) [1, 2], which describes the population of craters forming on planetary surfaces. The PF is used to extrapolate the measured CSFDs to a reference diameter (~1 km) whose frequency will give an absolute age from the lunar “chronology function” (CF) [1]. However, our understanding of the origin, rate, and timing of the impacting projectiles is far from complete. The impact flux is imperfectly known during the period of 4.5 – 3.8 Gyr. If no changes occurred in the PF then the large basins were formed in a smoothly declining flux of planetesimals, whose material originated from the leftovers of planetary accretion [3, 4]. If the PF changed over time, this indicates that more than one impactor population may have formed the lunar cratering record and that could be consistent with an impact spike, called the Late Heavy Bombardment (LHB) or lunar cataclysm occurred around 3.9 – 4.1 Gyr with a duration of few tens of Myr [5-13].

Methods: We derive the impact CSFDs for each of 30 lunar basins [9] using the CraterTools add-in in ArcGIS 10.3 [16] and a new crater counting method, the buffered non-sparseness correction (BNSC) [15]. This method is a combination of buffered crater counting (BCC) [14] and the non-sparseness correction (NSC) techniques. It includes all craters overlapping the counting area. We thus use a larger number of craters which decreases the statistical noise (BCC). Each crater is referenced to an area excluding regions in the study area that have been resurfaced by larger craters and their ejecta blanket (~1 crater radius) (NSC). In order to compare the results with [9], we use their dataset along with their geologic mapping and crater counting and test the BNSC technique on non-sparingly cratered surfaces. The crater counts include the results of lunar crater catalog (≥ 20 km) [8] and additional craters beyond that database [9]. To ensure that secondary craters are not included from the age determination we perform randomness analysis [17]. We determined model ages of lunar basins using the lunar PF and CF from [1] as well as the Craterstats software [18]. Then, we studied the relation of the model ages to stratigraphical observations [9, 19]. Finally, to compare the impactor population, we derived the shape of summed CSFDs of pre-Nectarian, Nectarian and Imbrian aged basins.

Results: The derived ages of individual lunar basins using the BNSC technique showed some minor intraperiod differences in basin sequence in compare to [9] and [19]. The major findings list the Apollo and Freundlich-Sharanov basins Nectarian in age, instead of pre-Nectarian. Birkhoff Basin is older than Coulomb-Sarton Basin [9, 18] and Serenitatis Basin clearly belongs to pre-Nectarian period based on stratigraphy [9] and age determination. Generally, the calculated absolute ages using the BNSC technique fit better to the production function [1] than those ages derived from previous crater counting methods (Figure 1). The shape of summed CSFDs shows similarities and a better fit to the PF [1] in the case of the pre-Nectarian (excluding South Pole-Aitken Basin (SPA)) and Nectarian-aged basins (including Nectaris), but there is no effect of the BNSC method on the Imbrian-aged basins (including Imbrium) (Figure 2). This result is in contradiction to previous studies, where the summed CSFDs showed a change in the shape of CSFDs [8, 9].

Figure 1. The model age of Smythii Basin using the new crater counting technique (BNSC) (green filled circle) fit better to the PF [1] (grey line) than the ages derived using the BCC (red circle) and traditional (blue circle) crater counting methods.
Thus multiple impactor populations and various transition times have been interpreted in the early bombardment history of the Moon [5-13].

Figure 2. Summed crater size-frequency distributions for pre-Nectarian-aged basins (excluding SPA), Nectarian-aged basins (including Nectaris) and Imbrian-aged basins (including Imbrium). The filled circle symbols show the results derived using the BNSC technique, while the square symbols represent the results of the BCC technique. The shape of summed CSFDs of respective ages shows similarities using the BNSC method and a better fit to the PF [1]. This suggests one impactor population, which formed all the lunar basins.

Conclusions: The shape of CSFDs from pre-Nectarian to Imbrian does not show changes over the time, thus we favor the hypothesis of a single projectile population originated from the declining number of planetesimals from planetary accretion. As the oldest and deepest impact structure on the Moon, the South Pole-Aitken Basin on the lunar far-side remains a high priority candidate for exploration and sample return mission for NASA’s third New Frontiers program, called MoonRise [20]. The question of the existence of LHB is still an unsolved problem and sample return missions from various key locations should be done in the future.

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References

Introduction: As the oldest and deepest impact structure on the Moon, the South Pole-Aitken Basin on the lunar farside is a high priority location for exploration and sample return [1, 2]. We examine a Design Reference Mission (DRM) architecture [3] for the release of the 2017 Global Exploration Roadmap [4] developed by the International Space Exploration Coordination Group (ISECG). This DRM involves a five-year human exploration campaign with five landing sites in the farside south polar region of the Moon and visited in subsequent years beginning in 2028. The five proposed landing sites have high scientific interests with respect to prioritized science concepts defined in a 2007 report by the National Research Council (NRC) [1]: Malapert Massif (85.9°S, 2.9°W), South Pole/Shackleton Crater (89.3°S, 130.0°W), Schrödinger Basin (75.4°S, 159.9°W), Antoniadi Crater (69.7°S, 172.0°W), and the South Pole-Aitken Basin center (60.0°S, 159.9°W). Here we reexamine and slightly modify the location of those landing sites and evaluate the science potential that can be accomplished by a human mission.

Mission architecture: In the DRM of [3], a crew of four lands at each landing site and traverses within a 100 km Mars-Forward exploration zone in a pair of Lunar Electric Rovers (LERs) which serve as a habitat and a geologic tool for the crew. Mission hardware includes: NASA’s Space Launch System (SLS), the Orion vehicle, an evolvable Deep Space Habitat (eDSH) developed by ESA, a reusable ascent/descent stage, and two reusable Lunar Electric Rovers (LER) with notional instrumentation packages (APXS, GPR, and Gigapan). Surface activities are composed of two 14-day-long traverse loops that return to the lander within a 28-day mission, if the LERs can operate at lunar night. A companion abstract [5] details the interlanding site traverse of the LERs driven telerobotically over the course of a year from one landing site to another. The eDSH will be positioned in a large southern halo orbital configuration around Earth-Moon Lagrange point 2 (EM-L2) to use as an orbital asset and enable greater than 80% coverage per orbital pass at each landing site for communications support [6].

Methodology: To determine the trafficability for both LERs and evaluate the potential science return at each landing site we used all available dataset from previous lunar missions as well as studies of [7-14] to ensure the maximal number of NRC scientific concepts are addressed [1]. Trafficability was determined via slope maps and digital elevation models derived from Lunar Orbiter Laser Altimeter (LOLA) data at resolutions from 5 to 100 m depending on latitude. Terrain was also visualized using Lunar Reconnaissance Orbiter Camera (LROC) Wide Angle Camera (WAC) mosaics of 100 m/pix and LROC Narrow Angle Camera (NAC) images of 1 m/pix to provide detailed information for sample collection at each sampling station along the traverses. Those traverses for both LERs were developed using ArcGIS 10.1.

Figure 1: Site overview. Base image LROC WAC mosaic 100 m/pix.

Concept of Operations: This study utilized LER capabilities and conops consistent with past lunar mission simulations [15-19]. Sample masses are consistent with CAPTEM recommendations [20]. For each intra-landing site traverse we construct a detailed timeline of crew activity (8.5 hrs per day) for the duration of their 28-day mission including communication dropout.
times due to eDSH orbital configuration to ensure maximum time available for sample collection during Extra-Vehicular Activity (EVA) [15].

Malapert Massif: The first human landing site is particularly notable because of its potential for direct-to-Earth communication, and the study of Permanently Shaded Regions (PSR) and highly illuminated regions, which experience constant illumination 74% of the lunar year [21]. These regions provide a multitude of In Situ Resource Utilization (ISRU) potential. Massif material samples provide an ideal opportunity to study cross-sections of the lunar crust. Six of seven NRC (1-4, 6, 7) concepts can be addressed.

South Pole/Shackleton Crater: Exploration of the second human landing site is unique due to its proximity to many PSRs. The study of such features is a high priority for [1] and sustainable exploration. Crew in LERs can explore regions of both H₂O and CO₂ stable subsurface temperatures [22]. Traverses are designed such that PSRs on the floor of Faustini Crater [14] and in the vicinity of de Gerlache and Shoemaker craters will be explored. In situ observations and sample collection can help address six of seven NRC concepts (1-4, 6, 7) and provide ISRU potential.

Schrödinger Basin: This basin is recognized as the highest priority landing site for addressing NRC objectives [6]. It hosts a large central pyroclastic deposit – a key target for both scientific and ISRU exploration. Sampling other geologic sites provide sample opportunities to test the lunar cataclysm and lunar magma ocean hypotheses, constrain lunar volatile cycling, and provide insight into the thermal evolution of the Moon. All NRC concepts can be addressed. While this study determined that the floor of Schrödinger is accessible to LERs, contingency extra-basin EVAs have been planned. Extra-basin exploration is limited in geologic context and lacking notable features such as: young mare, pyroclastics, feldspathic primary crust and impact melt products with geologic context.

Antoniadi Crater: Exploration of Antoniadi Crater, may serve to test the lunar cataclysm hypothesis, as it is the youngest impact from that epoch. Additionally, Antoniadi offers an opportunity to sample the central SPA basin impact melt sheet as well as some of the youngest volcanic rocks on the Moon. With over 40 different volcanic constructs, selective sampling can further enhance an understanding of material of ISRU interest. All NRC concepts can be addressed. Although it appears the floor of the crater is accessible to LERs, a contingency extra-basin traverse was designed, but it has less scientific potential.

South Pole-Aitken Basin Center: Exploration of the SPA center provides the best location to sample fragments of the SPA impact melt sheet, mare and cryptomare, and some of the oldest regolith on the far-side of the Moon. Sampling the diverse geology will elucidate to test the lunar cataclysm hypothesis, far-side ancient magmatism and regolith formation processes. Six NRC concepts can be addressed (1-3, 5-7). Discrepancies in existing geologic maps require updated mapping using new data before detailed traverse assessment can be made. As this is the last landing site, there is sufficient time to conduct such studies.

Discussion and Conclusion: This study, based upon a DRM by [3] as a prelude to the release of the 2017 GER, is a first-pass at the feasibility of a five-site, eDSH enabled, lunar sample return mission scenario which utilizes both human and robotic assets. The findings of this study, obtained through integration of multiple remotely-sensed lunar datasets, crew activity scheduling, robotic asset capabilities, and communications feasibility, show that a human-assisted robotic mission to the SPA Basin can address all 7 remaining NRC lunar science concepts [1], and would be a valuable resource for the early history and evolution of the solar system as well as for future Mars-Forward campaigns.

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**MARE BASALT VOLCANISM ON THE SOUTHERN LUNAR FARSIDE.** J. H. Pasckert¹, H. Hiesinger¹, and C. H. van der Bogert¹. ¹Institut für Planetologie, Westfälische Wilhelms-Universität, Wilhelm-Klemm-Str. 10, 48149 Münster, Germany. jhpasckert@uni-muenster.de

**Introduction:** The volcanic history of the South Pole-Aitken (SPA) basin and the lunar farside in general is key to understanding the volcanic evolution of the Moon. In contrast to the lunar nearside, the farside shows only isolated mare deposits within large craters and basins, like the SPA basin or Tsiolkovsky crater [e.g., 1-4]. The SPA basin is the largest (>2200 km in diameter) observed impact structure on the Moon [e.g., 4], and might have penetrated the lunar crust, although only ~3 - 4% of the basin are flooded by mare basalts (Fig. 1). To understand the volcanic evolution of the SPA basin and the southern lunar farside, we mapped 148 mare deposits (Fig. 1) using Wide Angle Camera (WAC) data obtained by the Lunar Reconnaissance Orbiter (LRO), including also the mare basalts of [5].

Basaltic volcanism on the lunar nearside was active for almost 3 Ga, lasting from ~3.9-4.0 Ga to ~1.2 Ga before present [6]. In contrast to the nearside, most eruptions of mare deposits on the lunar farside stopped much earlier, ~3.0 Ga ago [7]. However, [7] also found mare deposits that show much younger ages of 2.5 Ga. Consequently, [7] concluded that the farside volcanism might have occurred episodically, around 2.5 Ga and between 3.0 Ga and 3.6 Ga. Thus, they argued that the relatively large difference in the cessation of volcanic activity between the nearside (1.2 Ga) and farside (2.5 Ga) might be related to a thicker crust on the lunar farside, which hinders eruptions. However, according to the crustal thickness map of [8], based on new high-resolution gravity data obtained from the Gravity Recovery and Interior Laboratory (GRAIL), the crustal thickness of the southern farside in and at the edge of the SPA basin is thinner than ~35 km, hence, similar to the crustal thickness of the lunar nearside mare.

**Data:** Data from the LRO Wide Angle Camera (WAC: 100 m/pixel) and the Clementine FeO map [9] (100 m/pixel) have been used to identify and map individual volcanic deposits and to perform crater size-frequency distribution (CSFD) measurements. The digital terrain model derived by the Lunar Orbiter Laser Altimeter (LOLA) [10] with a horizontal resolution of 100 m/pixel was used to investigate the elevation of the mapped mare basalts.

**Results:** Most of the mapped mare basalts are located in impact craters and basins of different sizes, e.g., Tsiolkovsky, Poincaré, Ingenii, and Apollo. However, in the center of the SPA basin at the lowest elevations and outside the SPA basin around Rosseland crater, there occur some mare basalts that are not related to impact craters.

We derived absolute model ages for 120 individual mare basalts via CSFD measurements on WAC images. Our absolute model ages (AMAs) range from 1.5 Ga (~0.39 Ga), for a small mare basalt pond inside Rosseland crater at the western rim of the SPA basin, to 3.7 - 3.8 Ga for mare basalts in the center of the SPA basin and also north of Rosseland crater (Fig. 1). A large number of secondary craters and the burial of mare basalts by the ejecta of relatively large Eratosthenian impact craters, like Finsen (80 km in diameter), makes it difficult to define good counting areas.

![Figure 1: Color-coded map of AMAs for mare basalts in and around the SPA basin with the WAC mosaic as a base map (south polar stereographic projection). Letters indicate Tsiolkovsky (T), Poincaré (P), Ingenii (I), Apollo (A), Finsen (F), and Rosseland (R).](image-url)
for reliable ages for some of the mare basalts, especially within the SPA basin. Thus, 28 mostly small deposits of the 148 mapped basalts could not been dated.

Our AMAs are generally very similar to those derived by [6, 12, and 13] for farside mare basalts. For example, [7] obtained an AMA of 3.34 Ga for the mare basalts inside Jules Verne crater, which is within our error bars. They also found some younger ages between 2.44 Ga and 2.58 Ga inside the SPA basin; these ages seem to be resurfacing ages in most cases. We derived similar young model ages for the mare basalts in and around the SPA basin, but the majority of the mare basalts show older ages between 3.2 and 3.7 Ga. Our youngest AMAs, which are located in an around Rosseland crater (1.5 - 2.5 Ga) are younger than the youngest AMAs (2.4 - 2.6 Ga) derived by [6, 12, 13].

Estimates of the FeO content of each mare basalt unit with the FeO map of [9], reveal a range between 14 and 20 wt%, with an average of 18 wt%. This is generally very similar to the mare basalts investigated, for example, by [9]. A trend between the absolute model ages and the FeO content was not observed, which is consistent with the observations by [14].

We measured the mean elevation of each dated mare basalt to investigate the relationship between the topography and the AMAs (Fig. 3). Within the SPA basin, the topography more or less reflects the crustal thickness, and thus, this approach gives us an idea about the relationship between the crustal thickness and the AMAs. A trend between the AMAs and the elevation is not observed (Fig. 3), however, the majority of the mare basalts within the SPA basin seem to be generally older than those around the basin.

Most of the mare basalts inside the SPA basin are located below ~3 km elevation and have a relatively narrow range of ages (3.2 - 3.8 Ga), with some outliers between 2.2 Ga and 3.0 Ga. The mare basalts outside the SPA basin are all above ~3 km elevation and have a wide spread of AMAs (1.5 - 3.8 Ga).

Figure 2: (a) Absolute model ages derived by the current study of mare basalts inside the SPA basin. (b) Ages of all investigated mare basalts on the southern lunar farside from [5] and this study. (c) Ages of all investigated mare basalts on the lunar farside from [5], [7], [11], [12], [13] and this study. (d) Ages of mare basalts on the lunar nearside [6]. In all four histograms we observe a major peak between 3.2 and 3.8 Ga and a small peak at ~2.2 Ga.

Figure 3: Correlation between absolute model ages of the investigated mare basalts and their elevations.

Discussion and Conclusions: Our CSFD measurements show that the southern farside has been volcanically active over at least 2.3 Ga from 1.5 Ga to 3.8 Ga (Fig. 2a), which is a wider range than previously derived by [10-12], showing AMAs from 2.4 Ga to 3.9 Ga. However, although the SPA basin contains the largest occurrence of mare basalts on the lunar farside and globally excavated deepest into the crust, it does not show evidence for such a long period of volcanic activity (2.2 - 3.8 Ga) as the rest of the lunar farside and the nearside. The absence of young mare basalts cannot be explained by greater crustal thicknesses, because the SPA basin shows much lower crustal thicknesses (<25 km) than the rest of the farside. Thus, crustal thickness might not be the only factor to explain why volcanic activity stopped earlier on the lunar farside than on the nearside, as proposed for example by [7]. Alternatively, the lower amount of heat-producing elements like Thorium has been proposed as an important factor for the relatively early cessation of the farside volcanism [15]. However, the SPA basin is slightly enhanced in Th-content and thus, in combination with the thin crust, one might expect younger and large amounts of volcanic activity within the SPA basin. A possible explanation for the relatively large difference in the volcanic activity between the SPA basin and the large nearside basins could also be related to the impact melt sheet identified by [16] at the center of the SPA basin. The melt sheet could have hindered the magma reach the surface.

EFFICIENT AND REALIBLE SURFACE SAMPLING IN LOW-GRAVITY CONDITIONS. P. Paško, K. Seweryn, S. Abramik, J. Perz, W. Teper, G. Visentin, R. Wawrzaszek, L. Wolski, Z. Żyliński

Space Research Centre PAS, Space Mechatronics and Robotics Laboratory, Warsaw, Poland (ppasko@cbk.waw.pl), Electrotechnical Institute Gdansk Branch, Gdańsk, Poland, European Space Agency (ESA), Noordwijk, The Netherlands.

Introduction: In recent years, an increased interest in subsurface explorations of planets, asteroids and comets has been observed. Past missions such as HAYABUSA by JAXA, ROSETTA with PHILAE lander and MARS ROVERS missions have led to better understanding of other planets surface properties. As asteroids and other small space objects could be a source of minerals and volatiles more and more sampling mission would be performed to validate the usefulness of the candidate asteroid. The PACKMOON is the sample acquisition system for surface sampling in low-gravity conditions. It utilizes an innovative concept of the rotary hammering devices [1]. Its purpose is to collect the regolith sample from the planetary body, seal it and prepare for further transportation. The requirements for the PACKMOON device are formulated to be in line with ESA Mars Moon Sample Return Mission, but as a system PACKMOON can be adapted to other low gravity sampling missions e.g. to the Moon or asteroid. Currently the system is designed to be able to collect up to 150 cm$^3$ of lose regolith as well as consolidated material (up to 5 MPa compressive strength).

System description: PACKMOON is a Low Velocity Penetrometer (LVP) type mechanism, where the principle of operation is to perform movement by means of hammering actions. Such actions are an energy efficient way to insert thin element into the soil. Unlike the previous LVP devices described in [2] that generate linear movement, PACKMOON is a rotary hammering device that generates rotary movement of the jaws. As it is shown on Figure 1 and Figure 2 the system is doubled to cancel the reaction force and torques to the lander. The collection of the sample is done by gradual rotary movement of both jaws. A finite amount of soil is closed between the jaws, which at the same time can serve as a sample container. The main advantage of using hammering action is its high efficiency in regolith penetration, therefore the device requires low energy to perform its task.

Table 1: Assumed key parameters of the device

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>~3 kg</td>
</tr>
<tr>
<td>Volume (sample container)</td>
<td>150 cm$^3$</td>
</tr>
<tr>
<td>Dimensions of sample container</td>
<td>Ø150mmx100mmx</td>
</tr>
<tr>
<td>Hammering energy</td>
<td>2 J</td>
</tr>
<tr>
<td>Sampling Time</td>
<td>~10 min (goal 5 min)</td>
</tr>
<tr>
<td>Power</td>
<td>&lt;10 W</td>
</tr>
</tbody>
</table>

The principle of operation of PACKMOON device as well as a theoretical model which stay behind it was shown in [1]. It’s based on interactions between 3 elements: hammer, jaws and support masses (Figure 2). In difference to theoretical solution presented therein, hammers in the ultimate design is driven actively by the motors. Support masses consist of connected stators of BLDC motors, which accelerate the hammers in opposite directions to a certain level of energy so that the reaction torque of the motors is cancelled. Energy and momentum of the hammers is then transmitted to the jaws by short time stroke, which enforces the jaws to rotate. After a certain number of strokes, dependent on the regolith parameters, the jaws close and the sample is acquired, preserving its structure, and without thermal influence. Sampling phases beginning from delivery of the device to the surface, through hammering, and final sample collection are shown in Figure 1.
Prototype: Up to now two breadboards (one is presented in Figure 3) and one prototype (Figure 4) of the PACKMOON device were manufactured. Extensive tests were executed on both breadboards, allowing to prove the concept and to initially determine the performance of the sampling method. Tests included determination of device behavior in simulated low gravity conditions and evaluation of the tool influence to the lander.

Figure 3: Second breadboard with active BLDC drive

The tests were performed using various materials like lunar regolith analogue, Phobos analogue and two types of foamglass (with 2.1 MPa and and 4.4 MPa of uniaxial compression strength). Some of the results obtained during one of the test campaigns are presented below in Table 2.

Table 2. Test results

<table>
<thead>
<tr>
<th>Probe</th>
<th>Impacts</th>
<th>Vertical Force [N] (mean)</th>
<th>Vertical Torque [Nm] (mean)</th>
<th>Sample Mass [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phobos 1</td>
<td>57</td>
<td>34,5</td>
<td>6,6</td>
<td>297.1</td>
</tr>
<tr>
<td>Phobos 2</td>
<td>19</td>
<td>36,6</td>
<td>6,3</td>
<td>201</td>
</tr>
<tr>
<td>Phobos 3</td>
<td>35</td>
<td>32</td>
<td>6,7</td>
<td>320</td>
</tr>
<tr>
<td>Moon 1</td>
<td>12</td>
<td>13</td>
<td>3,6</td>
<td>382.2</td>
</tr>
<tr>
<td>Moon 1</td>
<td>10</td>
<td>17</td>
<td>5,8</td>
<td>423</td>
</tr>
<tr>
<td>Moon 1</td>
<td>10</td>
<td>6,7</td>
<td>5,7</td>
<td>400</td>
</tr>
<tr>
<td>Foamglass 1</td>
<td>150</td>
<td>25,1</td>
<td>6,8</td>
<td>-</td>
</tr>
<tr>
<td>Foamglass 1</td>
<td>213</td>
<td>17,1</td>
<td>5,8</td>
<td>-</td>
</tr>
<tr>
<td>Foamglass 1</td>
<td>148</td>
<td>9,4</td>
<td>5,8</td>
<td>-</td>
</tr>
</tbody>
</table>

In December 2016, the prototype of the PACKMOON device was developed. Compared to previously build breadboards it’s more compact and energy of the strokes is twice higher (~2J). Evaluation of its performance is currently ongoing outcomes should be available in April 2017.

Figure 4. The prototype of the PACKMOON sampling tool.

References:


Acknowledgments: This paper was supported by European Space Agency project no. 4000112603/12/NL/CBi.

Introduction: The Mini-RF instrument aboard NASA’s Lunar Reconnaissance Orbiter (LRO) is a hybrid dual-polarized synthetic aperture radar (SAR) and operates in concert with the Arecibo Observatory (AO) and the Goldstone deep space communications complex 34 meter antenna DSS-13 to collect S- and X-band bistatic radar data of the Moon. Bistatic radar data provide a means to probe the near subsurface for the presence of water ice, which exhibits a strong response in the form of a Coherent Backscatter Opposition Effect (CBOE). This effect has been observed in radar data for the icy surfaces of the Galilean satellites, the polar caps of Mars, polar craters on Mercury, and terrestrial ice sheets in Greenland. Recent work using Mini-RF S-band (12.6 cm) bistatic data suggests the presence of a CBOE associated with the floor of the lunar south polar crater Cabeus [1].

Background: The first Mini-RF bistatic campaign included 28 AO S-band observations of the lunar surface, polar and nonpolar, for a range of incidence angles and for bistatic angles from near 0° to > 10°. A variety of terrains were sampled, often within individual observations. They include mare, highland, pyroclastic, crater ejecta, and crater floor materials. Locations that showed evidence of an opposition effect were re-targeted on multiple occasions in an effort to determine the character of the response. This included the floor of the south-polar crater Cabeus – the target of the LCROSS impact experiment. The portion of the crater floor that was observed by Mini-RF was not in permanent shadow.

Method: AO observations illuminated the visible floor of Cabeus and surrounding terrains (Fig. 1) with a circularly polarized, S-band (2380 MHz) chirped signal that had a fixed peak power of 200 kw and tracked the Mini-RF antenna boresight intercept on the surface of the Moon for each observation. The transmitted pulses for all observations were 100 μs long, had a chirp start frequency of 2379.2 MHz, a chirp rate of 1.6 x 10⁴ MHz/s, and a bandwidth of 1.6 MHz. The resolution of the data is ~100 m in range and ~2.5 m in azimuth but can vary from observation to observation, as a function of the viewing geometry. For analysis, the data were averaged in azimuth to provide a spatial resolution of 100 m. This yielded an ~40-look average for each sampled location in an observation and an average 1/N1/2 uncertainty in the CPR measurements of ±0.16.

Observations: Mini-RF observations of the floor of Cabeus covered bistatic angles of 0.5° to 8.6° for incidence angles ranging from 82.4° to 86.6°. CPR measurements for the floor of the crater, as a function of bistatic angle, show a clear opposition surge (Fig. 2); something not observed for the floors of nearby, similar-sized craters that were sampled during the Mini-RF bistatic campaign (e.g., Casatus,
The opposition peak of Cabeus floor materials has a width of ~2° and features a ~30% increase in CPR. The bistatic observations of the region surrounding Cabeus indicate that mean CPR values for the portion of its floor that was imaged by Mini-RF are less than that of the surrounding highlands for bistatic angles > ~1.8° but similar to that of nearby radar-facing slopes. Mean CPR values for the imaged floor of Cabeus are higher than that of surrounding highlands and nearby radar-facing slopes for bistatic angles of 0.5° to 1.8°. Mini-RF data for bistatic angles < 0.5° were not acquired during the bistatic campaign. However, Mini-RF monostatic data (i.e., bistatic angle of 0°) of the crater floor were acquired [2] and ground-based CPR measurements at a bistatic angle of 0.37° have been made [e.g., 3]. Elevated CPRs were not observed in either case.

Summary: The goal of the Mini-RF bistatic campaign was to observe the scattering characteristics of the upper meter(s) of the surface, as a function of bistatic angle, and search for a coherent backscatter opposition response indicative of the presence of water ice. To accomplish this goal, a variety of lunar terrain types were sampled to search for and characterize the presence of an opposition response. A clear opposition surge was detected for a portion of the floor of the south-polar crater Cabeus that is not in permanent shadow. The opposition surge observed for the floor of Cabeus appears to be unique with respect to all other lunar terrains observed. Analysis of data for this region suggests that the unique nature of the response may indicate the presence of blocky, near surface deposits of water ice. However, understanding the differences between Mini-RF bistatic observations of Cabeus and observations gathered by Mini-RF monostatic and ground-based observations of the crater remains an open issue.

Future Work: The LRO spacecraft has begun its third extended mission. For this phase of operations Mini-RF is leveraging the existing AO architecture to make S-band radar observations of additional polar craters (e.g., Haworth, Shoemaker, Faustini). The purpose of acquiring these data is to determine whether other polar craters exhibit the response observed for Cabeus. Mini-RF has also initiated a new mode of operation that utilizes the X-band (4.2cm) capability of the instrument receiver and a recently commissioned X/C-band transmitter within the Deep Space Network’s (DSN) Goldstone complex to collect bistatic X-band data of the Moon. The purpose of acquiring these data is to constrain the depth/thickness of materials that exhibit a CBOE response – with an emphasis on observing the floor of Cabeus.

**ORIGIN AND IMPORTANCE OF ‘FEATURELESS’ PLAGIOCLASE ON THE MOON**  
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**Introduction:** Near-infrared spectroscopy is a powerful tool for evaluating the mineralogy of the lunar surface, largely because Fe-bearing minerals exhibit highly diagnostic crystal field absorptions that enable mineral identification [1]. Near-infrared spectrometers on earth-based telescopes initially allowed mafic rocks to be identified at immature or freshly exposed lunar surfaces based on the nature of their absorption bands. Anorthosites were tentatively identified by the opposite. Namely bright or immature areas with a lack of any ferrous absorption features (i.e., no detectible presence of iron-bearing minerals) were thus indirectly inferred to represent plagioclase or anorthositic regions on the Moon because they were effectively mafic-free.

Crystalline plagioclase, however, even with 0.1% FeO exhibits a broad feature near 1.25 μm due to transitions in ferrous iron [1]. This crystal field diagnostic feature depends on the structure of the mineral and the relation between the Fe2+ ion and surrounding anions. Plagioclase, unlike the mafic minerals, readily loses its crystal structure when heavily shocked, becoming maskelynite, or diaplectic glass. It had long been suggested that the pervasive impact history of the ancient plagioclase-rich lunar highlands destroyed the bulk crystallinity of plagioclase, resulting in a ‘featureless’ spectrum for anorthositic areas [2]. However, such a simple story does not really agree with the data accumulating from modern orbiting spectroscopic sensors and related laboratory analysis of samples, suggesting additional factors must be involved.

**Emerging views and challenges:** With spectroscopic sensors flown on SELENE (MI and SP) and Chandrayaan-1 (M3), crystalline plagioclase was detected at multiple highland locations with a 1.25 μm band [3, 4, 5, 6]. Because no mafic minerals were detectible, these sites were termed PAN, or pure anorthosite exposures [3]. The PAN detections were commonly observed at considerably higher spatial resolution than could observed with Earth-based telescopes but were often found in association with what had been interpreted as ‘featureless’ plagioclase.

Shown in the figure below are examples of PAN and ‘featureless’ plagioclase found together along the Inner Rook Peak Ring (Peak Ring) of Orientale. The PAN is highly localized, and boundaries appear sharp [e.g. 5]. This sharp change is similar to laboratory shock measurements [9] where a change from crystalline features occurs at about 25 GPa: no ‘featureless’ shocked plagioclase is seen, but the higher shocked material exhibit a distinctive maskelynite glass band. The steep continuum of ‘featureless’ plagioclase has been hypothesized to represent the presence of npFe2+, commonly observed with normal space weathering of lunar soils [10]. However, ‘featureless’ plagioclase is not really a soil; at least one very clear example of a coherent outcrop has been documented in Theophilus [11].

**Examples of crystalline and ‘featureless’ plagioclase found along the Orientale Inner Rook mountains [4].** Shown for comparison are laboratory spectra of clean maskelynite glass from the gabbroic lunar meteorite A881757 [7,8].

Crystalline and ‘featureless’ plagioclase have now been observed at numerous highland craters and basins [3,6]. However, lunar samples of plagioclase/anorthosite measured in the laboratory exhibit only the diagnostic 1.2 μm crystalline feature, even when petrographic analyses indicate abundant maskelynite [12]. The meteorite A881757 separate above exhibits the diagnostic maskelynite glass features [7,8], but no maskelynite has been identified remotely. Similarly, ‘featureless’ plagioclase is found extensively throughout the highlands, but no ‘featureless’ lunar plagioclase has (yet) been found in the returned samples, in spite of their varied shock history.

**Alternate Hypothesis.** In order to more confidently assess the abundance and distribution of plagioclase in the lunar crust, we need a better assessment/confirmation of ‘featureless’ plagioclase observed remotely. As described in [9], shock produces internal fractures and micro-surfaces. If abundant at a fine scale, such scattering interfaces will reduce the optical path length in a transparent medium. Whether glass or crystalline, transparent shocked plagioclase with multiple internal reflection interfaces cannot host a sufficiently large optical path length for detection of the plagioclase (or glass) diagnostic ferrous feature. This alternate featureless plagioclase hypothesis welcomes testing with additional laboratory data.

**References:**  
[10] Pieters and Noble 2016, JGR 121, 1865-1884  
[12] Cheek and Pieters, 2013, LPSC44 #2387
LUNAR IMPACT MELT RHEOLOGY. J. B. Plescia\textsuperscript{1}, \textsuperscript{1}Applied Physics Laboratory, The Johns Hopkins University, Laurel, MD USA 20723 (Jeffrey.Plescia@jhuapl.edu).

Introduction: Impact melt is observed over a range of impact crater sizes on the Moon. It occurs as the floor filling of basins and large craters, as ponds and flows along down-dropped terrace blocks, as isolated ponds, and as flows (Fig. 1). Understanding the volume of impact melt retained on a crater floor and rim, and its rheologic properties are critical to understanding the details of impact cratering energy partition, excavation, and ejecta emplacement.

Melt Flow Rheology: Because impact-melt is a molten silicate rock, its rheology can be understood in the same context as that of lava flows and analyses and modeling of terrestrial and planetary lava flows [1-10] can be used as a basis to study impact melt flows.

Rheologic models to calculate yield strength employ different morphometric parameters as well as local gravity and flow density. In some cases, the surface is folded and the fold wavelength and amplitude can be used to constrain the rheology [14-15]. A flow will have a width and thickness controlled by rheology only if the flow is topographically unconstrained. Similarly, the substrate is assumed to be smooth such that the downslope flow is not impeded.

Impact melt is initially deposited on the rim and begins to flow downslope. It can continue downslope as a broad sheet flow or coalesce into a well-defined flow. Multiple pulses are indicated by numerous overlapping lobes (Fig. 1B). Individual lobes have sufficient momentum to ride up and over topographic obstacles and to bulldoze boulders. Cooling of the flow occurs by radiation; ingestion of boulders and debris can significant influence the cooling as such material would be cold.

Flow material associated with about fifty craters, with visually well-defined impact melt flows, have been examined. Table 1 lists example results of the yield strength estimated using a number of different models.

Discussion: Impact melt flows exhibit a range of morphologies and a range of rheologic properties. Yield strengths vary over three orders of magnitude from $10^3$ to $10^5$ Pa. Modeled yield strengths overlap calculated and measured yield strengths of basaltic lavas at Kilauea and Mauna Loa [17-18]. The lunar values are also consistent with previous estimates of impact melt rheology [1, 17, 19]. Modeled yield strengths do not correlate with crater diameter or with target type. Yield strengths do correlate with flow morphology. Low yield-strength values are associated with the thin coatings. The high values are associated with large, bulbous morphology of some flows (e.g., Fig. 1C - the north flank of Tycho).

Conclusions: Lunar impact melt flows have rheologies similar to that of terrestrial basalts, however yield strengths range over three orders of magnitude. The variations likely reflect small-scale heterogeneities the amount of melting of target rocks, the initial temperature of the melt and the impact conditions (e.g., impact angle).

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
Crater & Lat. / Long. & D (km) & $\tau$ (Pa) \\
\hline
Lichtenberg B & 33.3° / 298.5° & 5.2 & 4 x 10^3 \\
Giordano Bruno & 35.9 / 102.8 & 22 & 10^6 \\
Fersman South & 13.6° / 234.5° & 9 & 10^4 \\
Byrgius & -24.6° / 296.2° & 19 & 1-2 x 10^3 \\
Mandel'shtam F & 5.1° / 266.1° & 15 & 9 x 10^3 \\
Das G & -29.0° / 227.2° & 11.7 & 3 x 10^4 \\
O Day M & -31.6° / 157.0° & 12.3 & 4 x 10^4 \\
Tycho North & -41.18° / 348.6° & 86 & 4 x 10^4 \\
\hline
\end{tabular}
\caption{Modeled Yield Strengths}
\end{table}

**PLAINS VOLCANISM ON THE LUNAR MARE.** J. B. Plescia, The Johns Hopkins University, Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel MD 20723 (jeffrey.plescia@jhuapl.edu).

**Introduction:** The most obvious and volumetrically important aspect of post-heavy bombardment lunar volcanism is the eruption of the basaltic mare [1]. These large, presumably high-rate eruptions fill the topographic depressions of ancient impact basins and embay the surrounding highlands. In addition to the mare, other styles of lunar volcanism include pyroclastics [2-4] and what have been referred to as "lunar domes" [5-10]. Lunar domes include features that exhibit variable morphology, composition [11-12] and possibly eruptive styles. Recently, [13] suggested the presence of huge, low-relief shields on the mare.

Here, a subset of the domes are discussed that are interpreted to represent a style of volcanism characterized by small-volume eruptions that primarily built low-relief constructs with low slopes, small diameters (few kms) and low relief (few hundred meters) (Figure 1). This style of volcanism has been termed "plains volcanism" [14] and is typical of Iceland and the Snake River Plains and is common in the Tharsis region of Mars. These features represent the terminal phases of mare volcanism (occurring after the emplacement of the flood basalts) and represent small volume, short-lived events. Understanding the timing, distribution and rheology of these features provides insight into how lunar volcanism evolved over time.

**Distribution:** The lunar low shields are scattered across the mare. In most cases they occur in widely spaced groups (e.g., the Cauchy field, Fig. 1), in other cases the grouping is might tighter (e.g., Marius Hills [15]). Additionally, there are isolated low shields. There are about a dozen groups and a total of more than 200 individual vents.

**Morphology and Morphometry:** Mare Tranquilitatis, adjacent to Rupes Cauchy, serves as an example. Figure 1 illustrates a typical morphologic range. Virtually all edifices are low shields, more or less equant in outline, with a summit vent. Lava flows are exceptionally rare; clearly defined flows have only been recognized with what might be cinder cones.

Figure 1 (A) illustrates a low relief construct with a summit crater. In many cases, the depth of summit crater exceeds the edifice height (i.e., the floor is at a lower elevation than the plains). The contact with the surrounding plains is gradual. Diameter is ~10 x 8.7 km and relief is ~100 m. A second type has a pancake-like cross-sectional shape (B in Fig. 1). Diameter is ~9 km with 100 m of relief; upper slopes are <1° and marginal slopes are 2°-5°; it has an abrupt contact. The third type (C in Fig. 1) are relatively steep-sided, have an abrupt contact and lack a summit crater. Surface morphology is hummocky and the slopes are 2°-5°. In addition, a small number of features appear to be the result of spatter or cinder cones.

**Conclusions:** Lunar domes consist of a variety of morphologic types. The primary is one built by eruption of small-volume flows of low viscosity for a limited duration. The sizes suggest that the volume of available magma was small. Most vents appear to be randomly distributed although a few are clearly tectonically controlled. The range of morphology and slopes for these features suggests that there are differences in either the eruption rate or composition of the lavas among the vents. The steeper features either represent more viscous lavas or much slower eruption rates compared with the constructs that have low slopes.

TEMPERATURE REGIME IN POTENTIAL LANDING SITES OF THE LUNA-25 MISSION. S. V. Pu- gacheva¹, E.A. Feoktistova and V. V. Shevchenko, ¹Sternberg State Astronomical Institute, 119899, Moscow, Russia (katk@sai.msu.ru).

Introduction: Twelve areas in the southpole region of the Moon have been previously suggested as potential landing sites for the Luna-25 (Luna-Glob) mission [1]. Currently three sites have been chosen as the most suitable for landing [1]: they include ellipses number 1, 4 and 6. The mission is set to begin some time between 2018 - 2020. Any potential landing site must satisfy certain criteria: 1) the sites needs to be in landing sector of the mission; 2) the landing site must be elliptical with dimensions of 15 ×30 km (the long axes along the meridional direction); 3) the surface slope of the landing site must not exceed 7º; 4) the illumination and hydrogen abundance must be maximal; 5) the duration of radio connection with Russian ground stations, such as Bear Like, Ussuryisk and Yevpatoria must be maximal too. The text will automatically wrap to a second page if necessary. The running head on the second page of this template has been eliminated intentionally.

Ellipse 1 (68,8° S, 21,21° E) is located to the south-west of Manzinus crater (67,31° S, 26,22° E); ellipse 4 - to the south of Pentland A crater (67,2° S, 13,15° E); and ellipse 6 - to the west of Boussingault crater (70,13° S, 53,44° E). We investigated the illumination condition in these areas for one diurnal period using the DEM from [2] with a step in latitude and longitude of 0,01° and a time step of 1/360 of a lunar day. According to our results there are not permanently shaded regions in these areas, and the average illumination does not exceed the 55 - 60 % for one diurnal period.

In this paper, we investigated the temperature regime in these selected landing sites. To do it, we used the model described in [3]. The heat conduction equation with the initial and boundary conditions was solved. The distributions of maximal and minimal temperatures for these regions are shown in Figure 1 and 2.

We found that the maximal temperatures in ellipse 1 ranges from 280 K in its northern and central part to 320 K in its southern part (Fig.1a), and that the average temperature is about 160 - 185 K. In the nighttime, temperatures in the region of ellipse 1 are decrease to 85 - 90 K (Fig. 2 a). The maximal temperatures in the region of landing ellipse number 4 are reache 320 K (Fig. 1 b). The average temperature in this area does not exceed 190 K, and the minimal (nighttime) temperature ranges from 86 - 90 K (Fig. 2 b). The values of the maximal temperatures of ellipse 6 range from 330 K in its southern part to 280 K in its northeastern part (Fig. 1 c). The average temperatures in the region of the ellipse 6 is about 160 K - 190 K,

Fig. 1. Maximal temperatures in potential landing sites of the Luna-25 mission: a - ellipse 1; b - ellipse 4; c - ellipse 6. Boundaries of ellipses are indicated by white lines.
and the nighttime temperature ranges from 85 to 90 K (Fig. 2 c).

The neutron spectrometer LEND on board the LRO has revealed the enhanced abundance of hydrogen in the potential landing sites regions for the Luna-25 mission [1]. The abundance of hydrogen may be due to the presence of deposits of volatile compounds in these areas. We investigated the thermal stability of deposits of volatiles on the surface and under a layer of dry regolith similar to those that were detected at the impact site of the LCROSS probe in the Cabeus crater in the lunar south pole region. These deposits included the following: H$_2$O, CO, H$_2$S, SO$_2$, NH$_3$, C$_2$H$_6$, CH$_4$, CO$_2$ and CH$_3$OH [4, 5]. The evaporation rates of volatiles compounds were calculated according to the model described in [3, 6]. We used three different thicknesses for the regolith layer in our calculation: 0.02 m, 0.05 m and 1 m. Our results show that the three main landing site ellipses do not contain areas of interest, so the existence of deposits of volatiles may be stable on the surface and under the insulating layer of regolith.

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References:
**SIMULATION AND DEMONSTRATION OF THE EXTRACTION OF WATER FROM LUNAR REGOLITH ANALOGUES FOR THE PROSPA SAMPLE ANALYSIS INSTRUMENT.**  P. Reiss¹, ¹Institute of Astronautics, Technical University of Munich, Boltzmannstr. 15, 85748 Garching, Germany, (p.reiss@tum.de).

**Introduction:** The broad understanding of lunar resources is key for a sustained future exploration of the Moon and includes not only the identification of such resources but also the assessment of their utilization potential, abundance, and distribution across the lunar surface. In this context, the instrument package PROSPECT (Platform for Resource Observation and in-Situ Prospecting for Exploration, Commercial exploitation and Transportation) onboard the Russian Luna 27 lander aims to further search for lunar water and deliver ground truths for its existence. The package contains the sample analysis instrument ProSPA (PROSPECT Sample Processing and Analysis) to investigate thermally extracted volatiles [1-4]. Similar to other gas analysis instruments for planetary exploration [5], the expected volatile constituents in the sample are extracted via heating and subsequently analysed in a mass spectrometer.

Compared to terrestrial laboratory analyses of soil samples, there are several challenges for the in-situ analysis. While the former can use pre-processed tiny samples that achieve approximately uniform temperature when being heated, the dimensions of the robotically obtained lunar soil samples are dictated by the drill core, the sample container, and very limited autonomous pre-processing. In combination with the low temperature and ultra-high vacuum (UHV) environment, the extremely poor thermal conductivity of the sample leads to large thermal gradients within the sample during heating. This makes it difficult to correlate the measured desorption signal of the gas analyser to a certain, ideally uniform, sample temperature. Other challenges in determining the characteristics of extracted volatiles include the possibility of readsorption within the sample and restricted mass transport due to the particle properties and gradients of temperature, gas concentration, and gas pressure.

Understanding the molecular and transport kinetics in the sample during the extraction of volatiles allows the estimation of important process parameters, such as the variation of gas pressure in the system, the process duration, the required temperature, heating profile and power consumption. Furthermore, key parameters and sample properties that affect the overall desorption characteristic can be identified. Different desorption patterns could potentially be interpreted in a way that allows to derive the initial sample properties, such as water content, bulk density and compaction, or bulk mineralogical composition.

To that extent, a dynamic simulation model, developed at the Institute of Astronautics at Technical University of Munich (TUM), allows the detailed study of the interaction of different heat and mass transport mechanisms in the sample. A simplified breadboard of the ProSPA instrument was set up to experimentally validate this model and study the characteristics of the gas extraction from a simulated lunar regolith sample in a relevant environment.

**Simulation Model:** The simulation model takes into account the pressure- and temperature-dependent thermal diffusion of heat into the sample, the desorption of water from the surface of regolith particles, and the diffusion and convective flow of desorbed molecules through the sample. The model is implemented and solved in the software COMSOL Multiphysics, with the additional use of MATLAB to compute the thermal conductivity and diffusivity as well as their partial derivatives.

**Thermal Diffusivity.** Thermal conductivity is calculated based on a model by [6], which takes into account conduction through the physical contact between solid particles, radiation between the particles, conduction through the gas in the pore spaces between the particles, and the coupling of solid and gas conduction. The model has so far been validated with the lunar regolith simulants JSC-1A and NU-LHT-2M for temperatures from 123 K to 723 K. For the application with ProSPA, the physical properties of the simulated sample were correlated to measurements of the Apollo 16 sample 68501 [7], and adjusted for lunar gravity. For the specific heat of lunar regolith, a model by [8] is implemented as it combines earlier models for Apollo 14, 15, and 16 soils between 90 K and 350 K and for silicate minerals above 350 K as well as molten regolith.

**Water Desorption.** The desorption of water is calculated as a first-order process with desorption energies in the range of 0.45 eV (water ice clusters) to 1.2 eV (strongly chemisorbed water), based on models and experiments of [9-11]. The temperature- and pressure-dependence of the desorption kinetics is taken into account by the model.

**Gas Diffusion and Convection.** Gas is transported through a porous medium by means of Knudsen diffusion, ordinary diffusion, and viscous or convective flow. The former two are driven by a concentration gradient, whereas the latter is driven by a pressure gradient. The model used in this study considers all three mechanisms depending on the variable temperature and pressure in the sample.
**Experimental Setup:** The breadboard (Figure 1 and 2) mainly consists of a high vacuum facility and a sample preparation setup. The latter includes a glovebox with humidity-controlled nitrogen atmosphere to prepare samples with different water contents, and additional liquid nitrogen cooling to create icy samples. The size of each sample in the cylindrical sample holder is 2.8 mm in diameter and 4.5 mm in height (ProSPA sample size). The controlled extraction of water and ice is done in the vacuum facility, which contains a scroll pump and turbo-molecular pump, a quadrupole mass spectrometer (1 to 200 amu), two cold cathode pressure gauges, and a feed for either dry nitrogen as purge gas or a reagent gas.

After transfer to the vacuum facility, the sample is evacuated to (ultra-)high vacuum ($10^{-7}$ to $10^{-3}$ Pa), while being kept at low temperature with liquid nitrogen. Heating with a constant rate then allows a continuous analysis of the evolved gases with the mass spectrometer. The thermal extraction of volatile water and other species is the major operational mode of ProSPA, referred to as Volatiles Extraction Demonstration (VED). The effect of different water contents, sample types, sample densities, etc. on the physical extraction process will be characterised with the help of the breadboard.

In a second operational mode, the breadboard can be used to chemically reduce the sample in a hydrogen atmosphere to produce water. This capability is also part of the ProSPA instrument and allows a first assessment of one of the most promising processes for lunar In-Situ Resource Utilisation (ISRU).

**First Results:** The simulation shows the dependence between desorption or outgassing of water from samples and different initial water contents, as well as the different durations of the process. Parametric studies with variable bulk density, water content, and heating rate have been performed to investigate the resulting outgassing profiles. Figure 3 shows an exemplary pressure and temperature profile for a sample with 1 wt% initial water content and 0.45 eV desorption energy. The mean and the boundary (maximum) temperature strongly diverge, especially at very low gas pressures. Absolute gas pressures in the sample can reach significant peak values in the range of $10^3$ Pa at some points during the extraction process. This behaviour is similar, but less pronounced, for lower initial water contents.

**References:**


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**Figure 1:** Schematic diagram of the test setup.

**Figure 2:** Picture of the test setup (not complete).

**Figure 3:** Simulated gas pressure and temperature in the sample for a heating rate of 6 K/min.

Introduction: The absolute and relative ages of planetary surfaces in the inner solar system have long been determined from the analysis of crater size-frequency distribution curves [1-4]. To derive such information from remote sensing data, impact craters on a geologically homogeneous surface [5] are processed by crater counting techniques [6-9]. Approaches such as Traditional Crater Counting (TCC) and Buffered Crater Counting (BCC) [6-8] are implemented in the ArcGIS Add-In CraterTools [6]. However, the recently developed Non-Sparseness Correction (NSC) and Buffered Non-Sparseness Correction (BNSC) [9] crater counting methods are not implemented and data processing in CraterTools is restricted to 32 bit single-core computing. To overcome these limitations and to efficiently implement NSC and BNSC crater counting techniques, we currently develop a new software tool for crater size-frequency measurements.

Crater Counting Techniques: Crater counting techniques determine which craters and which reference areas are considered for the determination of crater size-frequency information. Regarding the TCC approach, all craters which have their centroids inside the counting area are considered for the measurement. The reference area remains unchanged during this process (Figure 1A).

BCC is used to improve the statistics of crater size-frequency measurements. During BCC, impact craters which superpose the geologically homogeneous surface but are situated outside the reference area are included in the evaluation. Generally, craters within a distance of one crater radius to the counting area are considered. The measurement area changes for every crater during BCC and corresponds to the original area plus a surrounding buffer of one crater radius (Figure 1B). Thereby, the number of craters which are considered for crater size-frequency measurements is increased. BCC is particularly used for the investigation of linear features with a limited number of superposing impact craters [8].

NSC is applied to consider the effects of crater obliteration by larger craters. For every crater inside the counting area, the original reference area is reduced by all larger craters plus a surrounding buffer of one crater radius (Figure 1C). Here, the buffer corresponds to the zone affected by ejecta blanket and seismic degradation which eliminated smaller craters. The resulting crater size-frequency distribution better reflects the production function (Figure 2) [9]. This is especially noticeable when many large impacts occupy a significant fraction of the area. Thus, NSC is useful for heavily cratered surfaces.

BNSC is a combination of BCC and NSC crater counting approaches [9]. It is used to improve statistics by including craters which are situated outside the counting area and to consider resurfacing events by eliminating larger impact craters with their respective ejecta blankets. For every crater, all larger craters plus a surrounding buffer of one crater radius are removed from the reference area. Subsequently, the remaining area is buffered by the radius of the investigated crater (Figure 1D). BNSC is particularly suitable for linear features and heavily cratered regions but can generally be applied to any region of interest.

Figure 1: Reference areas of six individual craters for TCC, BCC, NSC and BNSC crater counting approaches. During TCC (A), the reference area remains unchanged. Crater 3 is excluded from the measurement. BCC (B) requires the mapped counting area to be buffered by one crater radius for each crater. Crater 3 is included in the measurement. For every crater during NSC (C), every larger crater plus a surrounding buffer of one crater radius (ejecta blanket) is removed from the counting area to simulate the effect of resurfacing by larger impacts. BNSC (D) combines NSC and BCC crater counting approaches. Resurfaced areas (larger craters plus surrounding buffer of one crater radius) are removed from the counting area while the remaining area is buffered by one crater radius [9].
Figure 2: Results from TCC and BNSC crater counting on the heavily cratered lunar highlands (A). TCC gives an absolute surface age of 4.31 Ga. However, the crater size-frequency distribution only fits the production function at larger crater diameter bins (B). In the BNSC approach, the given production function fits almost the entire crater diameter range, resulting in an absolute surface age of 4.27 Ga (C) [9].

**Implementation of NSC and BNSC:** NSC and BNSC approaches generate polygons with multiple inner rings during crater size-frequency measurements (Figure 1). Thereby, both approaches require far more computational resources than the BCC technique. As CraterTools only supports 32 bit and single-core computing, NSC and BNSC cannot be efficiently implemented in the ArcGIS Add-In. We therefore develop a new GIS application for the determination of crater size-frequency information which works independently from ArcGIS libraries and supports 64 bit computing as well as multi-core data processing.

To assess the performance of the new application, we conducted BCC crater size-frequency measurements of lunar basins using CraterTools and the new software tool. We found a significant performance increase of 60-1250 % when comparing the computational time of the new application to CraterTools. This increase is mandatory for the efficient implementation of NSC and BNSC crater counting techniques in planetary surface dating.

Future space exploration missions will involve both humans and robots, making use of the potential of human/robotic collaboration. The METERON (Multi-purpose End-To-End Robotics Operations Network) project’s aim is to prepare for human/robotic missions to the Moon in particular, as well as Mars and other celestial bodies. METERON is using an international framework to test communications and robotic control strategies and to evaluate operational considerations such as which tasks are best performed by humans, which are suited for automated robotic systems and what data is needed to support the monitoring and control of assets. The results serve as input to the planning of future exploration initiatives and the design of future infrastructure systems. A number of experiments involving a combination of human-robotic interaction and remote control of the robotic elements have already been performed in order to prepare for future robotic missions.

A special focus lies on scenarios involving astronauts orbiting a celestial body controlling or supervising robotic assets on the surface. The advantage of this approach is that it will reduce the signal latency compared to controlling rovers from Earth, which allows direct intervention from humans when needed, such as navigating in hazardous areas or identifying regions of scientific value. Areas of interest include the cooperation and handovers between the teams, safe and efficient ways of operating the robotic assets and handling of challenges like delays and outages of the communication links.

During the latest METERON experiment that took place in April 2016, ESA astronaut Timothy Peake operated a UK-based rover from the International Space Station (ISS). Experiment operations were coordinated from ESOC in Darmstadt, Germany. ESA, the UK Space Agency and Airbus Defence and Space UK collaborated to investigate distributed control of a rover in a simulated planetary environment located in Stevenage, UK. This experimental activity was called SUPVIS-M (Supervisory Control of Mars Yard Rover) and simulated a scenario of a rover located on the surface of the Moon with a human presence in lunar orbit. Figure 1 illustrates the implementation of the lunar scenario.

![Figure 1: High-level SUPVIS-M architecture, including a simplified overview of the data streams. Blue arrows indicate voice traffic while experiment data streams are shown in green.](image)

Preparatory activities and the relocation of the rover were performed by teams on ground. Once the rover was in its designated starting point for crew activities, rover control was handed over to the astronaut to perform time-critical complex tasks. The operations were designed around the goal of driving into a dark area, finding several targets and exiting the area within the allotted time slot, simulating the “need for speed” relevant for operating a solar-powered rover in a shaded crater. Control was handed to crew for the operations near and within the cave without providing any explicit path or routing instructions. An overview of the scenario is shown in Figure 2.

![Figure 2: Scenario simulated as part of the SUPVIS-M experiment with the dark area representing a simulated cave environment.](image)

The presentation will include the findings of the SUPVIS-M experiment, using data collected during the SUPVIS-M experiment, which includes ([11])

- covered Marsyard surface area
- safety of driving
- usage statistics on rover control software GUI elements
crew time spent on different tasks. Qualitative observations and user feedback were collected, especially regarding the rover operator’s situational awareness, one of the key areas of interest for this experiment. This data will also be presented.

References:
Introduction: High resolution Apollo 15 photography revealed the presence of an enigmatic landform, known as Ina [1,2], thought to have formed through volcanic processes [1-4]. Due to its small size (<3 km width) and inadequate observations, a definitive formation mechanism was elusive, and possibilities included effusive and explosive eruptions over a broad range of ages [1-3]. LROC provided high resolution imaging with a variety of lighting conditions, and stereo-based topography allowing a reinvestigation of Ina. A significant finding from LROC was the discovery of similar deposits occurring in over 50 locations spanning from eastern Mare Tranquillitatis across a broad arc (2500 km) to the Grünhuisen Domes [4]. Crater size–frequency distributions (CSFD, diameters $\geq 10$ m) from Ina were interpreted as indicating an age of $<100$ My [4], a result inconsistent with interpretations of lunar thermal models [5].

Morphology: Ina and related deposits known as Irregular Mare Patches (IMPs) share common landforms with distinctive textures. Perhaps the most striking landform is the smooth mounds (SM), which are characterized by shallow-sloped central areas terminated by steep lobate scarps [1-6]. Mounds are typically 5–20 m thick and a few 10s to 100s of m across [4,6]. The mounds exhibit superposed impact craters across a broad range of degradation stages (Fig 1A), from crisp and steep-walled to smooth and shallow. A variety of observations indicate that IMPs are formed of basaltic materials and most workers attribute smooth mound formation to effusive volcanic activity [1-5], perhaps with substantial inflation [6].

The SM are adjacent to a unit characterized by an uneven surface, with textures ranging from hackly toropy to boiroydial, exhibiting occasional patches of boulders and relatively few impact craters. Superposition relations between the SM and uneven materials (U) are ambiguous; typically mounds appear to be superimposed on the U (Fig 1A,B), however in some cases the reverse is true (Fig 1C,D) and in others the relation is as clear as an Escher drawing (Fig. E,F).

Regolith properties: Unusual target properties affect final crater size [7] and thus derived ages. To simulate such an effect, crater diameters for the Soignes IMP CSFD were increased by 50%, resulting in a model age increase from 18 Ma to 44 Ma [4]. Alternately the target materials may be significantly more porous than typical mare regolith, leading to smaller craters and an anomalously young age estimate for an old surface [8]. However, fresh craters on the IMPs exhibit raised rims (Fig. 1A-F) and ejecta deposits (Fig. 1A), boulders rest on the surface (diam.$>2$ m; mass $>10$ tons), and bench craters (Fig. 1A,B) are consistent with a m-thick regolith. There are small tongues (m thick, tens of m long, Fig. 1E arrows) that may be effusive flows on SM and U, consistent with nominal lunar surface porosities. Finally thermal infrared observations of Ina are not consistent with extremely high porosities [9].

The reflectance of the lunar surface is controlled by crystallinity (or lack thereof), grain size, porosity, and composition [cf. 10]. Observations across a range of phase angles can constrain surface materials. In a low phase angle image (11°) much of the U has reflectance significantly lower than the SM (I/F U=0.056 SM=0.060, -7%) and in the high phase angle (106°) image all of the U have reflectance significantly higher than the SM (I/F U=0.034 SM=0.027, +25%, Fig. 2). A similar phase angle dependent contrast reversal is also seen in the Sinus Aestuum area for materials interpreted as pyroclastic in nature.

Young or Not? The <100 My age for the IMPs was based on the CSFD, superposition of an IMP on the ejecta of Aristarchus crater, the existence of small landforms (meter-scale relief, Fig. 1), and steep margins of the SM (>30°). The latter two criteria assumed that small-scale landforms will be worn down or disappear due to micro- and macro-bombardment on a <billion year scale. However, young basaltic flows should exhibit decameter-scale fractures [6], similar to those seen on fresh impact melt flows, but none are seen on the SM and if they existed may be hidden by a regolith. The subdued nature of many craters on the SM is also consistent with a 1-m thick regolith that takes a $\sim 10^5$ years to form. However, pyroclastic materials may make up a significant volume of IMP material, giving the appearance of a regolith (see above) and thus older age.

Implications: The age and formation mechanism for the IMPs remains elusive. If the thermal models are correct (and IMPs are ancient volcanics), then the absolute calibration of crater ages for small targets is seriously flawed, or some extraordinarily unusual property or process is grossly altering crater retention for the IMPs (for which there is no compelling evidence). Alternately, thermal models may need revision.

Fig 1. Morphologic details Ina; M175246029, all panels 40 cm pixels, panel D 323 m wide, inc 46°, phase 74°, SM = smooth mounds, U= uneven materials, arrows in E indicate flow morphologies.

Fig. 2. (Upper) High phase Ina east-to-west oblique view (M1236500883LR, phase 106°, inc. 34°, ema. 75°.). (Lower) Low phase image, ~2700 m west-to-east (M1238927157LR, phase 11°, inc. 21°, ema. 18°).
ANORTHOSITE-RICH MATERIAL INSIDE OF THE SOUTH POLE-AITKEN BASIN. D. Rommel, A. Grumpe, C. Wöhler, H. Hiesinger, Image Analysis Group, TU Dortmund University, Dortmund, Germany (daniela.rommel@tu-dortmund.de); Institut für Planetologie, Westfälische Wilhelms-Universität Münster, Münster, Germany.

Introduction: The South Pole-Aitken basin (SPA) with its diameter of about 2500 km [1, 2] was formed during the pre-Nectarian period [1]. Due to its early formation and large size, the basin has been subject to further impacts, and on the basis of the ejected material conclusions can be drawn about the internal composition of the lunar crust. In this study, we construct petrological maps of the three craters Alder, Antoniadi and Dryden located inside SPA, revealing deposits of anorthositic material.

Methods and Dataset: Our analysis is based on the hyperspectral imagery of the Moon Mineralogy Mapper (M³) [3]. It can be divided into several steps:

Georeferencing of the image data. Due to failure of the spacecraft’s star sensors, the initial georeferencing of the M³ was inaccurate and had to be refined after the mission [4]. To remove the residual georeferencing errors, we computed a projective transform that maps each M³ image onto the LROC WAC mosaic [5], respectively.

Since the resolution of available digital elevation models (DEM), e.g., the GLD100 [6], does not not correspond to that of the M³ images, an image-based shape-from-shading based method [7, 8] is used in combination with the GLD100 to construct a high-resolution DEM. The Hapke model [9, 10] was used to describe the surface reflectance, where a low-resolution map of the single-scattering albedo was computed while the remaining parameters were adopted from [11]. The M³ reflectance spectra were then normalized to standard geometry (30° incidence angle and 0° emission angle [12]) using the refined DEM.

Construction of elemental abundance maps. The depth, width, position and continuum slope of the 1-µm absorption band and the continuum slope and depth of the 2-µm absorption band are used as spectral parameters to describe the two most prominent absorption bands in the M³ wavelength range [13]. Following the steps outlined in [13, 14], a polynomial regression of a M³-derived low-resolution mosaic of spectral parameters against abundance data of the elements Ca, Al, Fe, Mg, Ti and O acquired by the Lunar Prospector Gamma Ray Spectrometer [15, 16] was performed. Applying the obtained regression parameters to full-resolution M³ data then allows for the construction of high-resolution elemental abundance maps. From the Fe and Mg maps a petrological map based on the model suggested in [17] is derived, which is defined by the endmembers mare basalt, Mg-rich rock (especially orthopyroxene-rich norite) and feldspathic rock (especially ferroan anorthosite). As described in [17], the relative fractions are read out from the ternary Fe-Mg diagram and can be visualised in terms of an RGB image, where the red, green and blue channel corresponds to basalt, Mg-rich rock and ferroan anorthosite, respectively.

Results and Discussion: The crater Alder (82 km diameter, centered at 49° S, 178° W) is located near the center of the SPA. It exhibits a large ferroan anorthosite patch in its southern part (Fig. 2). This structure looks like a large debris flow of about 20 km extent. The central peak and the eastern part of the crater rim show a high Mg-rich rock content. The crater floor and the surrounding regions mainly show a basaltic signature.

The large crater Antoniadi (138 km diameter, centered at 69° S, 173° W) is situated in the southern part of SPA. Its has a flat floor covered by basaltic lava (see e.g. [18]). A high Mg-rich rock content is apparent for the the central peak and the inner peak ring (see petrological map in Fig. 3). The western crater wall displays a large patch of ferroan anorthosite in the western crater wall that looks like ejected material rather than a debris flow. Possibly this material has been ejected during the impact that formed the crater, its extensional direction indicating an oblique impact with the impactor approaching from the east.

The craters Alder and Antoniadi are located at about 400 km distance from the SPA centre, i.e. approximately on the rim of the SPA transient cavity with its radius of 410 km as given in [19]. Hence, our observations indicate anorthositic subsurface deposits also relatively close to the SPA center, indicating a complex layering of the crust. This finding is unexpected, given the model of [19].

The crater Dryden (54 km diameter, centred at 33° S, 156° W) is located in the eastern part of SPA at about 800 km distance from the basin centre between the two inner rings of the Apollo basin. Its central peak and crater rim show a significant Mg-rich rock content (Fig. 4). The floor is partially covered by basaltic material but still shows a signature of Mg-rich rock. The northeastern crater wall reveals a deposit with an anorthosite signature, which looks like a flow from the rim onto the crater floor.

The formation of the crater Dryden may have led to the excavation of an anorthosite subsurface deposit that probably resulted from crustal overturn and mixture with highland material as a consequence of the Apollo basin impact.

The craters Alder and Antoniadi were formed on a crust that had already been disturbed strongly by
the SPA impact. Before the formation of the crater Dryden, the crust had experienced even two giant impacts forming SPA and the Apollo basin, respectively. These strong disturbances presumably led to the deposition of anorthositic material at shallow depth below the surface which were excavated during the impacts that formed the three craters.

**Summary and conclusion:** We have performed a petrological mapping of the craters Dryden, Alder and Antoniadi located inside SPA, revealing anorthosite-rich deposits associated with them. Anorthosite-rich deposits have been mapped as close as 400 km to the SPA centre. Our observations indicate a highly complex layering of the crust at the crater locations.

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**Fig. 1:** Petrological map of the SPA. The white star indicates the SPA centre, the black dashed line denotes an inner circle with anorthositic deposits. Background map: LROC WAC mosaic [5].

**Fig. 2:** Petrological map of the crater Alder, overlaid on the refined DEM.

**Fig. 3:** Petrological map of the crater Antoniadi, overlaid on the refined DEM.

**Fig. 4:** Petrological map of the crater Dryden, overlaid on the refined DEM.

**References:**

Introduction: EURO-CARES is a project to roadmap an European Sample Curation Facility (ESCF) for sample return mission material from Mars, Moon, and asteroids [1]. It was funded by the EC H2020 COMPET program and runs from January 2015 to December 2017. While there have already been pro-jects to investigate the curation of extraterrestrial sam-ple return material in Europe, EURO-CARES is unique in being neither country-specific or mission-specific. While there have already been sample returns from asteroids and the Moon which we can learn from, a sample return mission to Mars requires new curation protocols, especially since such samples will have a planetary protection con-straints.

During 2016 we held a series of workshops to en-gage the community and stakeholders from research and industry. We have in-vited key participants from NASA and JAXA and also a number of experts from the industry to share their experience. Here is a summary of the current status of the project, organ-ised by the workpackages of the pro-ject: Planetary Protection, Facilities and Infrastructure, Instruments and Methods, Analogue Samples, Portable Receiving Technologies and Maximising Impact.

Planetary Protection:

For restricted samples that are a potential biohazard – e.g. Mars sample return, the protection of people and the environment is paramount. Lessons can be learnt from biohazard laboratories used for contain-ment and analysis of terrestrial pathogens (BSL-4 labs). These facilities can be operated safely, and operator error is the main cause of contamination. The operations to take place in the facility will need to feed in to the planetary protection team in order to design a facility that meets both the sample curation requirements and the planetary protection require-ments.

Facilities and Infrastructure:

This workpackage considers all the aspects of the building design, storage of the samples, and curation. A list of the different identified units and subunits of the facility was established and then several different possible scenarios for the building of the ESCF were envisioned to test the modularity of the facility. Importantly is that it is not mandatory to build all units at the same time, knowing that they should be designed to be structurally independent. This non exhaus-tive list of scenarios, includes, an "integrated approach" (with all units built on the same site, but not necessarily at the same time), a "restricted vs. unrestricted" scenario (with potentially biohazardous samples and non-biohazardous samples treated sepa-rately, i.e., with SRF/SCF built on different sites), a "distributed ap-roach" (with all functions, receiving and curation, scattered in different locations), etc.

In 2016 we also continued our visits of divers facil-ities and meetings with experts from different fields. An architecture Design Studio, in collaboration with the Vienna University of Technology, took place dur-ing teh first semester of 2016. Eighteen students at-tended the studio and produced whole concepts of the ESCF. The results of this exercise were published in a booklet [2].

Instruments and Methods: The instrumentation re-quired is the minimum necessary in order to:

(a) properly characterise a sample. This covers a wide range of measurements; from photo-documen-ta-tion of the samples primarily for identification purpos-es and detailed records of the samples sent out, to pre-liminary determination of the structure, mineralogy and organic inventory of the samples. More detailed characterization would be expected to be an activity undertaken by the scientific experts on allocated sam- ples. All characterization activities in the curation fa- cility should be conducted with little, or no, impact on the physical and chemical nature of the sample in order to preserve it for scientific re-search and storage.

EURO-CARES (EUROPEAN CURATION OF ASTROMATERIALS RETURNED FROM EXPLORATION OF SPACE) S. S. Russell1, C. L. Smith1, A. Hutzler2, A. Meneghin3, J. R. Brucato3, P. Rettberg4, L. Ferrière5, A. Bennett6, J. Aléon7, M. Gounelle8, I. A. Franchi7, F. Westall5, F. Foucher9, J. Zipfel9, L. Berthoud10, J. Vrublevskis5, M. Grady7, and the EURO-CARES Consortium. 1Department of Earth Sciences, The Natural History Museum, Cromwell Road, London, SW7 5BD, UK, 2Natural History Museum, Burging 7, A-1010 Vienna, Austria, 3INAF Astrophysical Observatory of Arcetri, Firenze, Italy, 4DLR, Deutsches Zentrum für Luft- und Raumfahrt, Cologne, Germany, 5Public Health England, Salisbury, UK, 6Museum National d’Histoire Naturelle, 57 rue Cuvi-er, 75005 Paris, France, 7The Open University, Milton Keynes, MK7 6AA, UK, 8CNRS-CBM, rue C. Sadron, 45071 Orléans, France, 9Senckenberg Gesellschaft für Naturforschung, Frankfurt, Germany, 10TAS UK, Coldharbour Lane, Bristol, BS16 1EJ, UK.

(Email: sarr@nhm.ac.uk).
(b) Sample selection and quality control on sample preparation. This task involves the identification and verification of the most appropriate samples to meet the requirements of approved sample requests, and if necessary, specific sample preparation (e.g. polished sections) for use by external scientists.

(c ) Monitoring of clean room operations. This will include analyzing witness plates and test samples regularly in order to measure contamination, and to ensure that cleaning and handling procedures are meeting specification.

We have discussed the relative models of roles of for the preliminary examination teams. A model involving many external teams seems likely to be the most appropriate for the ESCF.

**Analogue Samples:**

Analogue materials will be required in the ESCF for several tasks:

- To test transport protocols for movement of the returned samples within the facility and for shipment out of it. It will be necessary to practice with empty containers and appropriate analogue samples (cores, fragments, dust) (sample size and nature are important). In this case, analogue samples exhibiting different physico-chemical-technical etc. properties will be necessary.

- To establish sample preparation protocols, for example, sectioning, powdering, splitting, chemical/heat extraction, and imaging (optical-SEM EDS). Analogue types exhibiting appropriate physical/chemical properties will be appropriate.

- To train science and curation teams and perform science lab quality assessment, i.e. making sure that the external laboratory facility can handle/analyse the returned samples. ISAS/JAXA made a blind test of laboratories interested in analysing the Hyabusa 1 samples (Kushiro et al., 2003). Such activities would use reference analogue materials.

- Long-term storage needs to be tested using witness plates, hardware samples, voucher specimen and reference materials (including frozen materials).

We anticipate the ESCF will require approximately 40 kg of terrestrial rocks, ~40 kg of terrestrial analogues (rocks), ~1 kg separated minerals and ~1 kg meteorites.

**Portable Receiving Technologies:**

We have considered the design of the Earth Return Capsule (ERC). It will be designed to survive in the case of a hard landing, and therefore will withstand considerable force without breakage. To minimise the risk of sample loss, this will be a multi-layered structure. This is especially important for restricted samples with a planetary protection requirement. We are considering the actions to be taken in the case of non-nominal landing of a restricted sample, and the protocols to be followed will depend on whether particles of returned sample are released in the atmosphere or on the ground.

**Maximising Impact:** Public engagement is essential to allow us to communicate with the various scientists, engineers and decision makers who will contribute to the curation facility, as well as engaging children and adults to inspire and reassure them about the importance of sample return science. Public engagement will inevitably an essential part of the curatorial facility once it is built. We have produced educational materials and a MOOC (massive online course) associated with the project.

**Future Plans:**

We will assimilate the information we have gathered into a final document of our findings and conclusions. Our work over the next months will culminate in a workshop in July 2017, to be held in Florence, Italy. More details of our project can be found on our web-site:

[www.euro-cares.eu](http://www.euro-cares.eu)

At the end of the project, members of the team will work together to engage stakeholders in such a way as to ensure the curation facility to be built in preparation for sample return missions with European involvement.

**At this conference we will present the work of EURO-CARES with particular focus on the implications for state of the art curation of lunar samples.**

**Acknowledgement:** This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 640190. S. Häuplik-Meusburger and S.-H. Lu, both from the TU Wien (Austria), are thanked for the good collaboration.

AUTOMATIC DETERMINATION OF LUNAR SURFACE AGES IN MARE COGNITUM AND OCEANUS PROCELLARUM. Atieer L. Saileh\textsuperscript{1}, P. Schulte\textsuperscript{1}, A. Grumpe\textsuperscript{1}, C. Wöhler\textsuperscript{1} and H. Hiesinger\textsuperscript{2}, \textsuperscript{1}Image Analysis Group, TU Dortmund University, D-44227 Dortmund (athee.alameeni@tu-dortmund.de), Germany; \textsuperscript{2}Institut für Planetologie, Westfälische Wilhelms-Universität Münster, D-48149 Münster, Germany.

Introduction: In order to obtain information about the geologic history of a planet, e.g. to learn about its formation or about volcanic or other geologic processes, it is important to analyse its surface age. This helps to understand the transformation of the planetary surface over time. In order to estimate the age of planetary surfaces, it is possible to analyse rock samples collected by manned space missions or acquire images of the planetary surface through unmanned spacecraft. By calculating the impact crater size-frequency distribution (CSFD) on such images, it is possible to deduce the absolute age of the surface by relating the CSFD to the age obtained by laboratory analyses of returned samples [1].

The advantage of performing this procedure using an automatic crater detection algorithm (CDA) instead of manual crater counts is the possibility to calculate the absolute model age (AMA) for large areas on a planet much faster than a human could do (see e.g. [2] for an overview of CDAs). Nowadays, determining craters is commonly still performed manually by human experts. Although manual detection often still yields better object recognition results in images than automatic algorithms, it is also more time consuming. CDAs on the other hand are able to produce CSFDs for large areas within a relatively short time. Since CDAs commonly have some sort of sensitivity threshold, it is important to calibrate this threshold based on a small reference area for which manual crater counts are available [3]. In this study we perform a cross-validation of a CDA with detection threshold calibrated on five selected areas in Mare Cognitum applied to five other areas in Oceanus Procellarum. The accuracy of the procedure is examined by subsequently comparing the estimated AMAs with manually determined AMAs from [4].

Study Areas: According to previous studies, volcanism on the Moon has been active in the period between 1.2 and 4 billion years (Ga) ago [4]. A large variety of lunar mare basalt units formed during numerous eruptions. Fig. 1 shows the primary mare areas on the lunar nearside. To learn more about volcanic processes it is helpful to know the temporal sequence of individual volcanic activities and how the corresponding basalt areas have spread. Hence, this study focuses on the five areas C1-C5 defined in [4] located in Mare Cognitum and the five areas P4, P41, P49, P50 and P51 defined in [4] located in Oceanus Procellarum. All study areas lie in a latitude range between 15° S and 30° N and in a longitude range between 285° E and 345° E.

Methodology: Determination of the CSFD is a common approach to determine relative ages for individual geologic units on the Moon (e.g. [1]). The image data used in this study for determination of the CSFD are excerpts from the Wide Angle Camera (WAC) mosaic acquired by the Lunar Reconnaissance Orbiter (LRO) [5]. The resolution of the mosaic is about 100 m per pixel. Thus, craters can be detected easily for diameters exceeding 300 m, corresponding to about 3 image pixels.

To estimate the illumination angle of the regarded part of the WAC mosaic, the GLD100 topographic map [6] of the same area has been artificially illuminated using the Hapke model [7, 8], where the illumination direction was adjusted using a quasi-Newton method in order to maximise the similarity between the WAC mosaic part and the artificially illuminated GLD100 with respect to the shadows cast by the crater rims.

As a CDA, we used the template matching based approach described in [9]. The 3D cross-sections of three typical small craters obtained from LOLA profile data [10] were split in half at the crater centre and then rotated in order to obtain six representative artificial 3D crater models. Realistically appearing image templates were derived from these 3D models based on the Hapke model [7, 8] by artificial illumination using the illumination conditions previously inferred for the regarded WAC mosaic part.

The generated crater templates are now used for crater detection by scaling the templates to a given range of diameters and computing the normalised cross-correlation with parts of the image. A threshold value applied to the determined cross-correlation value decides whether or not the image area is a crater. Since several templates corresponding to different crater diameters may lead to the detection of the same crater, the crater detections undergo a fusion procedure such that multiple detections are re-
moved and a unique diameter value can be determined. The determined crater positions and diameters are then used to build the CSFD for the study region. As an example, Fig. 3 shows the craters for area C3 obtained by applying the described template matching based CDA.

Figure 2: Utilised set of 3D crater models.

Figure 3: Craters detected by the CDA in area C3.

Results and Discussion: Firstly, the optimal cross-correlation thresholds for the regions C1-C5 were calculated by comparing the CDA-based AMAs with the AMAs from [4]. The results are shown in Table 1.

<table>
<thead>
<tr>
<th>Area</th>
<th>Calibrated threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>0.6637</td>
</tr>
<tr>
<td>C2</td>
<td>0.6455</td>
</tr>
<tr>
<td>C3</td>
<td>0.6541</td>
</tr>
<tr>
<td>C4</td>
<td>0.6677</td>
</tr>
<tr>
<td>C5</td>
<td>0.6648</td>
</tr>
<tr>
<td>Average</td>
<td><strong>0.6592</strong></td>
</tr>
</tbody>
</table>

Table 1: Calibrated detection threshold values for the individual regions C1-C5 in Mare Cognitum.

The arithmetic mean of the five calibrated threshold values corresponds to 0.6592. Applying this “optimal” threshold value to the areas C1-C5 in Mare Cognitum yields the AMAs listed in Table 2, where they are compared to the reference AMAs from [4] obtained based on manual crater counts. In the next step, the same optimal threshold value was applied to the areas P5, P41, P49, P50 and P51 in Oceanus Procellarum, resulting in the AMAs listed in Table 2. It can be seen that the CDA-derived AMAs are similar to the reference AMAs from [4]. For area C5 two reference AMAs are given which are interpreted as the result of resurfacing [4]. The largest deviations between CDA-based and reference AMAs occur for regions P49 and P41 with reference AMAs of about 2 Ga, where the accuracy of CSFD-based AMA estimation in this age range is known to be low due to the low gradient of the production function (e.g. [6]).

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>C1 3.52</td>
<td>3.49</td>
</tr>
<tr>
<td>C2 3.46</td>
<td>3.45</td>
</tr>
<tr>
<td>C3 3.60</td>
<td>3.41</td>
</tr>
<tr>
<td>C4 3.43</td>
<td>3.36</td>
</tr>
<tr>
<td>C5 3.52</td>
<td>3.32</td>
</tr>
</tbody>
</table>

Table 2: CDA-based and reference AMAs for the study areas in Mare Cognitum and Oceanus Procellarum, obtained using the optimal detection threshold inferred from areas C1-C5.

Summary and conclusion: We have calibrated the detection threshold of a template matching based CDA on five study areas in Mare Cognitum and applied the identically configured CDA to another five study areas in Oceanus Procellarum. For each study area the AMA computed using the CDA-based CSFD has been compared with the AMA from [4] obtained based on manual crater counts. Most obtained CDA-based AMAs are consistent with the manually determined AMAs within about 0.1-0.3 Ga, suggesting CDA as a valuable tool for planetary surface age estimation.

Introduction: The next step for human exploration in space will begin with a return to the Moon, where In-Situ Resource Utilisation (ISRU) will be crucial in supporting an extended human presence on the lunar surface that is less dependent on the Earth’s resources. To determine the feasibility of lunar ISRU we must first understand the resources available. A number of missions are planned for the coming decade including the Luna-27 surface lander, which will provide a better understanding of the ISRU capabilities of the lunar south pole [1].

On board the Luna-27 mission will be ESA’s Package for Resource Observation and in-situ Prospecting for Exploration, Commercial exploitation and Transportation (PROSPECT). One of the components of PROSPECT is a Sample Processing and Analysis instrument, known as ProSPA. This miniature laboratory is in development with the aim to perform evolved gas pyrolysis, and stepped pyrolysis or combustion, to release volatiles which can be identified and quantified before undergoing isotopic analysis. Also, an ISRU demonstration is to be carried out by reducing mineral phases in the presence of hydrogen [2]. Together, these processes will enhance our understanding of resources available at the south pole and the feasibility of some extraction processes.

The reduction of ilmenite has long been considered a potentially viable technique to extract water, and consequently oxygen, from the lunar regolith with the purpose of producing fuels and life support gases. One of the ISRU demonstration techniques being considered for ProSPA is the reduction of ilmenite in the presence of hydrogen. The ilmenite reduction process is well understood, however most experiments are performed on a 100% ilmenite sample with a continuous flow of hydrogen. The ProSPA instrument is limited to a static system and will likely obtain samples with low concentrations of ilmenite. It is the purpose of this study to determine the extent to which the reaction will proceed in the ProSPA system.

Hydrogen Reduction of Ilmenite: Ilmenite, FeTiO₃, is a member of the oxide family of minerals, which are the second most abundant minerals on the Moon after silicates [3]. The ilmenite reduction process goes as follows:

\[
    \text{FeTiO}_3 + \text{H}_2 \rightarrow \text{Fe} + \text{TiO}_2 + \text{H}_2\text{O}
\]

The process requires relatively low temperatures (< 900 °C) compared to oxygen extraction from silicates (> 1100 °C), and hydrogen has been shown to be the preferred reducing agent over CH₄, CO, and electrolysis [4].

In order to demonstrate the feasibility of the extraction process in-situ, ProSPA will heat a ~ 30 mm³ regolith sample in the presence of hydrogen up to 900 °C in one of its ovens. Any water produced will collect at a ‘cold finger’ before being analysed in the ion trap mass spectrometer. A breadboard model is in development at The Open University to trial the reaction and determine its feasibility for use on ProSPA.

Experimental Set-Up: The breadboard model is comprised of ‘off the shelf’ parts and the layout is shown in Figure 1. The furnace will be operated at ~ 900 °C and the cold finger will be operated at ~ 190 °C. The connecting pipes will be heated to > 100 °C to inhibit condensation of water between the furnace and the cold finger.

![Figure 1 Schematic diagram of the ISRU demonstration model.](image)

Before any experiments are run, the system is to be cleared of contaminants by placing it under vacuum and heating to > 100 °C. A control reading will also be taken from the mass spectrometer to determine the quantity of any remaining contaminants. Similarly, a control reading of a lunar analogue without any ilmenite will be taken, to determine the quantity of any water that is produced from sources other than ilmenite.

Next, simulants doped with ilmenite will be used and the quantities of water produced will be detected. As the concentration of ilmenite is varied, so will the quantity of hydrogen used in the system. The minimum amount of hydrogen will be used to avoid increasing the pressure and limiting the movement of any water produced. This equates to one mole of hydrogen for each mole of ilmenite present.

A number of experiments are envisaged, as well as varying the concentration of ilmenite, such as varying the grain size distribution of ilmenite to determine any effect upon the reaction rate. The number of moles of hydrogen will also be increased to see at which point the movement of water is inhibited.
Reaction rate predictions: If a sample with 1% ilmenite present completely reacts, the quantity of hydrogen required for the reaction also increases as shown in Table 1. Considering these values it is possible to determine the gas flow type within the system. Gas flow can be characterised by its Knudsen number, $k_r$, which considers the mean free path of particles, $\lambda$, and the radius of the pipes, $a$, as $k_r=\lambda/a$. With a pipe radius of 2 mm, the Knudsen number is in the viscous flow region suggesting the water molecules produced must diffuse through hydrogen before collecting at the cold finger.

Table 1 The effect of ilmenite concentrations on the quantity of hydrogen required and diffusion time of the water molecules produced.

<table>
<thead>
<tr>
<th>Concentration of ilmenite (%)</th>
<th>Mass of hydrogen required (µg)</th>
<th>Pressure of hydrogen in system (Pa)</th>
<th>Time for diffusion of water molecules (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>3.0</td>
<td>731</td>
<td>0.5</td>
</tr>
<tr>
<td>1</td>
<td>5.9</td>
<td>1500</td>
<td>1</td>
</tr>
<tr>
<td>2.5</td>
<td>14.8</td>
<td>3700</td>
<td>2.5</td>
</tr>
<tr>
<td>5</td>
<td>29.6</td>
<td>7300</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>59.2</td>
<td>15000</td>
<td>11</td>
</tr>
<tr>
<td>50</td>
<td>296.1</td>
<td>73000</td>
<td>51</td>
</tr>
<tr>
<td>100</td>
<td>592.1</td>
<td>150000</td>
<td>101</td>
</tr>
</tbody>
</table>

As water molecules are produced they prevent hydrogen from accessing the remaining ilmenite grains and therefore must diffuse through the system before the reaction can continue. The rate of diffusion can be calculated with Fick’s law, $J_{AB} = -D_{AB} \frac{d\ln C_B}{dz}$, where $J_{AB}$ is the molar flux of gas A into gas B in the z direction, $D_{AB}$ is the diffusion coefficient, $C_B$ is the concentration of gas A, and $z$ is the distance of diffusion [5, 6]. Applying this equation with the assumption that all of the 1% concentration ilmenite present has reacted; all the water molecules produced are stored in the furnace volume; and the distance between the furnace and cold finger is 0.5 m, the molar flux of water is 0.23 mol m$^{-2}$ s$^{-1}$. The velocity of diffusion is therefore shown to be $\sim 0.5$ m s$^{-1}$ by dividing the molar flux by the average concentration, resulting in a diffusion time of 1 s. Table 1 shows how the diffusion time increases as the quantity of ilmenite, and therefore quantity of water produced, also increases. There are limits to this analysis due to the assumptions stated above. In reality there will be pressure changes as the water condenses, and the temperature will differ at each end of the system, both of which will significantly affect the diffusion rate.

The other rate controlling steps being considered are the diffusion of hydrogen in the product layer, and the chemical reaction at the interface. It has been shown that for a 100 % ilmenite sample, with a continuous flow of hydrogen (to reduce the effect of water molecules surrounding the sample), the reduction reaction completes in $\sim 20$ minutes and is controlled by the chemical reaction at the interface [7]. This suggests that with the diffusion rate of water also being considered, the time taken for the reaction to complete will be increased further. It is not yet known how the ilmenite concentration in the soil will affect the reaction rate.

Further considerations:
The grain size distribution of the lunar soil that is to be obtained from the Luna-27 landing site is not known, and it is understood that grain size distribution does affect the reaction rate of the ilmenite reduction process. If the grain size is too large then it would suggest that further beneficiation would be needed by future ISRU technologies in similar locations.

In the lunar mare regions, ilmenite can be present at relatively higher abundances, from 10 – 20 vol% [8] whilst the highlands are relatively depleted with an average concentration of < 1 vol% [9]. The mineralogy of the lunar poles is largely unknown as no direct measurements have been taken to date. However, based on remote sensing data, it is expected that the lunar poles will be mostly comprised of highlands-type material which may strongly limit the applications of this resource extraction technique, necessitating alternative considerations. On the other hand, if this process was applied on the ProSPA instrument it would give a ground truth indication for the ilmenite concentration at the lunar south pole and combined with the results of its other experiments, it will help to determine if the south pole is a viable location for resource extraction.

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LUNATUBE: A NEW MISSION DESIGN FOR LAVA TUBE EXPLORATION ON THE MOON. F. Sauro1, Loredana Bessone2, Luca Parmitano2, Ian Carnelli3, 1Department of Biological, Geological and Environmental Sciences, Italian Institute of Speleology, Bologna University, Via Zamboni 67, 40126, Bologna, Italy, cescosaur@gmail.com, 2Directorate of Human and Robotics Exploration, European Space Agency, Linder Höhe, 51147 Köln, Germany, loredana.bessone@esa.int, 3General Studies Program, European Space Agency, 8-10 Rue Mario Nikis, 75738 Paris, France, ian.carnelli@esa.int

Introduction

Lava tubes have long been supposed to exist on the Moon, with recent evidence of several skylights from SELENE and LRO images [1]. The scientific interest on these potential underground environments include several aspects of the geologic history of the Moon and their exploration would allow to study maria lava flow sequence, the compositional evolution of magma source regions, and the presence of volatiles and sublimate minerals in the underground. Recent numerical modelling [2] have shown that sublunar voids like lava tubes could attain an impressive size of over 1 km of width and hundreds of kilometres in length, as also suggested by GRAIL data [3].

It is therefore clear that lunar lava tubes could be important for the future of Moon human exploration because they could provide shelters from a range of harsh surface conditions. Lava tubes represent unique environments, shielded from cosmic radiations [4], characterized by less pronounced temperature excursions, protected by micrometeorite bombardment, and therefore potential candidates for human planetary base settlements.

In the last years space agencies has developed many different mission scenarios for the exploration of these underground environments, showing that the interest on these exploration target is rising. Nasa has performed a NIAC study phase 1 [5], while JAXA is developing potential scenarios in the UZUME program for the exploration of extraterrestrial caves [6]. Other programs, like ATlIT (CSA) and CAVES-SA and PANGAEA (ESA) are studying lava tubes as analogues on Earth, as a playground for testing and planning for future missions to the Moon or Mars. The exploration of lava tubes on the moon represents also a first technological test-bed toward the robotic exploration of underground voids in other planetary bodies like Mars and Titan.

In this abstract we present a new mission design, “LunaTube”, for exploration and scientific research in a lunar lava tube.

Mission objectives and targets

The mission objectives of LunaTube are the following:

- Characterize the environmental conditions of lava tube caves on the moon for scientific and habitability purposes
- Assess the potential for future resource exploitation in the subsurface
- Obtain first data and images of an extraterrestrial cave as a premise for caves exploration missions to Mars

The potential targets of the mission are mare skylights like those of Tranquillitatis and Marius Hills. Especially this latter one is the most promising because it is situated along a sinuous rill and with LRO low angle images showing free hanging walls and a potential cave access at the bottom. Marius Hill skylight is estimated about 45-50 meters deep from the edge to the bottom [1], which makes it also operationally simpler than other deeper skylights.

Mission concept and architecture

The mission concept is based on a multirobotic system (Fig. 1): 1) a lander, 2) a sherpa armed rover and 3) a cave robot. The lander will touchdown in a safe zone some tens or hundreds of meters from the skylight. Then the sherpa armed rover, equipped with scientific payload and an autonomous power system, will egress from the lander and move toward the edge of the skylight. Before getting in proximity of the edge the rover will perform a stability check of the ground through a GPR system. Once identified the best and safer position close to the edge the rover will fix itself to the ground through a 1.5 m drilling core on the back. Once fixed in position the Sherpa rover will deploy a winch arm over the free fall of the skylight. A tether will be deployed from the arm pulling down the cave robot to the bottom of the skylight (descent of 40-60 meters) and then releasing it to initiate the free exploration of the cavity.

The tether will be used as a power chain from the sherpa rover (solar panels) to the cave robot that after the exploration will be able to come back to the tether and connect for recharging for a series of exploration sessions. Communications will be managed through a double chain with a wireless radio system from cave robot to an antenna at the end of the tether, and from there to the sherpa rover and to Earth (for navigation data), and a backup system from tether connection directly to the sherpa rover and from there to Earth, for science and imaging heavy data.
Science payload
The sherpa rover will be equipped with a GPR system to assess both the lava flows layer thickness and rheology as well as the presence of voids approaching the skylights. Also the drill core could be used to perform chemical analysis at depth of the lava flows that originated the lava tube. The cave robot will be equipped with laser scanning technology to reconstruct precisely the skylight geometry during the tethered descent and for mapping and navigation inside the cave. Other payloads of the cave robot will be instruments to measure temperature gradients (similar to Mars-Tem), cosmic radiation (similar to RAD), presence of volatiles and a miniaturized XRF beam for rock elemental composition. A final sampling phase and recovery of the samples through the tether for later sample return could also be foreseen.

Conclusions
Moon is ESA’s next destination for exploration, first robotic and then manned. One of the frontiers in this lunar exploration strategy is surely represented by lunar caves where we have to assess environmental and habitability potential, the potential presence of usable resources, as well as scientific objectives. ESA has an internationally recognized expertise on caves and can provide the entire necessary analogue platforms, like CAVES-SA and PANGAEA for developing and testing such mission concept. Jointed cooperation with other agencies could provide the necessary fundings for different mission elements to make the mission happening in the next decade, also as one of the potential precursor robotic missions that are foreseen before a human return to the lunar surface. In addition we are sure that LunaTube could represents a highly inspiring mission not only for the science community but also for the general public: a return to the Moon, but to explore for the first time the absolutely unknown environments of the lunar subsurface, invisible also from satellites. It would represent the first look to the subsurface of a planetary body out of Earth.

Introduction

The need for geological training for astronauts was recognised at the beginning of the Apollo Moon missions in the 1960s [1]. At that time each NASA astronaut went on at least 16 field trips and spent up to 300 hours in the classroom to prepare for each lunar geological mission goal. The Apollo training was based on the principle “You learn by doing and then doing some more”, so repeated learning and practice in many environments similar to the Moon was an important step for the success of the missions. No substitute exists for working in the field to learn the principle of field observation and sampling [1]. Their geological field-training allowed Apollo astronauts to identify, collect and analyse samples on the Moon with efficiency and flexibility.

On future planetary missions astronauts will probably explore complex environments such as lava tubes, canyon rills and rough surfaces. Training on Earth in places with similar geological features and operational conditions will help the astronauts to communicate effectively between themselves and the ground support during geological investigations in our Solar System. Potential near future missions to the Moon will take into account newly-discovered features such as lava-tube skylights, or extreme environmental settings like sub-polar regions, which were not taken into account during the Apollo missions. But also the future Potential landing sites on Mars will cover a wide range of geological environments from volcanic regions, ice caps, sedimentary basins, deep trenches, craters, etc. Asteroids have a huge variety of features each target offering distinct differences. The recognition and interpretation of geological structures and processes requires experience, repeated exposures to the subject matter and detailed field studies.

In this preparatory context PANGAEA’s field training is teaching astronauts efficient observation, documentation and descriptive techniques, and tools for autonomous interpretation and decision making rather than wide and purely theoretical knowledge. Also the training is intended to put together a network of European field geologists focused in planetary studies to provide to the astronauts an overview of the potential scientific objectives for the future missions.

A side effect of the training has been the recognition of the necessity to develop a geological operational vocabulary to improve efficiency of surface operations, where communication b/w crews on a planetary surface and scientists on the ground is required to improve mission success.

The first edition of the training has been held in September/October 2016 with the participation of a crew of three ESA astronauts (Luca Parmitano, Pedreo Duque and Matthias Maurer) and a new edition is planned for autumn 2017.

Training objectives and design philosophy

PANGAEA stands for Planetary ANalogue Geological and Astrobiological Exercise for Astronauts, as well as being the name of the ancient supercontinent. This training course is part of the Basic or Pre-assignment Training of European Astronauts. The PANGAEA course was largely designed based on lessons learned from the Apollo programme [3], where it was evident the need to more broadly use flexibility, but still considering reasonable constraints associated with resource limitations, safety factors, and prioritization of objectives. The strategy emphasizes the coordinated efforts of the crew, the scientists on ground, and both analytical tools and mobile robotic systems.

The training is designed to provide European Astronauts with introductory but very practical knowledge of Earth and comparative Planetary geology processes and products, to prepare them to become effective partners of planetary scientists and engineers in designing future exploration missions, to impart them solid knowledge of current understanding of the geology of the solar system, and knowledge gaps from leading European scientists. PANGAEA also is the first step in preparing European Astronauts to become effective future planetary explorers during future planetary missions, enabling them and their science advisors on ground to effectively communicate, using a common, yet geologically correct language, aiming at achieving a fast and fruitful decision-making process in selecting scientifically relevant sampling sites.

PANGAEA enables Europe to develop future operational concepts for surface planetary activities, where humans and robots will need to effectively cooperate, amongst themselves and with ground scientists and engineers, making the best of Earth field geology and Planetary remote observation techniques.

The training enables Astronauts to attain a basic knowledge about geologic processes and environ-
ments on Earth, Moon, Mars and Asteroids, to develop observational and decisional skills in identifying prominent geological features on field, conducting efficient sampling and report correctly to the ground, and to describe the most important geologic environments that could host extra-terrestrial life.

The PANGAEA training philosophy includes the use of real scientific objectives in the planning of all practical exercises, and the subsequent analysis of all samples collected by the Astronauts in order to perform real science. The consequences of this choice are twofold: on one side, they provide motivation to the Astronauts to perform their tasks to the highest standard. On the other side, they allow scientists to test the overall operational cycle and to refine their plans such as to optimise future surface scientific operations.

**Structure and locations**

The PANGAEA course is subdivided in two main blocks:

1) Planetary Geology Introduction covering Earth, Moon, Mars and Asteroids sedimentary and volcanic processes and products, as well as geo-microbiology

2) Field Traverses on earth analogue sedimentary, volcanic and crater impact sites, focusing on geological site description, identification of sampling sites and sampling techniques

The course takes place at different locations. The first section is organized at the premises of the European Astronaut Center, in Germany, with a field traverse at the Ries Crater (as a Lunar Analogue). The second section is held in the Permo-Triassic terigenous sequence of the Italian Dolomites (as a Mars Analogue for sedimentary features). The third session is located in the Lanzarote Geopark in Spain (Mars and Lunar analogue for volcanism).

While the first two sections are mainly focused on theoretical planetary geology and to acquire the basic knowledge and methodology of field geology, the third phase in Lanzarote is dedicated to real geologic traverses on field. These self directed traverses are focusing on the application of the flexecution method and on understanding how different operational settings and supporting technologies influence the process. Flexecution is the standard concept of operation for terrestrial field geologists and should serve as the model for how planetary field geology is done: during the traverse the crew has the freedom to make real-time changes to the planned tasks based on their field observations, re-prioritization of science objectives, and unanticipated discoveries. Since future crews will require a high autonomy in the field, this clearly highlights the need for crews to achieve a decision-making capacity with limited support of the geologic experts or the ground team, but with the help of analytical tools and decision support systems. Flexecution leads to enhanced scientific understanding and to the ability to adapt to unanticipated discoveries.

**Applications to unmanned and manned lunar missions**

In view of potential missions to the Moon, PANGAEA is a fundamental training and testing step to improve the astronaut skills to understand geologic objectives and operational issues.

In future lunar missions astronauts could be involved in field geological activities even without necessarily being on the lunar surface. This is the case especially of robotic and rover operations that should have to be driven directly by the astronauts from a lunar outpost around the moon with negligible time delay. In view of a precursor sampling return mission to the Moon (LEAP) the role of the astronaut in geological documentation and sampling activities will have a fundamental role in the overall success: it is foreseen that rovers and robotic arms would be maneuvered following a flexecution approach where the skills and the geologic understanding of the operator can have a real impact in the choice of the right samples.

Obviously these requisites will be even more important during human missions to the surface, where EVA activities could be much longer and effective than those of the Apollo missions.

Even if the next lunar missions are foreseen in a timeframe of 10 (LEAP) to 20 years (for human landing), the preparation of such missions will require continuous training and testing in analogue environments. PANGAEA will represent one of the fundamental reference training and testing programmes in this preparatory phase.


MODELING OF LUNAR MAGMA OCEAN CRYSTALLIZATION AND IMPLICATIONS FOR THE PROPERTIES OF PRIMORDIAL LUNAR CRUST. S. Schwinger1, A.-C. Plesa1 and D. Breuer1, 1German Aerospace Center (DLR) (Rutherfordstraße 2, 12489 Berlin. Sabrina.Schwinger@dlr.de)

Introduction: The presence of ferroan anorthosites on the Moon’s surface is most readily explained through assuming that a global lunar magma ocean (LMO) existed in the early history of the Moon. During solidification of the LMO, the iron- and magnesium-rich phases crystallizing from the cooling magma sank to the bottom of the magma ocean, while plagioclase floated to the surface to form an anorthositic crust. Both the composition of the primordial lunar crust and the timing of its formation are influenced by the properties of the LMO (i.e. depth and bulk composition). In this study we aim to constrain the properties of the primordial lunar crust and the timing of its formation by modeling of LMO crystallization.

Methods: Modeling of LMO crystallization. We modeled fractional crystallization during LMO cooling using the software alphaMELTS[1,2,3]. Solid phases crystallizing in the LMO are assumed either to sink to the bottom, float to the top or remain in suspension, depending on their density relative to the density of the coexisting melt. Solids accumulating at the surface (plagioclase) and at the bottom (all other minerals) of the LMO are assumed to form homogeneous layers and are fractionated from the system in each crystallization step. In addition, the model allows for a fixed amount of the remaining liquid to get trapped in the pores of the bottom layers. The stable phase assemblages at the surface and at the bottom of the LMO are calculated with alphaMELTS[1,2,3], using the current local temperature, pressure, liquid composition and oxygen fugacity of the system as input parameters. The temperature difference between surface and bottom of the LMO is calculated assuming an adiabatic temperature gradient below a quench crust that forms a thin thermal boundary layer at the surface. The pressure at the bottom of the LMO is updated after each crystallization step using the volume of the crystallized layer given in the alphaMELTS output. The remaining liquid and any suspended solids are assumed to be in thermodynamic equilibrium at each temperature step due to vigorous convection of the liquid and sufficiently small grain sizes.

Comparison with crustal properties. To identify a realistic parameter range for LMO properties, we calculated the thickness and composition of the primordial lunar crust, assuming a fixed bulk composition (LPUM [4]) and varying the initial magma ocean depth, H2O content and amount of trapped liquid. Specifically, we calculated the magnesium numbers (Mg#=Mg/(Mg+Fe)) of plagioclase and co-crystallizing clinopyroxene and calculated the Mg# of a primordial anorthositic lunar crust consisting of 90% plagioclase and 10% clinopyroxene.

Results and Discussion: Crustal thickness. The modeled thickness of the lunar crust increases with increasing initial depth of LMO, increasing H2O content and decreasing amounts of trapped liquid (Fig. 1). However, the effect of trapped liquid is almost negligible for the range of 1 – 10% trapped liquid that is considered to be realistic for LMO conditions [5]. Crustal thicknesses of 34 – 43 km consistent with recent GRAIL data [6] are reached assuming either a shallow LMO (400 – 600 km depth) or high H2O contents (0.15 – 0.45 wt%) assuming the LMO bulk composition proposed by [4]. These results are consistent with experimental results by [7], indicating that the presence of up to 0.165 wt% H2O is required to form a 34 – 43 km crust from a 700 km LMO.
**Crustal composition.** The Mg# and Fe contents of plagioclase in ferroan anorthosites and in the bulk ferroan anorthosite are generally lower than predicted by the model (Fig. 2a,c). These lower Mg# and Fe contents could be explained either by exsolution of Fe and Mg by diffusion during plagioclase floating and emplacement in the crust or by a delay of plagioclase crystallization due to decompression melting. Since the density of the plagioclase is lower than the coexisting liquid, it will rise adiabatically towards the surface. Thereby it will reach pressures and temperatures at which, according to our calculations, it is not in thermodynamic equilibrium with the surrounding melt. As a consequence, plagioclase can be expected to dissolve during its ascent until it reaches the top of the thermal boundary layer where temperatures are low enough for plagioclase to be thermodynamically stable.

If plagioclase dissolution is fast compared to its ascent rate, plagioclase may dissolve completely so that the formation of a plagioclase crust will be delayed until the LMO has cooled enough for plagioclase to be thermodynamically stable at lower pressures. During further cooling, the melt evolves towards lower Mg# due to the crystallization of clinopyroxene. At the same time, the melt is richer in Al2O3 and CaO than in the scenario without decompression melting. Therefore the first plagioclase that reaches the surface will have lower Mg# than expected for a scenario without decompression melting. In addition, more Al2O3 and CaO might be incorporated into clinopyroxene, resulting in a smaller total amount of crystallizing plagioclase and a thinner crust. The Mg# and Fe contents of clinopyroxene in ferroan anorthosites are higher than predicted by the model (Fig. 2b). The higher Fe contents in clinopyroxene indicate a later crystallization from a more evolved melt as described above, which is consistent with a delay of plagioclase crystallization due to decompression melting.

**Conclusions:** Our results show that assuming the LMO bulk composition [4] we can obtain crustal thicknesses consistent with recent GRAIL data [6] by using either a shallow LMO (400 – 600 km depth) or a high H2O content (0.15 – 0.45 wt%). However, the models cannot explain the observed Mg# and Fe of the ferroan anorthosites. A possible explanation is that plagioclase will dissolve during ascent, which results in a later formation of the anorthositic crust, a change in the crust composition and potentially a change in crustal thickness. Therefore it is crucial to consider the timescale and kinetics of decompression melting during plagioclase floatation in the simulation of crust formation.

CONCEPTUAL DESIGN OF A LUNAR EXPLORATION ARCHITECTURE M. Schwinning¹, S. Belz¹, G. Detrell¹ and R. Ewald¹, ¹Institute of Space Systems, University of Stuttgart, Pfaffenwaldring 29 70569, Stuttgart, Germany (Schwinning@irs.uni-stuttgart.de).

Introduction: In 2019, the first Moon landing of Apollo 11 will see its 50th anniversary. Following this monumental achievement in 1969, a long list of successful space exploration missions led to the current outstanding example of international cooperation beyond political and cultural differences and to the largest structure ever built in space: The International Space Station.

However, with the end of operation of the ISS coming up probably during the next decade it is time to think about a successor platform to preserve long-duration human presence in space. Human exploration of the solar system is realized through a progressive series of space ventures, with each seeking to extend the reach of its predecessor. As an important step in this process, manned platforms in Earth’s proximity may be used to support exploration missions to Moon, asteroids or Mars as well as long-duration microgravity research. The challenges faced by such research outposts are ever-changing, as are the possibilities for their application. As such, new ideas and approaches are required in order to maximize the potential of these facilities.

In this frame, the Institute for Space Systems (IRS) at the University of Stuttgart instigates the annual Space Station Design Workshop (SSDW), which combines talented undergraduate and graduate students, as well as young professionals, in a cooperative yet competitive environment. Under guidance from experts in academia and industry these students are tasked with designing a manned platform in space in an intensive one-week workshop at the IRS facility in Stuttgart.

Over the long history of the SSDW since the beginning of 1990s, a lot of different conceptual designs were delivered, each answering an individual mission statement corresponding to current worldwide interests in space exploration. This abstract shortly concludes scenario outlines of the SSDWs that dealt with the lunar vicinity.

Moon base: When investigating the Moon, its composition, and the utilization of its resources, a surface base might be the most convenient solution. This solution not only minimizes the required logistic effort but also acts as a proving ground for a future planetary station on Mars.

Looking at the lunar surface, two landing sites are of major interest: the poles and the equatorial region. While the first one promises more scientific value due to the abundance of water, minerals and crater regions with permanent shading, it also entails logistic problems. While places with almost continuous illumination from the Sun for power generation via solar cells can be found, continuous visibility to Earth for the purpose of communication is a rather difficult issue. Relay satellites might be a solution but require a vast amount of coordination and maintenance. A relay station on a mountain can solve the problem with significant less effort.

One of the high advantages of positioning a station in the equatorial region of the Moon is the easy accessibility and all time return capability to Earth. Permanent visibility of Earth is also guaranteed when landing on the near side of the Moon. However, the eclipse times around the equator are roughly 14 Earth days, which constitutes crucial challenges for power generation and thermal control. As solar cells are probably not an option, the high power demands of a manned platform require the application of nuclear power. Consequently, high safety precautions need to be taken in order to mitigate potential risks to the crew. Once installed, a nuclear reactor generates enough power to operate a thermal control system that fulfils the high requirements of 14 days heating and 14 days cooling times near the lunar equator.

Low lunar orbit: Positioning a space station in low lunar orbit offers some crucial advantages in contrast to a surface base. First of all, the transportation scenario is much simpler, as the propulsion system is only required to perform an orbit insertion manoeuvre, instead of a surface landing, which is significantly more complex. Furthermore, short eclipse periods simplify the thermal protection and electrical power systems. In addition to that, if offers a high scientific value to the mission, as lunar polar orbits cover the entire surface of the Moon, which
can be of high interest when investigating different sites on the surface. In case the mission demands a permanent communication to Earth, a relay satellite will be required.

Naturally, a low lunar orbit will not be as suitable as a surface base when it comes to ground operations since a landing module will be required for each activity. Moreover, some of the surface areas have a high revisit time of the space station, depending on the orbit. This results in either long lunar ground activities or a limitation of landing sites. For instance, an almost 90° inclination orbit could only investigate the polar regions with reasonable time-intervals as it covers them every orbit. A 0° inclination orbit revisits the entire ground track every orbit, but only covers the equatorial region.

Figure 3 LLO space station (SSDW 2007)

EML 1/2: Another alternative when talking about positioning a manned platform in the lunar vicinity are the Earth-Moon libration points. More specific, the EML one and two are of high interest when considering lunar science as one of the mission goals. Choosing the radius of the halo orbit high enough (e.g. 5000 km), even a station at EML2 has 100% visibility to Earth. Furthermore, circling around any of the two libration points gives over 99% illumination from the Sun, simplifying power generation and thermal protection in contrast to the other presented options due to constant conditions. One concept of high interest can be to use a large panel of solar cells as front shield, always pointing towards the sun, while hiding most of the station behind it. Thus, the thermal housekeeping can be controlled via tilting solar panels in order to let sunlight reach the station or keep it away.

Positioning a station in one of the libration points does not offer a good capability of astronaut surface operations on the lunar surface. However, EML 1/2 give the perfect opportunity to perform telerobotic operations on the Moon, as they constantly face the same side of the Moon in contrast to an operator in low lunar orbit. They are still close enough, to avoid time delays having a significant influence remote control operations. Furthermore, especially a human-tended platform in EML 2 constitutes the perfect opportunity to act as an outpost for further deep space exploration. Either on the way out or on the way back from exploration missions, the spacecraft could dock to the station for resupply. Even on-orbit manufacturing and assembly of larger spacecraft could take place next to the station, giving the possibility to send only small components into space, significantly reducing the launcher requirements [1].

Figure 4 EML2 space station (SSDW 2015)

Lunar resource utilization: Looking at the material components that can be found on the Moon, different applications are feasible. Water can either be inserted into the ECLSS as resupply or split into hydrogen (89%) and oxygen (11%) with an electrolyser facility, stored and recombined in a fuel cell to generate electrical energy during peak power demands or solar cell failures. Depending on the deposit, Helium-3 could prove as a very precious component comprised in the lunar Regolith. It could either be used for scientific purposes on the station or stored and send back to Earth, as Helium-3 resources are rather limited.

The material with possibly the most diverse applications is the lunar Regolith itself. While proportions of rare minerals are rather uncertain, the raw material can be further processed in many ways. Experiments have shown, that the Regolith could be used for additive manufacturing in order to build new structural components. Future concepts include the extension of ground or space platforms by 3D-printed modules, truss segments or even solar panels. In addition to that, good capabilities in terms of radiation protection make Regolith an easy accessible and abundant existing resource for shielding measures [2].

Conclusion: This abstract discusses and compares three possible scenarios for a human tended platform in the lunar vicinity and on the surface. Whether a surface base or a space station might be most feasible will have to be decided based on the specific objectives for the next non-terrestrial human habitat. The SSDW at the IRS can help evaluating and investigating various ideas as well as developing corresponding architecture concepts and mission designs.

DIVINER THERMAL INFRARED OBSERVATIONS OF THE PERMANENTLY SHADED PORTION OF AMUNDSEN CRATER. E. Sefton-Nash1, B. Greenhagen2, J.-P. Williams3 and D. A. Paige1 1ESTEC, European Space Agency, Keplerlaan 1, Noordwijk 2201AZ, Netherlands (e.sefton-nash@cosmos.esa.int). 2Applied Physics Laboratory, Johns Hopkins University, MD, USA. 3Department of Earth, Planetary and Space Sciences, University of California Los Angeles, CA, USA.

Introduction: The Diviner Lunar Radiometer Experiment aboard NASA’s Lunar Reconnaissance Orbiter (LRO) spacecraft [1] has been systematically mapping the thermal state of the Moon since July 2009. Diviner measures solar reflectance and infrared radiance in 9 spectral channels with bandpasses from 0.3 – 400 μm.

With more than 7 years of continuous data acquisition, complete spatial coverage of the lunar surface has been achieved multiple times. Coverage of local solar time enables the diurnal curve to be well-resolved for a given subsolar point.

Polar regions have been a particular focus for the mission science objectives, further driven by the discovery of significant water vapour in the plume created by the LCROSS impactor [2].

Diviners’ 4 thermal channels (6-9) have bandpasses designed to capture the black-body peak for the full range of the lunar thermal environments (~20 - 400 K). The long wavelength channels 8 and 9 are best placed to observe the very coldest temperatures, i.e. those that are relevant to detection of thermal signals that could be influenced by the presence of volatiles on the lunar surface or in the subsurface.

Permanently shadowed regions (PSRs) persist at the lunar poles due to the Moon’s low axial tilt. Crater interiors and other topographic depressions act as cold traps and may offer conditions suitable for long-term stability of surface or subsurface volatiles [3]. The predominant sources of radiation in PSRs are limited to upwelling heat flow from the lunar interior, stellar radiation, secondary illumination by reflected or scattered light from illuminated surfaces, or thermal emission from nearby warmer shadowed surfaces. These radiative sources are often negligible, allowing PSRs to remain at very low temperatures that are more akin to those observed on bodies in the outer solar system [4].

Evidence from observations of the lunar poles by instruments aboard LRO has been applied to isolating potential signatures of such volatiles. The body of results to date does not conclusively answer the question of volatile abundance at the surface or in near-surface regolith layers.

Delineating PSR boundaries is accomplished either by ray-tracing using digital terrain models, as was performed for results in [3], or more crudely by plotting maximum observed brightness temperature. The distribution of maximum observed temperatures indicates a significant portion of the south polar region remains below the volatility temperature of water-ice. However, measures of the thermal environment may not be a reliable predictor of H concentration [5], which is assumed to be a major indicator for the presence of water-ice. Consequently, questions remain regarding the presence, supply rate and mobility of water-ice.

Spatial variations in angular emissivity may be connected with the presence of surface water frost. The variation in emissivity as a function of emission angle of a permanently shadowed target suffers less from the complicated effects of surface roughness (small scale shadows) on apparent radiance that are present for EPF observations of illuminated regions [6].

Presently, coverage of emission angle for polar locations is relatively sparse in the Diviner dataset, but an ongoing campaign seeks to acquire angular emission functions for PSR targets. Control observations of normally illuminated (and therefore assumed to be volatile free) regions at night are also made for comparison. Ideally, observations of PSRs and non-PSRs should be made at a similar season to minimize differences in the thermal state of the surface, which could be misinterpreted as due to differences in emissivity.

Comparison between the angular emission function of targets and control regions may indicate anomalous emissive properties that could be attributed to the presence of surface volatiles. Input to target selection is from identification of PSR boundaries as well as results that indicate anomalous emissive properties, e.g. in the UV [7].

Method: The northern floor and wall of Amundsen crater is a PSR that shows water equivalent hydrogen concentrations above that of the surrounding terrain (up to ~ 0.5% [5]). We report on the status of observations obtained a range of emission angles of one control and one study target in Amundsen; normally-illuminated (NPSR1) and permanently shaded (PSR1) (Fig. 1).

Image 310x97 to 523x218

Figure 1: Slope map (LOLA 120m/pix) of Amundsen crater, near the lunar south pole, and location of


PSR1 and NPSR1 targets. The area of permanent shadow [8] is marked by the shaded area.

Annual night-time temperatures range from 20 – 60 K for PSR1, and around 40 – 90 K for NPSR1. Observations were obtained at observation opportunities since March 2016, and emission angle coverage is shown in Figure 2.

![Figure 2](image2.png)

**Figure 2:** Distribution of emission angles at which PSR1 and NPSR1 have been observed to the end of 2016.

We define target boundaries at a 3km radius around centres of 93.1047°E, 84.5523°S and 91.2826°E, 83.6889°S for NPSR1 and PSR1, respectively. This distance is sufficient to exclude areas of high slope (Fig. 1) that would otherwise cause excessive mixing of emission angles due to variable topography within each observation footprint, which could reduce the ability to constrain angular emission within target boundaries.

At high emission angles, the footprint of each observation is extended in the horizontal direction of the look vector. To understand the extent to which this could increase radiance contributions from outside the target boundaries, the ground-projected effective field-of-view (EFOV) for each observation must be constrained. Using knowledge of instrumental effects and observation geometry, EFOVs are calculated according to [9]. The effects of a non-infinitesimal instantaneous field-of-view, detector lag, spacecraft motion during integration time, off-nadir observation geometry and surface topography are accounted for.

This technique is of particular importance for polar observations, because even though our observations are constrained to nighttime (a tenuous definition at the poles) sharp illumination boundaries and ‘sweeping’ shadows caused by low sun-angles could cause large heterogeneity within EFOVs, via contribution from illuminated areas. Even if no illuminated terrain is included, primary or secondary emission from normally illuminated surfaces may play a role.

We note this effect may be at work for the angular emission function so far observed in Diviner channel 9 (sensitive to 100-400 μm, brightness temperatures < 43K [1]) for NPSR1, where increased radiance is observation at emission angles ≥ 50° (Fig. 3).

![Figure 3](image1.png)

**Figure 3:** Apparent mean radiance observed from NPSR and PSR targets in Amundsen as a function of emission angle.

**Conclusions:** Initial results suggest that detection of differences between the angular emission of cold traps and normally illuminated surfaces is complicated by the ground-projection of EFOVs at high emission angles in polar regions, which we continue to work to better constrain. Further necessary considerations include seasonality of the thermal behavior of both targets, and crucially, the meaning of any differences that are detected, since a limited amount of laboratory and model data exist regarding the angular emissivity of dry vs volatile-bearing lunar regolith at PSR-relevant temperatures.

REGOLIGHT: SINTERING AND SHAPING LUNAR REGOLITH BY SOLAR LIGHT. Matthias Sperl¹, Miranda Fateri¹, Alexandre Meurisse¹ and the RegoLight Consortium, ¹Institute of Materials Physics in Space, German Aerospace Center DLR, 51170 Cologne, Germany (matthias.sperl@dlr.de), ²DLR, Space Applications Services, Comex, Bollinger + Grohmann, Liquifer Systems Group.

Introduction: Additive Manufacturing (AM) technologies have shown they could take place in the construction of a Moon village. Studies of contour crafting mixing regolith with a binder [1-2] proved the feasibility of concepts combining new technologies and architectural designs of lunar habitats. Following this trend, the H2020 project RegoLight aims at refining existing solar sintering techniques to reach a Technology Readiness Level (TRL) of 5 in solar 3D printing. With a concurrent engineering approach, the sintering technology is carried from the fundamental process of sintering grains all the way to a building element and to the design of habitats.

Solar sintering: Sintering lunar regolith layer by layer was demonstrated using a laser [3] for relatively small scale products. Proof of concept has also been shown for other techniques, such as microwaving [4]. When targeting larger scale constructions, concentrating solar energy to 3D print regolith can be the appropriate technology. Within this project, a solar 3D printing process was developed at DLR in Cologne using a solar oven in order to be able to 3D print interlockable building elements out of JSC-2A lunar simulant as shown Figure 1. The 3D printed material is then characterized mechanically in order to adjust the geometry into a usable interlockable building element. These building elements are in turn combined into the design of realistic constructions.

On the fundamental level, parameters such as variation of regolith composition or the presence of vacuum are quantified regarding their impact on the sintering process [5]. The mechanical properties from sintering are then used in structural engineering to optimize both building elements and full constructions for a Lunar environment.

Scenarios: The designed study targets the building of a bearing structure capable of shielding pressurized and unpressurized modules from radiation and meteorites. The dome-shape structure, shown in Figure 2, will be made of individual interlockable solar sintered building elements which could be used as well for terrain modelling.

References:
[1] Khoshnevis B. et al. (2005), 43rd AlAA ASM.

Figure 1: Solar 3D printed regolith element 190mm x 120mm x 40mm. This part is made of JSC-2A sintered solely with concentrated sunlight in less than 3 hours.

Figure 2: Dome-shaped structure made of interlockable building elements over an inflatable dome. The structure is stable at any step of the construction.
TEMPORAL OBSERVATIONS OF REGOLITH GARDENING CAUSED BY SECONDARY IMPACTS. E.J. Speyerer1, R.Z. Povilaitis1, M.S. Robinson1, P.C. Thomas2, R.V. Wagner1, 1School of Earth and Space Exploration, Arizona State University, Tempe, AZ (espeyere@asu.edu), 2Cornell Center for Astrophysics and Planetary Science, Cornell University, Ithaca, NY.

Introduction: Much of what we know about the Moon on a global scale stems from orbital remote sensing measurements that probe the top few microns to 10s of centimeters of regolith. Therefore, it is essential that we understand the physics of regolith mixing and overturn. Dynamics of the upper lunar regolith was previously modeled using meteoroid flux data [1-3]. New observations from the Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC) [4] are providing fresh insight into the impact process and [5,6] suggest secondary impacts may play a larger role in near-surface regolith gardening than previously considered.

Swarms of Secondary Impacts: From temporal imaging (before and after observations) Robinson et al. [5] characterized an 18 m impact crater that formed on 17 March 2013. In addition to identifying the newly formed primary crater, they discovered 248 new localized albedo changes surrounding the crater, with some as far as 30 km away from the impact site. These localized albedo changes, described by the authors as splotches, do not have a visible crater rim or any other morphologic signature at the NAC pixel scale (100 cm). Robinson et al. [5] also noted that some splotches were grouped in herringbone patterns indicating a direction of emplacement consistent with a secondary impact from the 17 March event (Fig. 1).

Fig 1. Examples of directional splotches in temporal ratio images with black arrows pointing toward the 17 March crater. Each panel is ~200 m wide (From [5]).

Using a semi-automated change detection algorithm, we have cataloged over 47,000 splotches in over 14,000 LROC NAC temporal image pairs that were randomly targeted across the Moon (50°S to 50°N). While some of the splotches are likely the result of small primary impacts, we identified several dense clusters of splotches surrounding newly formed impact craters. Fig. 2 shows the density of splotches observed as a function of longitude (10° average bins). The spike observed near 330°E corresponds directly to four newly formed impact craters with diameters ranging between 34 and 75 m. This increase in splotch density is consistent with clusters forming as the result of large impact events.

To determine the percentage of splotches that are the result of secondary vs. small primary impacts, we measured the density of splotches in regions void of obvious splotch clusters. This background rate was compared to the entire splotch population. With this initial dataset, we estimate that ~50% of splotches are the result of secondary impacts. If we consider that some of the splotches used to derive our background rate are also distal secondary impacts and not primaries, the percentage of splotches due to secondary impacts increases. Collection of additional temporal image pairs during the LRO Cornerstone Mission (CM) will enable us to further constrain the splotch formation rate and further separate the rate due to secondary impacts and the rate due to small primary impacts.

Fig 2. Observed splotch density as a function of longitude. The spikes in the distribution correspond with recent impact events.
Impact of Splotches on Regolith Gardening: Laboratory experiments conducted by Schultz and Gault [7] showed that clustered impacts at relevant speeds (~200 m/s) create a pitted surface surrounded by a subdued rim with a depth:D ratio of 1:30. These simulations imply that most splotches would only churn the top few cms of regolith within the mature zone. Of the 47,000 newly formed splotches, over 90% of splotches exhibit lower reflectance (average -4%) than the same region before they formed. In the remaining cases, the reflectance was higher (average +10%) or exhibited mixed reflectance. This is consistent with churning of mature regolith in cases of a lower reflectance splotch and mixing of optically immature regolith in cases of a high reflectance splotch. Additionally, many of the high reflectance splotches occur on steep slopes or in areas that have been recently resurfaced, which would tend to have a thinner optically mature regolith layer.

Using a conservative estimate for the churning depth relative to splotch diameter (1:50) and the observed spatial coverage of new splotches formed in temporal pairs, we derived a gardening rate for the upper few cm of regolith. We estimate that 99% of the lunar surface is altered by 1-m and larger splotch events over a period of ~80,000 years (Fig. 3), which churns the upper ~2 cm of regolith during that period. This rate is >100 times faster than predicted by Gault et al. [1] at this depth, but is consistent with measurements of short-lived cosmogenic radionuclides ($^{26}$Al; $t^{1/2}$=7.3×10$^4$ yr) in Apollo drive core samples that indicate the upper 2-3 cm of regolith was continuously reworked over a period of 10$^4$ to 10$^6$ yrs [8-10]. While secondary splotches may rapidly churn the upper few cm, the effectiveness at overturning regolith at depth is limited due to the overall size and speed of the secondary projectiles. However, splotches clearly modify the observed surface for many remote sensing instruments and must be considered with evaluating and modeling surface properties.


![Fig 3. Rate of splotch accumulation for 1 m and larger splotches.](image-url)
METAL-SILICATE PARTITIONING OF K AS A FUNCTION OF COMPOSITION AND TEMPERATURE AND ITS ABUNDANCE IN THE LUNAR CORE
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Introduction: ⁴⁰K has been proposed as a possible heat producing element in planetary cores [1-3]. Heat from ⁴⁰K decay could affect the thermal evolution of the lunar interior, the evolution and onset of a lunar core dynamo and the timing and nature of inner core crystallization [3-4]. The variables that affect the metal-silicate partition coefficient (D) of K are not well constrained and it is unclear to what extent K resides in the lunar core. Some studies suggest that silicate melt composition profoundly affects the metal-silicate partition coefficient (D) of K, whereas other studies suggest significant temperature (T) effects [3,5]. Pre-2003 experimental studies used oil- or water-based polishing techniques, which has been proven to preferentially remove K from the metal during polishing [3], prohibiting adequate comparison between many datasets. Recent geochemical models of lunar core formation [6-10] have provided new constraints on plausible metal compositions and temperatures (T) during core formation. To reassess the role of K as a major heat producing element in the lunar core, we report new D(K) values as a function of T and composition.

Approach: We performed experiments at 1 GPa and between 1683–1883 K using Pt-C or MgO capsules. Capsules were loaded with synthetic equivalents of diopside (GA), a lunar granite (LGK) or A15C lunar green glass (GGK), to study possible effects of silicate melt composition on D(K). Metals consisted of Fe, FeC, FeCSi or FeS alloys, to constrain the effects of metal composition on D(K). Run times varied between 15-120 min. As K is highly soluble in oil-water based liquids [3], samples were dry polished. Potassium abundances were quantified using LA-ICP-MS and EPMA.

Results: Run products consisted of well segregated metallic blobs within a homogeneous quenched glass (Fig. 1). In agreement with previous work, we observed that K is heterogeneously distributed in the metal [3]. We find that there is in general good agreement between LA-ICP-MS and EMPA measurements of K abundances (Fig. 2). No significant K loss was observed relative to the starting compositions and a time series confirmed equilibrium is attained within <15 min at 1683 K.
**Metal composition:** Addition of S significantly increases the solubility of K in liquid metal and this dependence is well quantified (Fig. 3). This is in agreement with [3,5], but does not agree with [11], who suggest that dissolved O solely enhances D(K).

**Temperature:** At similar composition and constant P, we find a clear and significant increase of D(K) with T, even within the relatively limited range of 1683-1883 K of this study (Fig. 4). This is again consistent with most previous work [3,5,12], but not with [11]. Note that [5,11] relate this T effect to dissolved O in the metal, which in turn would enhance D(K). If T dependencies on D(K) are the result of enhanced solubility of O, this would imply T dependence on D(K) obtained for FeS liquids potentially cannot be used to predict the T dependence of D(K) in other metal alloys, as the solubility of O in these alloys may be different.

However, Rubie et al. [13] found that O solubility in FeNi alloys are not significantly affected by addition of up to 30 wt% S. This is supported by the similar T dependencies of D(K) for Fe and FeS systems reported by [12] from a compilation of several D(K) datasets. The D(K) values of our GGK series with coexisting FeSi metal also suggest an increase with T.

**Silicate composition:** At identical P-T and similar metal composition, there seems to be a significant increase of D(K) with nbo/t. This would be in agreement with the observations of [5,14], but opposite to that observed by [3], who suggest a significant decrease. Bouhifd et al. [12] reported no effects of nbo/t on D(K) from nbo/t = 0.8±0.4 to 3.1, though only one experiment was performed at nbo/t = 3.1. Our initial results seem to suggest that D(K) increases linearly with nbo/t. This has to be confirmed by additional experiments, which will be reported at the meeting.

METAL-SILICATE PARTITIONING OF VOLATILE SIDEROPHILE ELEMENTS: CONSTRaining VOLATILES IN THE EARLY EARTH-MOON SYSTEM E. S. Steenstra1, A. X. Seegers1, Y. H. Lin1, R. Putter1, M. J. Crockett1, D. Dankers1, N. Rai2, S. Matveev1, J. Berndt1, S. Klemme1, W. van Westrenen1 1Faculty of Earth & Life Sciences, Vrije Universiteit Amsterdam, NL (e.s.steenstra@vu.nl), 2Indian Institute of Technology Roorkee, India 3Department of Petrology, Utrecht University, Utrecht, NL 4Department of Mineralogy, University of Münster, Germany.

**Introduction:** Siderophile element depletions in the silicate Moon are an important tool to constrain differentiation conditions of the Moon [1-4]. The depletions of volatile siderophile elements (VSE) provide important insights in the early lunar volatile budget, if their partitioning behavior is well quantified. To assess to which extent these elements were depleted through formation of a lunar core, and to assess the effect of the minor element content of the lunar core, we have been performing a wide range of high P-T metal-silicate partitioning experiments for the VSE [5-8] with S and/or C present in the metal. Although not directly relevant for the Moon, we also used FeSi alloys to assess if VSE partitioning is affected by metallic Si [6,8]. The Earth’s core is believed to contain several wt% Si and these results can be used to provide constraints on the VSE in the early Earth.

**Approach:** Experiments were performed between 1-2.5 GPa and 1683–1883 K using a single (MgO) or double capsule (C-Pt). Samples consisted of synthetic equivalents of A15C green glass, a lunar granite composition or terrestrial Knippa basalt combined with Fe metal plus trace elements. EMPA and LA-ICP-MS were used to quantify major and trace element concentrations in metals and co-existing silicate melt, to determine the metal-silicate partition coefficients D, for elements i. Effects of metal composition were studied by considering Kp [see 10], which is independent of fO2. The metal activity calculator was used to calculate γFe and the amount of C in metal [9]. Lunar mantle depletions of VSE were calculated using D(c/m) = (C(BM)/x)(C(BSM))/C(BM)), where C( BM) is the concentration by weight of element i in the bulk Moon (BM), C(BSM) is the concentration by weight of element i in the bulk silicate Moon (BSM) and x is the mass fraction of the BSM, assumed here to be 0.975-0.99 [3,10]. Bulk Moon (BM) abundances were considered to be equal to bulk silicate Earth (BSE) [11,12]. The BSM abundances were taken from [13].

**Results:** Graphite saturation resulted in 5-6 wt% dissolved C in metal. We find that C increases Kp As, but lowers Kp Sb, Pb, Cd and D (Se, Te). Our results suggest that Kp As, In, and Sb decrease with S in the metal, whereas Kp Cr, Mn, Se, Cd, Te, and Pb are increased. The addition of variable amounts of FeSi resulted in up to 14 wt% Si in the metal. We find that the activities of all VSE considered here are decreased with Si. The fO2 dependence of D(Se,Te) changes with P, becoming less siderophile at higher P at low fO2 (Fig. 1). Positive P effects are also evident for D(S,Se,Te) and Kp Si, whereas Kp Sb decreases with T.

**Fig. 1: D(Se, Te) as a function of fO2**

**Discussion:** With our large database we can now assess to what extent S, Se, Te, Sb are depleted in different lunar core formation scenarios and if these values match with our experimentally determined D’s. Fig. 2 shows their D’s as a function of P for C-free data (blue) and C-saturated data (yellow) [8]. It is evident that their depletions can be readily matched in a deep lunar magma ocean (LMO) scenario. If C is the dominant light element in the lunar core [4], their depletions can still be readily matched albeit at slightly higher P. A deep LMO (4.5 GPa) was also inferred from the depletions of 13 other siderophile elements [3]. The P dependencies of D(Se,Te) are also nearly identical for both datasets. We also explored the possibility of a FeS-rich lunar core [14]. We find that addition of S to the lunar core would only further increase the feasibility of explaining Se and Te abundances by core formation (Fig. 3). D(Sb) decreases with S in the metal and its depletion in the lunar mantle is consistent with a S-poor core, consistent with [4].
**Volatiles in the early Earth-Moon system:** Our work shows that the lunar mantle depletions of S, Se, Te, Sb can be explained by metal-silicate equilibration during core formation only. No volatile loss during lunar formation is required. A deep LMO also produces S/Se and Se/Te ratios for the BSM [5] that are within error with that of the BSE [11,12]. We have shown that the maximum effects of a late veneer will not significantly affect our conclusions [5].

**Fig. 2:** D versus P. All data was corrected to the lunar mantle FeO content of 10 wt% [5].

If volatiles were not lost and the Moon is made from the BSE as suggested from many geochemical considerations, it implies that the BSE S/Se and Se/Te ratios were already set before formation of the Moon. These ratios are now considered as a major line of evidence for the existence of a volatile-rich late veneer. Alternatively, the BSE S/Se and Se/Te ratios were set by core formation. Partitioning of Se and Te in the Earth’s core may not have been that efficient due to P effects on their FeO dependence at low fO2 (Fig. 1). Recent work showed that interaction coefficients may also considerably change with P [15].

**Fig. 2:** D versus S in metal. All data was corrected to the lunar mantle FeO content of 10 wt% [5].

MINI-RF BISTATIC OBSERVATIONS OF COPERNICAN CRATER EJECTA. A. M. Stickle¹, G. W. Patterson¹, J. T. S. Cahill¹, and the Mini-RF team ¹Johns Hopkins Applied Physics Laboratory, 11100 Johns Hopkins Rd., Laurel, MD, USA 20723 (angela.stickle@jhuapl.edu).

Introduction: The Mini-RF instrument aboard NASA’s Lunar Reconnaissance Orbiter (LRO) is currently acquiring bistatic radar data of the lunar surface at both S-band (12.6 cm) and X-band (4.2 cm) wavelengths in an effort to understand the scattering properties of lunar terrains as a function of phase angle. Previous work, at optical wavelengths, has demonstrated that the material properties of lunar regolith can be sensitive to variations in phase angle [1-3]. This sensitivity gives rise to the lunar opposition effect and likely involves contributions from shadow hiding at low phase angles and coherent backscatter near zero phase [1]. Mini-RF bistatic data of lunar materials indicate that such behavior can also be observed for lunar materials at the wavelength scale of an S-band radar (12.6 cm). The ejecta blankets of seven lunar craters have been observed to date, and the Circular Polarization Ratio (CPR) examined as a function of phase angle.

Bistatic Operations: Radar observations of planetary surfaces provide important information on the structure (i.e., roughness) and dielectric properties of surface and buried materials [4-7]. These data can be acquired using a monostatic architecture, where a single antenna serves as the signal transmitter and receiver, or they can be acquired using a bistatic architecture, where a signal is transmitted from one location and received at another. The former provides information on the scattering properties of a target surface at zero phase. The latter provides the same information but over a variety of phase angles. NASA’s Mini-RF instrument on the Lunar Reconnaissance Orbiter is currently operating in a bistatic architecture with the Arecibo Observatory in Puerto Rico and the Goldstone DSS-13 antenna in California. The Arecibo Observatory serves as the transmitter for S-band operations and DSS-13 serves as the transmitter for X-band operations. In both cases and Mini-RF serves as the receiver. This architecture maintains the hybrid dual-polarimetric nature of the Mini-RF instrument [8] and, therefore, allows for the calculation of the Stokes parameters (S₁, S₂, S₃, S₄) that characterize the backscattered signal (and the products derived from those parameters).

Observations: A common product derived from the Stokes parameters is the Circular Polarization Ratio (CPR),

\[
c = \frac{S_1 - S_4}{S_1 + S_4} \quad (1).
\]

CPR information is commonly used in analyses of planetary radar data [4-7], and is a representation of surface roughness at the wavelength scale of the radar (i.e., surfaces that are smoother at the wavelength scale will have lower CPR values and surfaces that are rougher will have higher CPR values). High CPR values can also serve as an indicator of the presence of water ice [9].

As part of the Mini-RF bistatic observation campaign, CPR information for a variety lunar terrains is being collected over a range of bistatic and incidence angles. The first campaign (during LRO extended mission targeted a variety of Copernican-aged impact craters in order to characterize the opposition response of materials known to be rough at radar wavelengths [10]. Patterson et al. [10] showed the ejecta properties for three of these craters: Byrgius A, Kepler, and Bouguer, as a function of bistatic angle. Both Kepler and Bygius A exhibited an opposition effect, while Bouguer did not. The opposition responses of Byrgius A and Kepler ejecta lead to increases in CPR of ~30% and 15%, respectively, as bistatic angle approaches 0°. The mean CPR of Byrgius A and Kepler ejecta at bistatic angles outside of their opposition responses averages ~20% higher than surrounding materials. The mean CPR of Bouguer averages 5% above surrounding materials. Patterson et al. [10] suggest that the radar scattering characteristics of the continuous ejecta for these three craters, coupled with age estimates based on crater statistics and geologic mapping, suggest a relationship between the opposition response of the ejecta and the age of the crater (i.e., Byrgius A is the youngest of the craters observed and shows the strongest response). Thus, describing the CPR response as a function of phase angle may be a way to determine relative age between deposits. Here, we examine the ejecta of seven Copernican aged craters (Table 1) and document CPR characteristics as a function bistatic angle in order to test that hypothesis. The spatial resolution of the data varied from one observation to another, as a function of the viewing geometry, but averaged ~100 m.

Four of the examined craters exhibit CPR characteristics suggestive of an opposition effect: higher CPR at lower bistatic (phase) angle (Figure 1). The increase in CPR occurs near 2-4 degrees bistatic angle. These craters occur in both highlands and mare regions, and are all characterized as young (Table 1). Three other examined craters exhibit CPR that remains relatively constant across phase angle. This may be for a couple reasons. 1) The craters are older (though still Copernican), and so the opposition effect will be less pronounced, or 2) there are few observations of these craters, with none to few over very small angles. An opposition effect may be present, and not yet observed. Continuing observations are targeting these regions to increase the phase an-
gle coverage. Additional study is ongoing to fully characterize the CPR response with viewing geometry for these young craters. All of these targets will also be targeted in X-band, as well as adding additional craters (e.g., Schomberger, Copernicus).


Table 1. Summary of Mini-RF bistatic observationsof young lunar craters examined here

<table>
<thead>
<tr>
<th>Crater</th>
<th>Diameter</th>
<th>Center</th>
<th>Terrain</th>
<th>Age Estimate</th>
<th>Bistatic Angles Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Byrgius A</td>
<td>19 km</td>
<td>24.5S, 63.7 W</td>
<td>Highlands</td>
<td>48 My [11]</td>
<td>0.72-13.57</td>
</tr>
<tr>
<td>Bouguer</td>
<td>22 km</td>
<td>52.3N, 35.8W</td>
<td>Mare</td>
<td>Copernican [14]: ~1.2 Gy</td>
<td>1.01-5.42</td>
</tr>
<tr>
<td>La Condamine S</td>
<td>4 km</td>
<td>57.3N, 25.2W</td>
<td>Mare</td>
<td>Copernican</td>
<td>0.04-10.26</td>
</tr>
<tr>
<td>Harpalus</td>
<td>39 km</td>
<td>52.6N, 43.4W</td>
<td>Mare</td>
<td>Copernican</td>
<td>5.68-14.98</td>
</tr>
<tr>
<td>Anaxagoras</td>
<td>50 km</td>
<td>73.4N, 10.1 W</td>
<td>Highlands</td>
<td>Copernican</td>
<td>4.05-15.89</td>
</tr>
<tr>
<td>Aristarchus</td>
<td>40 km</td>
<td>23.7N, 47.4W</td>
<td>Mare</td>
<td>Copernican</td>
<td>0.02 - 9.28</td>
</tr>
</tbody>
</table>

Figure 1. CPR as a function of phase for 4 examined craters. All four craters here exhibit differences in CPR with bistatic angle, with higher CPR at lower bistatic angles (characteristic of an opposition effect).

Figure 2. CPR as a function of phase for 3 examined craters. All three ejecta blankets exhibit relatively constant CPR values as a function of bistatic angle.
Introduction: U-Pb dating of zircon is a powerful tool to study the magmatic evolution of the Moon. The main advantage of zircon chronology is its resistance to thermal disturbance, i.e. the closure temperature for Pb diffusion in zircon is estimated to be around 900-1000 °C [1]. Nevertheless, some U-Pb ages of lunar zircons were interpreted to represent impact related resetting of the U-Pb system [e.g. 2] instead of crystallisation ages. Partial resetting has also been observed in zircon from an Apollo 15 breccia [3]. Two impacts at 1.4-1.5 Ga led to discordance of the zircon analyses and a large scatter of U-Pb ages [3]. However, in most cases partial resetting is difficult to detect in relatively old grains (>3.9 Ga) due to the lack of visible discordance.

Despite the lack of discordant analyses, partial Pb loss was recognised in Apollo 12 breccia 12013 [4, 5], based on textural relationships indicating crystallisation from the same source rock and the obtained U-Pb ages revealing a large scatter of ages [4, 5]. Given the relatively low closure temperature for the U-Pb system in Ca-phosphates, the U-Pb ages of such grains in the 12013 breccia are interpreted as defining the age of the last thermal event, which also resulted in Pb loss from the zircon. In this ongoing study, the idea of partial resetting is further developed by thoroughly studying microstructures and changes in Th-U concentrations of the analysed zircon grains to distinguish between reset grains and those that might have retained their original crystallisation ages.

Sample description: 12013 is a complex breccia, which is made up of a mixture of two polymict breccias, one black in colour, the other grey [6]. Both lithologies are thought to have formed in a single impact event [7]. The black lithology is characterised by lithic fragments consisting mainly of plagioclase and noritic rocks. The grey lithology is dominated by granitic material, which forms a skeletal intergrowth of silica and K-feldspar [7]. Based on the observation that both lithologies show reaction of clasts with the matrix and plastic deformation, Quick et al. [7] interpreted the breccia as having formed at high temperatures around 990-1100 °C.

Analytical methods: U-Pb analyses were conducted using the CAMECA IMS1280 ion microprobe at the NordSIMS facility, Swedish Museum of Natural History, Stockholm. The analytical protocol and SIMS methodology followed a similar procedure as published elsewhere [e.g. 8]. In all analytical sessions, the U-Pb ratios in phosphates were calibrated against the 2058 Ma apatite crystal BRA-1, whereas zircon analyses were calibrated against the 1065 Ma zircon crystal 91500. The mass filtered 16O2 primary ion beam (with intensity between 0.7 and 2.0 nA for phosphates and 1.5 and 3.4 nA for zircon) was reduced through Köhler apertures of 50 and 100 μm to obtain spot sizes of 5 and 10 μm, respectively. A 12 μm square area was pre-sputtered for 70 seconds before each phosphate analysis, and an area of 20-25 μm was pre-sputtered for 80 seconds for the zircon analyses. In the following, all individual results and weighted average calculations are presented at 2σ uncertainty.

U-Pb results: The Ca-phosphates yielded an average 207Pb/206Pb age of 3924±3 Ma (n=29, MSWD = 1.2, P = 0.22). The observed age homogeneity of individual Ca-phosphates, regardless whether they occur within the grey or black part of the breccia, indicates complete resetting of the U-Pb system during the last thermal event. Contrary to this, zircon grains located within the grey lithology exhibit a spread of 207Pb/206Pb ages from 4154±7 Ma to 4308±6 Ma and zircon grains analysed within the black part of the breccia yielded a range of ages from 4123±13 Ma to 4328±14 Ma. Similar results for zircons within thin section 12013,6 were obtained by Zhang et al. [4].

Textural relationships and microstructures:

Grey lithology: Zircon grains located within the felsite most likely crystallised during a single crystallisation event. However, the observed age range from 4154±7 Ma to 4320±6 Ma (this study and [4]) implies disturbance of the U-Pb system. While Zhang et al. [4] interpreted these ages as several impact events, we suggest variable Pb loss during a single event as an alternative interpretation. Firstly, several grains form a mineral assemblage with iron-titanium oxides, indicating that these grains are co-genetic. Nevertheless, zircon ages within this assemblage range from 418±14 Ma to 4306±16 Ma and the simplest explanation is partial resetting of the U-Pb system induced by a single impact event. Moreover, the grains have rounded irregular boundaries and several small (~5 μm²) zircon patches surround the larger grains indicative of dissolution and solid state reaction (Fig. 1). During this process the U-Pb system was open for Pb diffusion, which led to variable Pb loss and resulted in the spread of ages.

Black lithology: Zircon grains within the black lithology occur as fragments in the matrix and thus, lack information about their source rocks. Therefore, the observed age range from 4005±20 Ma to 4328±14 Ma (this study and [4]) may be interpreted as different crystallisation ages. Some grains are characterised by CL features such as oscillatory and...
sector zoning, which are usually taken as an indicator for magmatic crystallisation. Nevertheless, at least two grains yielded non-identical $^{207}$Pb/$^{206}$Pb ages for different bright and dark CL zones [4], which suggest that these grains also experienced partial and variable Pb loss. Furthermore, one grain exhibits a bright CL spot at the edge, which might imply recrystallisation and thus, could facilitate Pb diffusion. Another grain has visible planar deformation features (PDFs) in the CL image and the BSE image reveals subsequent thermal annealing. PDFs are seen as pathways for Pb diffusion and thus, enable variable and partial resetting of the U-Pb system.

**Th-U concentrations:**

Grey lithology: The U contents of zircon grains within the felsite vary from ~200-1500 ppm and Th concentrations from ~800-1100 ppm, and there is a correlation between U and Th concentrations (Fig. 2). Moreover, the Th/U ratios plotted against the U content shows a systematic behaviour. These observations support the interpretation that these grains are cogenetic (i.e. crystallised at the same time from the same melt). However, U and Th content as well as the Th/U ratios decrease within the younger grains, which can be taken to indicate that U and Th were partly mobilised in the grains most affected by Pb loss.

Black lithology: In general the U and Th concentrations are lower when compared to the zircon grains within the felsite. The U content varies from ~20-340 ppm and the Th content from ~10-250 ppm. Only a few grains have similar U concentrations to the felsite zircon but these grains also have higher Th concentrations, resulting in higher Th/U ratios. These findings imply a different origin from zircon grains that crystallised in the felsite.

**Conclusions:** Zircon grains located within the grey lithology are interpreted as having formed during one crystallisation event. The observed spread of individual $^{207}$Pb/$^{206}$Pb ages of ~170 myr is thus suggestive of partial Pb loss. This interpretation is supported by characteristic microstructures like dissolution of some of the grains and recrystallisation. During these processes, the U-Pb system was opened for Pb diffusion. Moreover, the Th and U concentrations appear to decrease systematically with decreasing $^{207}$Pb/$^{206}$Pb ages. Based on these findings, only the oldest $^{207}$Pb/$^{206}$Pb age of 4308±6 Ma can be taken as minimum crystallisation age for the felsite. The thermal disturbance that led to the variable resetting is dated by the Ca-phosphates to 3924±3 Ma. Zircon grains within the black lithology also exhibit a spread of ages of ~300 myr and a few grains have microstructures (PDFs and recrystallisation) which might function as Pb pathways and lead to partial Pb loss. However, based on the observed general intra-grain age homogeneity and the fact that these grains occur as individual fragments, the majority of grains might have kept their original crystallisation ages. Whether these zircon grains originated from the same source rock or have different origins remains unknown.

As shown in this study, the disturbance of the U-Pb system in zircon can result in variable resetting, which, if not detected, may lead to a misleading and meaningless distribution of U-Pb zircon ages. Hence, the interpretation of zircon U-Pb ages requires full understanding of processes that might disturb the U-Pb system and cause a scatter of U-Pb ages. It is crucial to investigate which conditions lead to Pb diffusion and partial resetting of the U-Pb system.

**References:**

TARGET PROPERTY EFFECTS ON CRATER SIZE-FREQUENCY DISTRIBUTIONS REVEALED AT THE KING CRATER IMPACT MELT DEPOSIT. C. H. van der Bogert1, H. Hiesinger1, C. Dundas2, T. Krüger3, A. S. McEwen1, M. Zanetti1, and M. S. Robinson4. 1Institut für Planetologie, Westfälische Wilhelms-Universität, Wilhelm-Klemm-Str. 10, 48149 Münster, Germany (vanderbogert@uni-muenster.de); 2USGS Astrogeology Science Center, Flagstaff, AZ; 3Albert-Ludwigs-Universität, Freiburg, Germany; 4University of Arizona, Tucson, AZ; 5Western University, London, Ontario, Canada; 6Arizona State University, Tempe, AZ.

Introduction: A discrepancy in crater size-frequency distribution (CSFD) measurements between impact melt and ejecta units was observed during the Apollo era, but not understood. CSFDs of impact melt deposits at many Copernican-aged craters give significantly younger relative [e.g., 1-5] and absolute model ages (AMAs) [e.g., 6-10] than the ejecta deposits (Fig. 1). Possible sources of the discrepancy include differing illumination angles, occurrence of subsequent volcanism and/or the formation of endogenic craters, layering within the target, pollution of the primary crater population by distant/field secondary and/or self-secondary craters, and the effects of differing target properties on the size-distribution of the small craters (<~1 km diameter). Understanding the causes of discrepancies in CSFDs of small craters on contemporaneous units is important for ensuring the appropriate use of CSFDs for the derivation of AMAs and understanding their limitations, particularly for young and spatially limited geological units.

Background: The final diameter of an impact crater in the strength regime is affected by target properties, including density, strength, and porosity [e.g., 11-22]. For example, young platy-ridged Martian lava flows exhibiting different surface textures (rough ridged areas and smooth polygonally patterned areas), but thought to be coeval based on similar terrestrial occurrences, exhibit differences in crater diameters on the order of 50% for craters less than 100 m in diameter [23].

On the Moon, the transition from strength- to gravity-controlled scaling begins at ~300 m [5] or ~400 m [15] crater diameters, depending on the material strength (Y), so the transition occurs at larger diameters for targets with higher yield strengths [15]. Crater diameters >10 km are completed gravity-controlled. The crater diameters in between are controlled by a mixture of both strength- and gravity-scaling between the two regimes [e.g., 5, 24]. Target property effects are particularly important for lunar craters <~3 km [5] because these craters form in an increasingly strength-dominated regime.

Approach: We measured the size-frequency distributions of craters with diameters across the diameter range where scaling shifts from strength- to gravity-controlled on the large melt pond northwest of King crater. The largest known melt deposit was selected for this study because (1) measurements on ejecta blankets show significant variability of ambiguous origin(s) [10, 25 and references therein], and (2) large bodies of impact melt likely did not solidify until after the emplacement of self-secondary craters was completed. If target properties indeed have an effect on CSFDs, we would expect the CSFDs of the impact melt units to converge with their respective ejecta units, when gravity rather than target strength

Figure 1. CSFDs in cumulative (a) and relative (b) forms for King crater deposits (blue triangles and black circles [9]; red circles [10]). The Poisson age probability functions for the absolute model age fits show that the two young ages are statistically identical and the two old ages have a >68% probability of similarity (inset, the dark gray portion of each distribution represents ±14%).
plays the dominant role in the determination of the final crater diameter. We also performed pi-group scaling calculations similar to those presented by [23] with lunar parameters to make comparisons between theoretical targets and real lunar melt pond and ejecta characteristics, the details of which are presented in [10] (Fig. 2).

**Results:** A 162 km² portion of the large impact melt pond to the northwest of King crater follow the previously measured impact melt pond isochron [9] at crater diameters <170 m, while crater diameters >~320 m are similar to the ejecta blanket (Fig. 1a). Craters with diameters from 170-315 m transition from the impact melt pond isochron to that of the ejecta blanket of [9]. The R-plot shows that the shift from the younger to the older isochron occurs at crater diameters of 230 – 320 meters (Fig. 1b). The cumulative plot of the impact melt pond measurement by [9] moves off its isochron starting at diameters of ~170 m towards the ejecta isochron. The transition up to the ejecta isochron was not well-constrained in their data set, because the 23 km² count area only contains five craters >~170 m in diameter, whereas our count area is much larger and contains 39 craters >170 m. Absolute model ages determined using Poisson timing analysis exhibit age probability functions showing that the two young ages are statistically identical and the two old ages have a >68% probability of representing similar crater populations (Fig. 1 inset, the dark gray portion of each distribution represents ±34% of the probability function). The likelihood that the data points fit with an age of 930 Ma could instead have an age of 378 Ma is much less than 16%. Given that the impact melt pond can reasonably be expected to yield a single model age, and arguably excludes the effects of self-secondary crater contamination, our results support the occurrence of target contrasts great enough to cause coeval units to give discrepant absolute model ages.

**Conclusions:** Our study shows that coeval materials with differing target properties exhibit discrepant absolute model ages. Because the recent lunar CF [26] is calibrated using CSPDs collected on the ejecta blankets of Copernicus, Tycho, North Ray, and Cone craters, stronger and less porous Copernican-aged units dated using the Neukum et al. [2001][26] chronology give falsely young absolute model ages. This is the case for the discrepancy in ages between impact ejecta and melt units. The ages determined for Copernican-aged irregular mare patches might also be skewed by their target properties, which may be even stronger and/or less porous than the reference mare basalts that have been bombarded for billions of years. If the craters formed on IMPS are systematically smaller than the reference production function, IMPs may be older than previously thought [27]. However, [28] applied a theoretical 50% diameter correction to show that the ages are still late Copernican. We also did not observe target property-related effects on pyroclastic deposits in Taurus Littrow [29].

Target property effects are likely not as pronounced for older than Copernican-aged surfaces, due to the homogenization of the properties via long term bombardment. Also, the PF for 3 Ga and older surfaces is calibrated, not to ejecta blanket surfaces, rather to mare basalt units visited by the Apollo and Luna missions [24]. The chronology has been heavily used to date mare basalt occurrences [e.g., 30], which have similar target properties as the reference units. However, very old target surfaces, including ancient ejecta or highland surfaces could yield ages that are slightly older than the reference mare basalts, as postulated by [5]. Thus, it is important to consider potential target contrasts between study regions when interpreting AMAs.

**References:**

THE EFFECT OF WATER ON THE METAL-SILICATE PARTITIONING BEHAVIOUR OF MODERATELY SIDEROPHILE ELEMENTS. A.R.W. van der Waal1, E.S. Steenstra2, S.M. Luginbühl2, A.X. Seegers2, IL. Ten Kate1 and W. van Westrenen1, 1Faculty of Earth Sciences, Utrecht University, Budapestlaan 4, 3584 CD Utrecht, The Netherlands (a.r.w.vanderwaal@students.uu.nl), 2Faculty of Earth & Life Sciences, Vrije Universiteit Amsterdam, Netherlands.

Introduction: Classic models of Moon formation and early lunar evolution generally assumed that initial differentiation occurred in essentially dry circumstances [1-3]. However, hydrogen has been found bound to various lunar minerals and in olivine melt inclusions on the lunar surface [4-7]. Early lunar differentiation models are partly based on the partition coefficients (D) of siderophile elements, a common method to study core formation conditions during the early evolution of terrestrial bodies [8-11]. Quantifying partitioning behaviour relies strongly on constraining the effect(s) of pressure (P), temperature (T), oxygen fugacity (fO2) and composition (X) on partitioning. Water is known to affect silicate melt properties and thus may also affect D [12]. Previous work based on a relatively small number of elements and experiments has suggested that the effect of water on metal-silicate partitioning is negligible [13,14]. Here we quantify the effect of water on the partitioning behaviour of moderately siderophile elements (P, W, Ge, Ni, Mo, Sn, V, Cr, Cu and In) at high pressure and temperature.

Approach: Experiments were conducted in an end-loaded piston cylinder press at 1 GPa and temperatures between 1400-1600°C using either AuPd (1400-1450°C) or Pt (1500-1600°C) capsules with a graphite inner capsule. These were loaded with a mixture of a synthetic basaltic composition [15] and a Fe-metal plus trace element powder. The water was introduced in to the silicate fraction in the form of Al(OH)3 to attain either 2 or 4 wt% H2O. To trace the water we doped the sample with 2000 ppm Cs as a tracer for the water and used the H/Cs ratio [16]. Run times were sufficient to attain equilibrium. Next the samples were mounted in epoxy, polished and analysed for major and trace elements with EMPA and LA-ICP-MS. Carbon contents in metal were determined using an online metal activity calculator [8].

Partitioning systematics were determined using multivariate linear regression [8-11]. Instead of D, we use the exchange coefficient K_D which corrects for variable fO2. The valences we use for K_D calculations are +1 for Cu, +2 for Ge, Ni and Cr, +3 for V and In, +4 for Sn, Mo and W and +5 for P. Metal blobs are all C-saturated due to the use of graphite inner capsules. Thus we assume the effects of C to be similar for all samples and ignore it in calculations. Therefore, a regression is made of log(K_D) against T, ΣX, and OH⁻ content to assess their effects on K_D. A variable is deemed to have an effect if F < 0.05 during regression.

Results: The run products show well segregated metal blobs within in a homogeneous silicate melt (Fig. 1). In some samples degassing textures are observed indicating that water was retained during the experiment. This is further supported by the H/Cs ratios which indicate that around 80% of the water is recovered at the end of the experiment. The hydrogen will mostly be present in the form of OH⁻ and minor amounts of H₂ and CH₄ which forms due to interactions between the H and graphite capsule [17].

Temperature: Temperature effects on K_D are observed for W, Ge, Ni, V, Cu and In. We find that V and W become significantly more siderophile while Ge, Ni and Cu become less siderophile with increasing temperature. These observations are in partial agreement with previous studies [9-11]. They also report more siderophile behaviour for Cr and P as a result of temperature which we do not observe.

Water content: Water is shown to have an effect on the partitioning behaviour of P, W, Sn, V and Cr (Fig. 2). We find that W becomes more siderophile while P, Sn, V and Cr become less siderophile with increasing OH⁻ content. Ni, Cu, In, Ge and Mo are unaffected (Fig. 3). This is in partial agreement with [14] who had similar results for Ni and Mo, but report more siderophile behaviour with increasing OH⁻ for P and find that W is unaffected by OH⁻. [13] report Ni, Ge and P becoming slightly and W signifi-
cantly more lithophile in a hydrous environment which also does not fit our observations.

**Discussion:** Comparison of data obtained for dry, 2 and 4wt% H₂O indicates that there is an effect of water on the siderophile element partitioning of P, W, Sn, V and Cr. The data shows that the K₀ values may differ between ±0.1-0.4 log units per wt% OH added. Based on modelling of the richness of the lunar plagioclase-rich crust, it is estimated that the lunar mantle contained between 270-1650 ppm H₂O [18], or up to 1.56 wt% OH. This may generate an offset of K₀ values up to 0.65 log units. Based on modelling of the thickness of the lunar plagioclase-rich crust, it is estimated that the lunar mantle contained between 270-1650 ppm H₂O [18], or up to 1.56 wt% OH. This may generate an offset of K₀ values up to 0.65 log units. This water content is significantly higher than that found in lunar surface rocks [4-7] indicating that water was lost from the lunar interior at some point. Since the Moon partially degassed, the values found in lunar rocks must represent the lower bound [19] implying that OH concentrations must have been higher during the early stages of lunar evolution. This implies that the effect of water on the partitioning behaviour of these elements used to be larger in the past which may have significant implications for the validity of lunar evolution models that assume a dry Moon. Of course, it is also possible to use these K₀ values to model other terrestrial bodies known to contain a hydrous component of some form such as Mars or Vesta.

**Conclusion:** Our data suggests that water may have a significant effect on the exchange coefficients of multiple siderophile elements. It increases K₀ for W and decreases it for P, Sn, V and Cr. Therefore it should be taken into account when modelling core formation processes on terrestrial bodies containing a hydrous component.

MINERALOGY OF FARSIDE LUNAR BASALTS: A REMOTE SENSING PERSPECTIVE

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Introduction: The mineralogy of volcanic basalts in the feldspathic highland terrane (FHT) of the lunar farside is poorly understood despite the availability of high spatial and spectral resolution datasets. Understanding the composition of the farside basalts would further increase our insights into lunar volcanic history. In this study the Chandrayaan-1 Moon Mineralogy Mapper (M3) datasets are used to determine the spectral properties of selected lunar farside volcanic units by deriving spectral parameters such as band centers and integrated band depths from their corresponding reflectance spectra.

Study Regions: The studied farside FHT volcanic areas include Campbell crater (45°N, 152°E), Buys Ballot crater (21°N, 175°E), Dewar crater (2.7°S 165.6°E), Humboldt crater (27.2°S 80.9°E), Kohlschutter crater (15°N, 154°E), Mare Moscovienne (27°N, 148°E), Tsiolkovsky crater (20.4°S 129.1°E), Compton-Belkovich (61.1°N, 99.5°E) and two lacus bodies, namely Lacus Luxuriae (19°N, 176°E) and Lacus Solitudinis (27.8°S 104.3°E) (Fig. 1).

Datasets used: The Chandrayaan-1 Moon Mineralogy Mapper (M3) Level-2 hyperspectral datasets are used to study the reflectance spectra characteristics [1,2] and to derive spectral parameters such as band center at the absorption centers and the integrated band depth ratio. These datasets are corrected for their optical and thermal effects; however residual thermal effects could be expected in the longer wavelength end of the spectra (say, beyond 2.5 µm) [3]. The crater sizes chosen for the spectral studies are measured using the LROC Actreact Quickmap weportal. The thorium abundances of the study regions were derived using the Th elemental maps of the Lunar Prospector (LP) Gamma-Ray Spectrometer (GRS) ‘thorium_halfdeg’ data, downloaded from the PDS Geoserver Node. The LP GRS Th-abundance datasets used in this study have a spatial resolution of 0.5° x 0.5° pixels (Fig. 2).

Derivation of spectral parameters: All the spectral parameters are calculated from the continuum-removed spectra with offsets at 699 nm and 1578 nm for 1 µm absorption and near 1578 nm and 2538 nm for 2 µm absorption feature. The band center near the absorption band centers at 1 µm (BC1) and 2 µm (BC2) is derived by fitting a 2nd order polynomial at the end of the curve and the minima of the curve corresponds to the band center of the absorption feature. The integrated band depth ratio (IBDR) is defined by the ratio of the integrated band depth at 2 µm (IBD2000) to the corresponding 1 µm (IBD1000) where IBD1000 and IBD2000 are defined in [4, 5].

Methodology: As we focus on mare volcanic deposits in the study, the major mafic minerals that could be identified in the M3 spectra are olivine and pyroxene. The unique absorption feature near ~1000 nm for olivine and the two spectral absorptions at ~1000 nm and ~2000 nm for the pyroxenes can be studied by deriving spectral parameters such as band center of their absorption feature and the integrated band depth which shows the strength of absorption feature. The spectral parameters are compared using the graphical plots between the BC1-IBDR to identify the proportion of olivine-pyroxene mixture in the spectra [5, 6]; and the BC1-BC2 are compared for studying the nature of pyroxene [7, 8]. These plots not only show the characteristics of the olivine and pyroxene but also show other effects such as mixture of Fe-glasses, the dominant cations in the mineral, and also spinel inclusions if present [9]. The spectral parameters such as band center and...
integrated band depth are derived from the reflectance spectra of small fresh craters in the respective mare field. The fresh craters expose the bedrock mineralogy, and additionally the freshness of the crater wall and ejecta of these small craters minimizes the optical maturity effects induced in the spectral properties. Thus the spectral plots along with the characteristic reflectance spectra of the mare volcanic deposits in the study regions are used for the comparative mineralogy assessment which will therefore help in understanding the style and nature of lunar farside volcanism.

**Results:** The spectral behavior of the studied farside basalts is discussed in terms of their average spectral parameter plots for BC1-IBDR (Fig. 3a) and BC1-BC2 (Fig. 3b). The farside lunar magma compositions can be divided into five mineralogical classes, namely augitic/cpx (Buys-Ballot, Lacus Luxuriae), intermediate/opx-cpx mixtures (Lacus Solitudinis, Humboldt, Tsiolekovsky, Kohlschutter), noritic/opx (Campbell, Dewar), dunitic (largest sampling crater of Lacus Luxuriae), rhyolitic (Compton-Bellkovich).

A key result of this work is the discovery of a unique dunite-type lithology excavated by the largest crater in the Lacus Luxuriae region (diameter ~2424 m excavating material from a depth of ~240 m deep) which is shown by large yellow triangle in Fig. 15. The possible deepest region excavated by this largest crater could potentially expose a very ancient pluton. The BC1-IBDR plot (Fig. 3a) shows that this data point lies in the olivine-enrichment zone, and the BC1-BC2 plot (Fig. 3b) clearly shows that the data point lies above the pyroxene region. As olivines have the largest band center near 1 µm with no absorption near 2 µm region, the spectral plots clearly distinguish this crater from all other study regions.

**Conclusions:** The spectral plots denoting the derived spectral parameters such as band centers and integrated band depth ratios, along with the characteristic reflectance spectra of the volcanic deposits in the study regions, were used for the comparative spectral, spatial and temporal assessment of farside lunar volcanism. The various magma compositions contributing to the lunar farside volcanism are reported for the first time. Future work will concentrate on combining the spectral behavior of lunar nearside and farside basalts in order to understand the collective behaviour of lunar volcanism in a global setting. The study reveals significant spectral heterogeneity within the FHT basalts, indicating varying magma compositions on the lunar farside for over ~1 Ga (i.e. >3.8-2.7 Ga) of lunar history. Future work will focus on the comparative spectral mapping of lunar basalts in the nearside of the Moon which have an absolute age of ~2.7-3.8 Ga with that of the farside basalts; this would help us to understand the role of crustal thickness, crustal mixture with the basaltic extrusions, Th-dependent volcanic activity, and possible depth of source regions.

**References:**
LABORATORY SPECTROSCOPY OF LUNAR ANALOGUE SOIL. H. C. Vos\(^1\), A. Kołodziejczyk\(^1\), M. Harasymczuk\(^1\), J. Vago\(^1\), B. H. Foing\(^1\), IESA/ESTEC, Postbus 299, 2200 AG Noordwijk, NL (heleen_c_vos@hotmail.com), \(^3\)ILEWG, \(^3\)Vrije Universiteit Amsterdam.

Introduction: Several measurements of Moon analogue soils were performed in the UV/VIS spectrum using a USB4000 spectrometer. The goal of these analyses was to determine the detectability of minerals, elements and rock types that are also known to be present on the lunar surface. Especially the detectability and quantification of TiO\(_2\) and iron and the spectrum of pyroxene, ilmenite were studied since these elements and minerals are known to influence the visible spectrum of the Moon [1-3]. By creating a database of relevant minerals and rock types we can contribute to the interpretation of the spectrum of lunar regolith.

Method: The analyses were performed using the USB4000 in a dark environment as a continuation of previous studies [4]. The fibre of the USB4000 transmitted between 188 and 888 nm, making it possible to measure between the wavelengths. As a light source an incandescence light source was used. However, this lamp did not emit enough UV light to obtain useful data from the UV spectrum. The integration time for the measurements was 200 milliseconds and the number of scans to average was 20. A dark spectrum was measured before every sequence and the reference spectrum was determined before every measurement.

The USB4000 spectrometer is a relatively small spectrometer. The size makes it mobile and suitable to use in the field and on a lander or a rover. However, there are clear restrictions in using this spectrometer for measurements, the first restriction being the fact that a VIS spectrum gives very limited information about a surface compared to an infrared spectrum. One of the minor objectives of this study was to determine what the best conditions are for performing measurements on this spectrometer as a continuation of earlier research [2]. Examples of such parameters are the scans to average, the integration time, operations and the light source.

Results: In total 21 different minerals and rocks were measured and analysed. Figure 1 shows the spectrum of pyroxene and ilmenite samples. Figure 2 shows the 415/750 ratio versus the 502/750 ratio which is known to correlate with the TiO\(_2\) and ilmenite content and are similar to ratios that have been used to analyse lunar surface [1-3]. However, this is only one example of the many distinction methods possible to analyse this data and use it as an analogue reference material.

The data that was obtained can be used for further analyses and comparison with lunar spectra. Because of accurate and comprehensive quality of the data these spectra are very suitable to create a calibration method. Expanding the database with more samples and data from the NIR and IR spectrum could contribute to further lunar surface analyses.

IS THERE CORRELATION BETWEEN GRAVITY SIGNATURE AND AGE OF LUNAR BASINS?
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Introduction: Impact craters are the most prominent landforms on the Moon over a wide range of scales. We focus on craters with diameters larger than 200 km, so-called lunar basins. Studying the characteristics of the basins, information about the early evolution of terrestrial planets can be obtained. They provide insights about the distribution, mass, and timing of the late accretion flux in our solar system. Furthermore, by investigating their formation, we are able to learn more about the state of the Moon during this time.

The Gravity Recovery and Interior Laboratory (GRAIL) mission provided high-resolution gravity data (spherical harmonic models up to degree and order 1200) of the complete Moon for the first time. Gravity is complemented by a topography model, which was obtained by the laser altimeter (LOLA) on board of the Lunar Reconnaissance Orbiter (LRO). By combination of the gravitational data and topography, we are able to revise characteristics of the basins described in former studies [1], which were based on data with low accuracy and resolution. Utilizing the most recent data, we will set up a new inventory with reprocessed relevant features.

Gravity signature as an evidence of age? Based on the studies by Neumann et al. [2] we investigated the relationship between the gravity signatures of lunar impact basins and their relative ages.

Bouguer gravity anomalies of lunar basins reveal a center peak, which is similar in size to the innermost topography ring. Further out from this ring a depression in Bouguer anomaly can be found, which extends to the rim crest. The Bouguer anomaly contrast is defined as the difference between the maximum gravity signal in the center and the lowest signal towards the rim crest. A correlation between size of an impact basin and the Bouguer anomaly contrast has been demonstrated [2].

We wish to test if Bouguer anomaly contrast correlates with age: material, which has been reshaped during an impact process, is expected to relax and assume isostatic equilibrium for basins of given scale, if appropriate thermal conditions and sufficient time are available. Since the crust and the upper mantle of the Moon were much warmer in the past and thus less viscous, structures, formed during an impact, probably relaxed fast. For later events, when the interior was colder and therefore more viscous, these structures probably relaxed more slowly. Furthermore, basins which had been formed earlier had more time to relax than younger basins. In both cases a lower Bouguer anomaly contrast could be associated with an older age, a more pronounced contrast to a younger age.

We used the Bouguer anomaly contrast given by Neumann et al. [2] and normalized them for rim-to-rim basin diameters. We sorted the basins by the normalized anomaly contrast and compared contrast with basin ages [3][4], determined from crater statistics. However, no correlation was found. Since the crustal thickness may play a role regarding thermal conditions and the speed of relaxation, we used crustal thickness maps [5] to split the basins in different groups, which we investigated separately. But also for this approach no correlation was found.

Discussion and Outlook: We suggest that additional factors like a difference in thermal conditions or variations in thickness of mare fill must contribute to the gravity signature of lunar basins. This may affect basin relaxation in complicated ways. Possible errors in estimated rim diameters, which were used for normalizing the Bouguer anomaly contrast, may also impact our results. Besides, our basin inventory may not be complete, a fact which will introduce biases in our statistics. All of these factors make an age determination of impact basins by considering gravity signature alone difficult.

For a deeper understanding of the formation of lunar basins and the conditions which prevail on the Moon during this time we will study basin candidates in more detail. We start our investigation with revisiting the basin inventory under new perspectives. We begin with the working list of Wood [1]. Since the topography of lunar impact basins is often highly degraded due to subsequent cratering or erosion, especially older basins are difficult to recognize. The high-resolution gravity field offers new possibilities to identify lunar basins: on one hand, subsurface structures are typically not affected by events happening on the surface. Thus, also the oldest, most degraded basins can be investigated. On the other hand, during the basin formation mantle material was lifted up, causing a pattern of positive anomaly in the center, surrounded by a depression in gravity signature towards the rim crest, where crustal material was removed [1]. This new finding can be used for recognizing impact basins and defining their individual properties.

For basin candidates we calculate gridded data from LOLA tracks and create small topographic maps. Likewise, we compute maps of the corresponding free-air gravity anomalies using coeffi-
ponents of the Goddard Space Flight Center (GSFC) Lunar gravity field GRGM1200A obtained from the Planetary Data System (PDS). Figure 1 shows a topographic map of Orientale basin with a spatial resolution of approximately 400 m (top) and the corresponding free-air anomalies, with a grid size of around 7 km (bottom). Correlations between topography and free-air anomalies are apparent. As a next step we will use the free-air anomalies and the topography for re-calculating Bouguer anomalies, which will be the basis for further investigation. By re-calculating the Bouguer anomalies we are able to test different crustal densities for individual basins and validate the data used in the present work.

**Conclusion:** With the most recent data from GRAIL and LRO missions we are able to take a fresh look on lunar basins and their characteristics. High-resolution gravity data may help in the identification of basins and may give new constraints for impact simulations. No correlation could be found between the gravity signature and relative ages of lunar basins.


While former criteria for basin identification were mainly based on topography, like the existence of a rim bounding a circular topographic depression [4], today, gravity structures can be used for recognizing impact basins. Our plan is to develop an algorithm, which identifies basin structures and assesses their probability independently from visual judgements.
EXTRACTION OF LUNAR CRATER POPULATION ON APOLLO 17 LANDING AREA USING HIGH-RESOLUTION LROC-NAC DTM. Jinfei Wang1,2, (jfwang@uwo.ca), Radu Dan Capitan1 (rcapita@uwo.ca), Ian Pritchard1,2 (ipritch@uwo.ca), and Stooke, P.J.1,2 (pjstooke@uwo.ca), 1Department of Geography, Western University, London, ON Canada, 2Center for Planetary Science and Exploration (CPSX).

Introduction: Crater extraction from stellite imagery and DEMs provides useful tools for interpreting the stratigraphic constraints and ages of extraterrestrial surfaces [1]. As crater population within a given region of interest can be quite large due to improved resolution, the search for a fully robust and scale-invariant automated crater detection algorithm (CDA) has led to the creation of a variety of creative systems for such purpose. Nonetheless, the applicability of automatic crater extraction procedures on high-resolution datasets has never been tested for the lunar surface. Such a testing would imply comparison to manual crater extraction procedures over the same area to infer about accuracy and finally to draw conclusions about Standard Frequency Diameters (SFD) ages. This is necessary for improving the crater extraction systems and interpreting the results.

Method: The automatic crater detection routine was run on the LROC NAC DEM elevation data, with a spatial resolution of 5 meter/pixel, for the area located within Apollo 17 landing site (Red square, Figure 1). The AutoCrat system [2,3] is a two-step crater detection process. This first portion output all basins in the landscape, without yet weeding out the non-craters (Figure 2).

Figure 1. Location of study area in Taurus-Littrow Valley, Moon. LROC-NAC DTM is draped over WAC nearside mosaic 100/pixel imagery (Source:NASA/LROC imagery)

Furthermore, the second part of the algorithm uses machine learning software to remove any non-craters using a training set [4]. Future work will include the second part of the automatic algorithm.

The second method of crater extraction involves manual extraction of craters using CraterTools in ArcGIS 10 software as described by [5]. Here, instead of using visual imagery to extract craters, we used the same DEM rasters used by automatic procedure, and computed derivates (slope, aspect) for visualization enhancement (Figure 3). We then plotted the ages derived by the manual procedure below the correspondent DEM rasters.

Figure 2. Automatic crater extraction using crater rim delineation through a rule-based approach [2]. Image width is 3 Km.

Preliminary Results: As expected, the detection results were heavily dependent on the terrain type [7] and the general gradient of altitude, which here has a clear eastward slope.

In an initial detection algorithm provided here medium-size craters were best extracted, whereas a number of double detection is visible (Figure 2). Manual extraction has the disadvantage of being time-consuming but the pros are the ability to extract craters more accurately within an acceptable size of the test area (Figure 3).
Manual extraction of craters using DEM/aspect/slope superposed rasters in ArcGIS 10.4 and CraterTools extraction procedure [4]. SFD age plot of the area indicating a young cratering resurfacing in the Apollo 17 landing area.

**Interpretation:** As expected, the detection results were heavily dependent on the dataset resolution and the capacity of the algorithm to detect depressional areas. Manual crater extraction from DEM and derivative rasters rely on the researcher’s ability to detect especially the small-size craters.

While the automatic procedure is still foreseen to reflect better the relationship between crater retention and formation age for this marginal Mare Serenitatis depression (i.e., after the application of the second step algorithm data will become available), the manual crater extraction depict better the subsequent cratering resurfacing due to small crater accumulation in post-LHB era [6,9], and described here in SFD, Figure 3, ~80 Myr isochron (i.e., crater resurfacing).

Further sampling in the Taurus-Littrow depression is needed to strengthen the pros and cons of both procedures. Comparative evaluation of crater detection procedures within small areas at high-resolution LROC DEM datasets is needed to to provide an assessment of the quality of crater extraction [10], and draw conclusions on the ages that are described by the bulk of cratering detected by either method.

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**Figure 3.** Manual extraction of craters using DEM/aspect/slope superposed rasters in ArcGIS 10.4 and CraterTools extraction procedure [4]. SFD age plot of the area indicating a young cratering resurfacing in the Apollo 17 landing area.
INVESTIGATION OF LUNAR SPINELS AT SINUS AESTUUM. C. M. Weitz\(^1\), M. I. Staid\(^1\), L. R. Gardis\(^2\), S. Besse\(^3\), and J. M. Sunshine\(^4\), \(^1\)Planetary Science Institute, 1700 E Fort Lowell, Suite 106, Tucson, AZ 85719 (weitz@psi.edu), \(^2\)Astrogeology Science Center, U. S. Geological Survey, 2255 N. Gemini Drive, Flagstaff, AZ 86001; \(^3\)Camino Bajo del Castillo s/n, Ur. Villafranca del Castillo, 28692 Villanueva de la Canada, Madrid, Spain; \(^4\)Dept of Astronomy, University of Maryland, College Park, MD.

Introduction: Recent remote sensing observations by the Moon Mineralogy Mapper (M\(^3\)) on the Chandrayaan-1 spacecraft and the Spectral Profiler (SP) on the SELENE Kaguya orbiter have identified spinels in numerous locations across the Moon [1-3]. The Mg-rich spinels have a prominent 2 µm absorption and lack any 1 µm absorption, which allows them to be identified and distinguished from other lunar materials. SP data analyzed by [3] was used to identify a visible-wavelength absorption feature around 0.7 µm along with a strong 2 µm absorption only at Sinus Aestuum (SA). They attributed the 0.7 µm feature to the presence of a Fe- or Cr-bearing spinel rather than the Mg-spinel more commonly identified on the Moon [2]. The Fe- or Cr-rich spinels in the SA region are associated with widespread, dark pyroclastic deposits [1,3,4].

In this study, we analyzed M\(^3\) data for spinel locations at SA, and then examined visible images from the Lunar Reconnaissance Orbiter (LRO) Narrow Angle Camera (NAC) and Wide Angle Camera (WAC), as well as the Kaguya Terrain Camera (TC) and Multiband Imager (MI) images to correlate these spinel signatures to surface morphologic features. We extracted M\(^3\) spectra of several spinel locations and attempted to understand what was creating the signatures throughout SA. Finally, we examined the locations where SP data showed visible-wavelength features in the spinel spectra and compared them to locations where M\(^3\) data showed a 0.7 µm feature.

Observations: We identified the strongest and largest spinel signatures in widespread sites across the highlands and some mare of Sinus Aestuum (Fig. 1, where green circles indicate that a 0.7 µm absorption is present and blue circles mark sites with a weak or no 0.7 µm signature). We then examined WAC, NAC, and Kaguya TC visible images for these spinel locations. In all cases, we identified an impact crater in association with the spinel signature (Fig. 2). The crater diameters ranged from ~100 m to ~4 km, which corresponds to transient crater excavation depths of ~25-1000 m [5,6], although for the larger craters (i.e., >1 km diam.) the spinels were observed along the upper crater walls rather than in the ejecta, suggesting shallower depths for the spinels. The majority of spinel deposits are associated with DMD on the highlands. Nine of the circles correspond to small impact craters with spinel deposits that are on the highlands but not associated with any obvious surface exposures of DMD. The remaining spinels are found in association with craters on the mare.

Figure 1. Sinus Aestuum spinel-rich sites. (a) M\(^3\) mosaic showing the 2 µm integrated band depth (IBD) ratioed to the 1 µm IBD. The areal extent of the DMD on the highlands is noted by the yellow line. White circles represent locations where [3] identified spinels with visible-wavelength signatures in Kaguya SP data. (b) Color M\(^3\) mosaic (R=1 µm IBD, G=2 µm IBD, B=700 nm IBD). White arrow identifies a mare pond in the SA highlands. (c) Color ratio MI MAP mosaic (R=750/415 nm, G=750/950 nm, B=415/750 nm) merged with WAC basemap mosaic.
The main morphologic difference between those craters that exhibit the strong 0.7 µm absorption and those that do not appears to be in the freshness of the crater appearance, although there are exceptions. Our observations are consistent with a spinel deposit of variable thickness and a widespread, heterogeneous distribution, with likely variable ratios of mixtures of spinel and DMD within the highlands regolith.

We identified several larger (>1 km diameter) highland impact craters that exhibit spinel signatures along the interior crater rim but not in the ejecta. The spinel is best identified in fresh exposures of the regolith, such as along the crater interior walls where mass wasting on the steeper slopes exposes immature regolith containing the spinels. For all these craters, there is no obvious source layer for the spinel observed along the crater walls.

We identified nine larger spots in Figure 1 where we found a spinel signature in the highlands but outside of the mapped DMD. Examination of NAC and TC images for these nine locations showed a small (100–400 m diameter) impact crater associated with the spinel signature. The remaining spinel spots are associated with four larger (3.5-11 km diameter) impact craters (Gambart B, Gambart G, Gambart L, and Schroter D) and one smaller crater (350 m diameter) in the mare. All four larger craters have low reflectance debris along portions of their interior walls that corresponds to the spinel signatures. The dark spinel-bearing materials are observed starting near the top of the walls and spread down to the crater floors. There is no obvious layer or bedrock within the crater wall that appears to be the source for the spinel. Spectra taken from the crater surroundings show remnant highland materials are present within the mare, and it appears that the spinel signatures actually occur in highland materials rather than in the mare.

We also examined all thirty-seven spots from [3] in our M\textsuperscript{3} data. Most of the SP sites are only 1-2 SP pixels across, which equates to <100 m in size. A search for these small SP sites in M\textsuperscript{3} data did reveal possible corresponding spinel detections within the latitude and longitude range listed in Table S1 of [3]. In contrast, SP data did not find all the M\textsuperscript{3} detections of spinels with 0.7 µm features.

**Discussion:** Our new M\textsuperscript{3} results indicate that Fe- or Cr-spinels with 0.7 µm absorptions are mixed into most of the DMD across the Sinus Aestuum highlands. The discrepancy between spinel detections made by SP and M\textsuperscript{3} is simply a function of the more limited spatial distribution of the SP data compared to M\textsuperscript{3} data across the SA region. Consequently, our M\textsuperscript{3} analysis provides a more comprehensive understanding of the spinel distribution at SA. The M\textsuperscript{3} spectra extracted from spinel-rich locations show a visible-wavelength absorption, consistent with the SP results, although the location and width of the visible signature varies. Not all spinel spectra exhibit a strong visible-wavelength absorption, especially those spectra taken from slightly older craters.

The spinel deposits are strongly correlated to the distribution of pyroclastic deposits, indicating the two materials were most likely emplaced together as part of an explosive volcanic deposits. The spinels may have formed in the same magma chamber that produced the pyroclastic beads, or the spinels may reside in a pluton at depth that was assimilated into the magma as it made its way to the surface.

Although the spinels and pyroclastics may have once existed as a homogeneous deposit on the highlands, mixing by craters and regolith development over billions of years has created a heterogeneous distribution of both spinels and pyroclastics within the highlands of SA, and buried the deposit beneath younger lava flows on the mare. All the strongest visible-wavelength features in M\textsuperscript{3} data correspond to the freshest-looking craters, although there are examples of young fresh craters in the highlands that do not display a spinel signature, consistent with a heterogeneous distribution of spinels within the highland soils.


**Fig. 2.** Colored circles identify craters that have strong spinel signatures. (a) M\textsuperscript{3} 2 µm IBD divided by the 1 µm IBD ratio image. (b) NAC mosaic with images taken at high incidence angles and (c) small incidence angles.
A GEOPHYSICAL MONITORING STATION FOR ROBOTICALLY DEPLOYED NETWORKS
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\textbf{Introduction:} This paper presents a geophysical monitoring station for future lunar seismic surveys which has been developed within the frame of the Helmholtz alliance \textit{Robotic Exploration of Extreme Environments} (ROBEX). The concept for this station is inherited by DLR’s Mobile Asteroid Surface Scout (MASCOT), currently enroute to its target asteroid on-board JAXA’s Hayabusa 2 mission \cite{1}.

\textbf{Monitoring station and application:} This monitoring station is a highly integrated instrument carrier with dimensions of 340mm x 240mm x 200mm and a mass of ~10kg (Fig.1). Its intended lifetime is up to several weeks. The modular design \cite{2} enables the accommodation of different payload types and adaptation to various deployment concepts. In the ROBEX reference scenario, the carrier is equipped with a seismometer to serve as a geophysical monitoring station.

![Monitoring station with deployed solar array (top) and interior view with bus and payload compartment](image)

Main elements of the monitoring station are shown in Figure 1: (1) antennas, (2) docking interface to lander, (3) deployable solar array, (4) bus compartment, (5) instrument compartment with self-leveling seismometer, (6) grapple interface to a rover’s manipulator arm. The sensor is a modified Lennartz LE3Dlite Mark III short period seismometer, from which the three geophones and the internal electronics board are re-used. Two variants of seismometer integration are realized for development and test purposes: (i) a more lightweight but fixed installation and (ii) a heavier, more complex but self-leveling housing.

![Opened seismometer housing with geophones and front-end electronics](image)

\textbf{Application scenarios:} The ROBEX lunar reference mission considers two scenarios: (i) seismic profiling: the rover deploys (and picks-up again) the seismic station at several measurement spots along a linear path with increasing distance from an active seismic source. Such an active seismic experiment would help resolve the uppermost subsurface layering of the lunar crust. (ii) Seismic network: Four stations are deployed as a Y-shaped array (Fig 3.) to passively monitor natural seismic activity such as quakes and meteorite impacts, meaning a robotic build-up of a system infrastructure on the Moon.

![High-level view on system architecture, its main elements and Y-shaped array](image)

In both scenarios a medium sized lunar lander with ~1400kg landed mass, and ~160kg payload is assumed to deliver four seismic stations and the roving unit. The Lightweight Roving Unit \cite{3} autonomously deploys the monitoring stations with ground
segment involvement only at check gates to assure and confirm the correct build-up.

Field testing: The key elements Monitoring Station, Rover, and Control Center were deployed on the occasion of a Moon analogue field test conducted near the Laghetto cinder cone on Mt. Etna / Sicily in September 2016. During this field campaign the individual elements were tested in preparation of the end-to-end mission demonstration of the active and passive scenario planned for summer 2017. This early field campaign and additional laboratory tests comprised autonomous rover navigation and vision-based recognition of the seismic payload carrier including robot arm manipulation and handling of the seismometer stations (Fig.4).

Fig.4 – Grasping, handling and deployment tests

Figure 5 shows a deployed station whose seismic data acquisition was commanded by a control center. The telemetry and telecommand (TM/TC) protocol used CCSDS [4] which allow an autonomous sequence for each node.

Fig.5 – Deployed station, test article w/o solar arrays and with fixed seismometer assembly

A 5-kg hammer and an aluminum disk as hammer target were used as active source, as usually done in short distance seismic profiling. Benchmark measurements were made between the telecommanded seismic station and off-the-shelf Lennartz seismometers as reference (Fig. 6). The first seismogram obtained from the monitoring station is shown in Figure 7. It clearly exhibits the signals from the hammer strokes.

Fig.6 – “Active seismic source” during the field-test

Summary: The presented seismic monitoring station is a derivative of DLR’s MASCOT spacecraft concept. It demonstrates technologies necessary for follow-on missions and a science case for future geophysical monitoring missions. Application purpose is either as a stand-alone station or as part of a larger network. Deployment mode is in both cases by robotic means. Intensive laboratory and field-testing of this geophysical monitoring station is in progress to verify and validate the involved technologies and the overall scientific approach.


Fig.7 – Sample seismogram obtained during the field test in September 2016, recording six hammer strokes
NUMERICAL MODELLING OF THE DAYTIME DEPENDENT LUNAR SURFICIAL HYDROGEN AND HYDROXYL COLUMN DENSITIES. C. Wöhler¹, A. A. Berezhnoy², A. Grumpe¹, V. V. Shevchenko²,
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Introduction: Hydrogen on the Moon has been detected in the polar regions based on Lunar Prospector gamma-ray and neutron spectrometer data [1] and based on near-infrared reflectance spectra of the Moon Mineralogy Mapper (M3) instrument [2, 3]. Using M3 spectral reflectance data, the presence of OH can be inferred from the depth of the absorption band at around 2.8-3.0 μm wavelength [3], where a commonly accepted formation mechanism is the adsorption of solar wind protons reacting with oxygen atoms bounded in the surface material (e.g. [4]). An early description of OH absorption depth variations depending on the lunar daytime has been given in [4]. In more detail, such variations have been analysed for the crater Boguslawsky located in the illuminated southern polar region at (73° S, 43° E) in [5] and for the crater Dryden located at a lower latitude in the South Pole Aitken basin at (33° S, 155° W) in [6]. A fundamental description of the physical processes governing the behaviour of H and OH on regolith surfaces has been given in [7]. A refined analysis of H based on Monte Carlo simulations has been undertaken in [8].

This study provides a numerical treatment of the daytime dependent behaviour of the density of lunar surficial H and OH based on an extension of the continuity equation approach suggested in [8]. A comparison with OH absorption depth observations for the lunar craters Boguslawsky and Dryden is provided.

Numerical modelling: In [8] for the temporal behaviour of the number density of the adsorbed solar wind protons the continuity equation
d
\[
d_{\text{OH}} = \frac{F_{SW}}{h} - \tau_{d,\text{H}} n_{\text{H}} - \tau_{\text{react}} n_{\text{H}} + \tau_{p}^{(0)} T \frac{d n_{\text{OH}}}{d t}
\]
(1)
is suggested. The last summand of Eq. (1) is not given in [8], it corresponds to the increase in H density due to photolysis of already existing OH, where the relation \( \tau_{p} = \frac{\tau_{p}^{(0)}}{\cos \bar{\theta}} \) with \( \bar{\theta} \) as the solar incidence angle and \( \tau_{p}^{(0)} = 14 \) h (derived from the sum of experimental rates for quiet sun in [9]) is used. In Eq. (1) \( F_{SW} = F_{SW}^{(0)} \cos \bar{\theta} \) is the solar proton flux with \( F_{SW}^{(0)} = 3 \times 10^{12} \text{ m}^{-2} \text{ s}^{-1} \) as the orthogonal solar proton flux [10] and \( h = 10^{-7} \text{ m} \) as the implantation depth [8], \( \tau_{d,\text{H}} \) is the diffusion (evaporation) time of H, \( \tau_{\text{react}} \) the reaction time of H with O bounded in the surface minerals, leading to the formation of OH, and \( \tau_{p} \) the photolysis (photodissociation) time of OH. For the H evaporation time the Arrhenius law is assumed in [8] according to \( \tau_{d,\text{H}} = \tau_{d,\text{H}}^{(0)} \exp(U_{\text{act}}^{\text{H}}/kT) \) with \( k \) as the Boltzmann constant and \( T \) as the surface temperature. From the considerations in [7, 8] a value of \( \tau_{d,\text{H}}^{(0)} = 4.3 \times 10^{-8} \text{ s} \) can be inferred. For the reaction time \( \tau_{\text{react}} \) it is shown in [8] that \( \tau_{\text{react}} > 10^{5} \text{ s} \) for large \( \bar{\theta} \). A sputtering term mentioned in [8] is considered negligible in that work.

It is proposed (but not analysed further) in [8] to complement Eq. (1) by a second, coupled differential equation describing the temporal behaviour of the number density of OH molecules, consisting of a production term due to reactions of solar wind H with bounded O, an evaporation term and a photolysis term. Here we use the form
d
\[
d_{\text{OH}} = \tau_{d,\text{OH}} n_{\text{OH}} - \tau_{\text{react}} n_{\text{H}} - \tau_{d,\text{OH}} n_{\text{OH}} - \tau_{p}^{(0)} T \frac{d n_{\text{OH}}}{d t}
\]
(2)
of this second differential equation. In Eq. (2), \( \tau_{d,\text{OH}} \) is the diffusion time of OH, where again the Arrhenius law is assumed according to \( \tau_{d,\text{OH}} = \tau_{d,\text{OH}}^{(0)} \exp(U_{\text{act}}^{\text{OH}}/kT) \) [7], where the considerations in [7, 8] for OH in SiO2 imply that \( \tau_{d,\text{OH}}^{(0)} = 7 \times 10^{-5} \text{ s} \).

The surface temperature \( T \) is estimated using the adaptation in [5] of the thermal equilibrium based method of [11]. The coupled differential equations (1) and (2) are solved numerically for the period of time between sunrise and sunset using the finite difference method. The initial (sunrise) values of \( n_{\text{H}} \) and \( n_{\text{OH}} \) are set to 10^{24} \text{ m}^{-3} \) (see [8]) and 0, respectively. The numerical solution procedure is iterated, setting the sunrise values of \( n_{\text{H}} \) and \( n_{\text{OH}} \) of the current iteration cycle to the sunset values of \( n_{\text{H}} \) and \( n_{\text{OH}} \) of the previous iteration cycle. For the parameter settings applied here, this iteration converges towards number density curves with identical sunrise and sunset \( n_{\text{H}} \) and \( n_{\text{OH}} \) values, respectively. It is physically plausible that \( n_{\text{H}} \) and \( n_{\text{OH}} \) do not change during the lunar night due to the low surface temperature and the absence of incoming solar protons.

Results: In our simulations the model parameters were chosen as described above, and the reaction time was set to \( \tau_{\text{react}} = 10^{5} \text{ s} \). The activation energies \( U_{\text{act}}^{\text{H}} \) and \( U_{\text{act}}^{\text{OH}} \) were adapted such that the time dependence of the OH column density \( n_{\text{OH}} \) was qualitatively similar to the observed behaviour of the integrated OH band depth inferred using M3 data (as described in [5]) for test areas near the example craters Boguslawsky and Dryden (Fig. 1). Here we made the assumption of an approximate proportionality between the integrated OH band depth and the OH column density.
Crater Boguslawsky. The value of $U_{\text{act}}^{H}$ was chosen large enough to obtain a relative decrease of $n_{OH}$ between lunar morning and midday similar to that suggested by the observations, resulting in $U_{\text{act}}^{H} = 0.68$ eV. Furthermore we set $U_{\text{act}}^{OH} = 1.0$ eV, where it was possible to increase $U_{\text{act}}^{OH}$ to 1.5 eV and higher without any noticeable change of the behaviour of $n_{OH}$. The corresponding behaviour of the column densities $n_{OH}^H$ and $n_{OH}^H$ is shown in Fig. 2. According to [7] it is $U_{\text{act}}^{H} < U_{\text{act}}^{OH}$ because $U_{\text{act}}^{OH}$ refers to free H and $U_{\text{act}}^{OH}$ to OH in SiO$_2$. Increasing the reaction time $\tau_{\text{react}}$ by a factor of 2 yields a largely uniform scaling of the $n_{OH}^H$ curve by a factor of about 0.6.

Crater Dryden. The value of $U_{\text{act}}^{H}$ was chosen such that the relation between the $n_{OH}$ morning values for Boguslawsky and Dryden is similar to the observations, resulting in $U_{\text{act}}^{H} = 0.85$ eV. We again set $U_{\text{act}}^{OH} = 1.0$ eV. The behaviour of the column densities $n_{OH}^H$ and $n_{OH}^H$ resulting from this parameter setting is shown in Fig. 3. The general shape of the $n_{OH}^H$ curve is similar to that of the crater Boguslawsky. In the morning, the modelled OH column density is slightly lower than for Boguslawsky, and the relative decrease around lunar midday is stronger. The observed slight increase of the OH absorp-

tion depth in the morning and the relatively high observed midday values cannot be fully reproduced by the model. Here it is possible that the Arrhenius law used for modelling the evaporation of surficial OH is not fully appropriate for a regolith surface exposed to the vacuum. Alternatively, one might consider the presence of a more strongly bounded water/OH component as proposed e.g. in [12], not being subject to diffusion and photolysis and adding up with the daytime-dependent component to generate the observed absorption behavior.

Summary and conclusion: We have presented results of numerical modelling of the density of lunar surficial H and OH, which are qualitatively consistent with MP-based observations at low and high southern latitudes. Future work will involve the addition of H$_2$O to the model. Further tests of the model will require observations of specific regions at many different days, which are hardly available in the MP data set. Ground-based near-infrared spectrometers such as the LIS instrument to be deployed on the upcoming Russian lunar landers [13] will allow for a more refined comparison between observations and modelling results of daytime-dependent variations of the surficial OH abundance.

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Introduction: The Moon’s reflectance spectrum records many of its important properties. No spectra had previously been measured on the lunar surface. Here we show the first set of reflectance spectra of the Moon acquired on the lunar surface by the Visible-Near Infrared Spectrometer (VNIS) onboard the Chang‘E-3 (CE-3) “Yutu (Jade Rabbit)” rover.

Instrument and Data: The VNIS uses acousto-optic tunable filters (AOTFs) as dispersive components and consists of a VIS/NIR imaging spectrometer, a shortwave IR (SWIR) spectrometer, and a white calibration panel that is protected from dust. The default spectral sampling interval is 5 nm, and the total number of sampling bands is 400 (100 bands for the VIS imaging spectrometer and 300 bands for the SWIR spectrometer; note that the bands between 900-945 nm overlap). The nominal spatial resolution of the VIS imaging spectrometer is 0.53-0.61 mm/p and the field of view is an isosceles trapezoid with a height of 20.6 cm and two parallel sides of 13.5 cm and 15.7 cm.

![Fig. 1. LROC NAC image shows the track of the rover and the locations of the four measurements for VNIS. The image width is ~200 meters.](image)

Table 1. Data acquisition conditions of the four sites analyzed by VNIS. Angles are in degrees.

<table>
<thead>
<tr>
<th>Site</th>
<th>Local Time</th>
<th>Inci angle (i)</th>
<th>Emis angle (e)</th>
<th>Phase angle (a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>15:09</td>
<td>59.90</td>
<td>48.17</td>
<td>107.94</td>
</tr>
<tr>
<td>6</td>
<td>15:57</td>
<td>67.50</td>
<td>47.41</td>
<td>85.61</td>
</tr>
<tr>
<td>7</td>
<td>7:48</td>
<td>69.70</td>
<td>47.08</td>
<td>86.00</td>
</tr>
<tr>
<td>8</td>
<td>9:29</td>
<td>54.05</td>
<td>44.40</td>
<td>95.29</td>
</tr>
</tbody>
</table>

During the 114-m travel of the Yutu rover four measurements of the soil were made by the VNIS (Fig.1 and Table 1). Image from the Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC) revealed an area of increased reflectance (Fig.1). We consider Site 8 (~43 m from the lander) to be visually undisturbed and Site 5 to represent soil that experienced the most disturbance.

In situ absolute reflectance: Figure 2 shows the in situ reflectance compared with some of the recent mission instruments and lunar sample. Note that soil 71501 very nearly has the darkest hue and the highest value for FeO (16.5 wt.%) + TiO₂ (9.31 wt.%) in the Lunar Soil Characterization Consortium (LSCC) soil from the RELAB dataset. The differences in the measurements of these instruments are very large and indicate inherent differences in their absolute calibration. The Moon Mineralogy Mapper (M²) onboard the Chandrayaan-1 and the Chang‘E-1 Interference Imaging Spectrometer (IIM) measurements are much smaller than the LROC Wide Angle Camera (WAC) and the Spectral Profiler (SP) onboard the SELENE, and the VNIS measurement falls between these two pairs. So the measurements of the LROC WAC and SP are too high and too red. The laboratory reflectance of lunar samples is significantly larger and even redder than the actual lunar reflectance measured from orbit and on the lunar surface. When using the Moon as a radiance source for the on-orbit calibration of spacecraft instruments, one should be cautious about the data.

![Fig. 2. Comparison of reflectance from VNIS sites 6 and 7 with other missions and lunar sample.](image)

In situ Space weathering: Reflectance increasing, as shown in Fig. 1, after spacecrafts landed, have been observed for CE-3, Apollo, Luna, etc [1-4]. These studies suggest that smoothing of surface roughness is the main cause of the observed increase in reflectance and exposure of less mature soil was rejected because the maturity of core samples within the first tens of centimeters of regolith depth do not
change significantly. The four spectra show that the reflectance, absorption strength, visible slope, and optical maturity (OMAT) all increase for sites closer to the lander, it suggests that:

1) brightness increases after the spacecraft landed are due to removal of the finest, highly weathered particles, not smoothing of the surface.

2) the uppermost surficial regolith is much more weathered than the regolith immediately below.

3) the finest fraction is much more mature than the coarser fraction.

4) the effects on the spectral slope caused by space weathering are wavelength-dependent: space weathering increases the near-infrared continuum slope (VNCS) while decreasing the visible slope. That is, the in situ spectra reveal an opposite trend in the visible slope with respect to space weathering to the previously known trend. It is consistent with the ultraviolet observations for the Moon [5] and asteroids [6] and extends to the visible bands.

**In situ thermal effects:** The two spectra showing marked upturn (sites 5 and 8) correspond to local times having higher surface temperatures, and the two spectra which do not show upturn (sites 6 and 7) correspond to local times having lower temperatures (Table 1). The analysis indicates that the VNIS detected thermal radiation emitted from the lunar surface. The calculated temperatures are 80.3°C and 79.3°C for sites 5 and 8, which are much higher than expected from the theoretical model (Table 2). This discrepancy has also been found for many atmosphereless objects observed by remote sensing data and was explained by similar models such as subpixel hotspots [7] or micro scale roughness [8]. These models have only been developed because of the low spatial resolution of remote sensing data. The discrepancy derived from in situ measurement supports the remote sensing observation, and the clear views of the regolith particles confirm the hypothesis.

**Table 2.** Temperatures measured by the VNIS and Diviner and modeled by the theoretical model.

<table>
<thead>
<tr>
<th>site</th>
<th>VNIS</th>
<th>Modeled</th>
<th>Diviner</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>353.3</td>
<td>331.6</td>
<td>323.3</td>
</tr>
<tr>
<td>6</td>
<td>309.9</td>
<td>299.7</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>302.4</td>
<td></td>
<td>287</td>
</tr>
<tr>
<td>8</td>
<td>352.3</td>
<td>344.9</td>
<td>335.8</td>
</tr>
</tbody>
</table>

The temperatures measured by Diviner are quite lower than the measured and modeled temperatures (Table 2). This is different from the above conclusion that the observed surface temperatures are significantly hotter than what theoretical models would predict. The reason is unknown but a re-check for the calibration of Diviner data is suggested.

**In situ compositions:** The M³ spectra from a fresh 350 m crater located 4.7 km southwest of the CE-3 landing site, which represents the rocks CE-3 landed on, display long and broad 1 μm, strong 1.3 μm, and very weak 2 μm absorptions. It indicates that the CE-3 unit is rich in olivine and depleted in pyroxene compared with Apollo landing sites, representing unsampled mare basalts. M³ spectra from the nearby older, low-Ti unit show both strong 1 μm and 2 μm absorptions suggesting that the unit underlying the CE-3 landing site contains more pyroxene.

![Fig. 3. The VNIS spectra and M³ spectra.](image)

![Fig. 4. Gaussian deconvolution of the 350-m fresh crater](image)

The spectral deconvolution using the modified Gaussian model (MGM) [9] shows that the wide 1000 nm band is composed of three bands centered at 876, 1026 and 1339 nm. It suggests that the olivine here is richer in iron compared with the Apollo 15 olivine, which has an average composition of Fo77.8 for the basalt olivine.

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**References:**
LASER-ABLATION MASS SPECTROMETRY FOR IN SITU ANALYSIS OF MATERIAL ON PLANETARY SURFACES. P. Wurz1, M. Neuland1, R. Weisendanger1, A. Riedo2, S. Frey1, and M. Tulej1, 1Physics Institute, University of Bern, Sidlerstrasse 5, 3012 Bern, Switzerland, peter.wurz@space.unibe.ch; 2Leiden Observatory, Sackler Laboratory for Astrophysics, Leiden University, The Netherlands.

Introduction: We present a miniature time-of-flight laser ablation mass spectrometer (LMS) for the in situ analysis of solid matter on planetary surfaces. The LMS was originally designed for use on a lander and rover on Mercury [1,2]. An instrument prototype was built and refined and optimised over the years at the University of Bern for application in space exploration. The small size and light weight of the instrument make it feasible for operating on a lander or rover on a planetary surface.

Instrument Description: The LMS instrument is a time-of-flight mass spectrometer that uses a femtosecond laser for ablation and ionisation of sample material for mass spectrometric analysis. It has a mass resolution in the range of m/Δm = 500–900, with an accuracy of the mass scale better than 1 permile [3], a detection limit around 10 ppb depending on mass [3,4], a dynamic range of 8 decades [3], quantitative measurements of almost all elements in laser ablation mode [4,5,6], and detection of complex molecules in laser desorption mode [4,7]. Comparison with laboratory-scale LA-ICP-MS and ICP-MS instruments gave comparable results for composition and their accuracies.

The laser removes material from the surface with each laser pulse; thus, when staying at the same spot the sequence of mass spectra resulting from these laser pulses can be used to derive a depth profile of the atomic composition at the sampled location [8,9,10]. We find that the obtained depth resolution is better than 1 nm, depending on laser intensity [9]. Even complex molecules could be identified at grain boundaries by switching to laser desorption mode at the appropriate depth [7].

Since planetary samples typically are highly heterogeneous, for example meteorites, it is necessary to perform measurements of the chemical composition on small spots commensurate with the typical grain size within the object. Typically, a spatial resolution, which is given by the size of the laser spot on the sample, of 10–20 µm is adequate to cover the range of mineralogical complexity. In the LMS instrument we can focus the laser beam down to about Ø 10–15 µm, which defines the best spatial resolution for investigation on a sample. We compile two-dimensional compositional maps of the sample surface by an array of spots on the surface. We have completed several such investigations on a piece of the Allende meteorite, a carbonaceous chondrite, and we achieved good agreement with other analyses of the chemical and mineralogical composition [11]. A typical LMS measurement campaign and chemical analysis is shown in Fig. 1. In the image of the untreated meteorite the heterogeneous composition is seen, with a large inclusion at the lower right in the matrix material at most of the other areas. The chemical composition of this inclusion is clearly different from the surrounding matrix material as can be seen from the three element maps shown as an example. Similarly, the measurements on the Sayh al Uhaymir 169 Meteorite, a lunar meteorite with a large KREEP fraction, showed good agreement with prior analyses of chemical and mineralogical content [12].

Finally, the LMS measurements can be used to infer the mineralogy of the sample [6,11,12,13]. For example, based on the mineralogical composition a zircon inclusion was identified in the Sayh al Uhaymir 169 Meteorite with LMS. In this zircon inclusion the abundance of rare earth elements were measured from which the U-Pb age of the sample was deter-
mined as (3520±130) Myrs. Moreover, from the Ti content in the zircon the crystallisation temperature of 1180±100 K was derived.

Recently, we added a microscope system to the LMS instrument allowing for colour imagery at 2 μm spatial resolution. In addition to providing context information of the investigated sample (like presented in Fig. 1), one can select from the microscope images the locations of interest on the sample for mass spectrometric investigation with LMS, for example when searching for fossils of microbial life [14]. We proposed such an instrument for an asteroid mission [4].

**Summary:** We developed a miniature laser ablation mass spectrometer, LMS, for the investigation of solid matter for in situ planetary research. Although the performance still is less than much larger laboratory instruments, LMS enables many different in situ measurements, which have not been possible on a planetary surface so far. Among these measurements are the element and isotope composition of rock samples on a planetary surface, dating of rocks, to derive the mineralogy, and to address related geological questions on formation of the sampled material. Therefore, employment of the LMS instrument on a lunar rover in the South Pole Aitkens basin promises to yield many exciting scientific results. Moreover, prior LMS measurements of a rock on the lunar surface will assure that we return a sample of high scientific interest to Earth.

**References:**
RHEOLOGICAL CONTROL ON LUNAR MAGMA OCEAN OVERTURN. Shuoran Yu¹, Sabrina Schwinger², Nicola Tosi²,³, Doris Breuer², Long Xiao¹,⁴ ¹Space Science Institute, Macau University of Science and Technology, Macau SAR, China ²Institute of Planetary Research, German Aerospace Center (DLR), Berlin, Germany. ³Department of Astronomy and Astrophysics, Berlin Institute of Technology, Berlin, Germany ⁴Planetary Science Institute, China University of Geosciences, Wuhan, China. Contact: shuoran.yu@icloud.com

Introduction: The crystallization and differentiation of the lunar magma ocean (LMO) determines the structure of the primitive lunar mantle and can lead to a gravitationally-unstable density stratification that overturns into a stable configuration. Ilmenite, the major carrier of titanium in lunar minerals, crystallizes when about 87-95 vol.% LMO has solidified [1,2]. As the density of ilmenite is much larger than the typical density of mafic minerals, the ilmenite-bearing cumulate (IBC) may sink, leading to a large-scale compositional overturn. This hypothesis may provide an explanation for the origin of high-Ti basalt [3], the magnetic field anomaly between 3.9 and 3.6 Ga [4], the partial melt layer in the deep lunar interior [5], as well as for the global asymmetry in lunar volcanism [6]. Even though the overturn hypothesis provides an explanation to many aspects of the early lunar evolution, it still encounters some difficulties from a dynamical standpoint. The stagnant lid forming on top of the lunar mantle can rapidly lock the IBC and prevent it from sinking downwards [7]. In this study, we aim at elucidating the rheological conditions under which the LMO overturn can take place.

Methods: We use the mantle convection code GAIA [8] to solve the dimensionless conservation equations of mass, momentum, thermal energy, transport of composition and of heat sources in a 2D cylindrical domain. We use the Boussinesq approximation and assume incompressible Stokes flow of a Newtonian fluid with temperature-dependent viscosity (η) defined according to the Arrhenius law for diffusion creep:

\[ \eta = \eta_{ref} \exp(E/(RT) - E/(RT_{ref})), \]

where \( \eta_{ref} \) is the reference viscosity attained at a reference temperature \( T_{ref} = 1573 \) K, \( E \) the activation energy, and \( R \) the gas constant.

We calculate the crystallization sequence for a magma ocean, assuming that solid phases crystallize at the bottom of the LMO and successively form a layered cumulate. The type and composition of the phases crystallizing at each temperature step during LMO cooling is calculated using the software alphaMELTS [9], [10], [11] and assuming a bulk Moon composition according to [12]. To consider different crystallization sequences, the initial depth of the LMO, the amount of liquid trapped in the cumulate during crystallization, the amount of crystals mixed into the remaining liquid can be adjusted in the model.

Based on the crystallization sequences calculated with the above method, we initialize our dynamic simulations assuming a simple three-layer model consisting of a low-density anorthosite crust, an IBC layer of high density, and a uniform mantle with an olivine-pyroxene composition. The initial temperature profile is set at the solidus and supplemented by an upper thermal boundary layer comprising the crust where the temperature grows linearly with depth. Heat-producing elements are distributed according to the obtained crystallization sequence, with the consequence that most of the heat sources are enriched in the two uppermost layers.

In order to determine the rheological conditions that allow the IBC layer of varying thickness to sink, we test the effects of the activation energy (\( E \)), which controls the rate of stagnant-lid thickening, and of the reference viscosity (\( \eta_{ref} \)), which controls the onset time of convection.

![Figure 1](image-url) Time evolution of the fraction of IBC that remains trapped in the growing stagnant lid for reference viscosities of 10²¹ Pas (a) and 10¹⁹ Pas (b), and different activation energies.
**Results:** In Fig. 1 we show model runs assuming an IBC layer thickness of 100 km. Low values of both $E$ and $\eta_{ref}$ tend to favour an early overturn. On the one hand, with a reference viscosity of $10^{21}$ Pa s, the typical viscosity of dry peridotitic upper mantle, the onset of convection is relatively slow and the overturn of a very small fraction of the IBC occurs only for an activation energy lower than ~100 kJ mol$^{-1}$ (Fig. 1a). On the other hand, with a reference viscosity of $10^{19}$ Pa s, representative of a wet mantle, convective instabilities grow rapidly. For all tested values of the activation energy, part of the IBC can overturn (Fig. 1b). The amount of IBC that can actually sink to the core-mantle boundary varies significantly: between 90% of the crystallized layer for $E = 100$ kJ mol$^{-1}$ and 50% for $E = 500$ kJ mol$^{-1}$. These values, however, also depend on the initial thickness and the upper boundary of the IBC layer. The thicker and the deeper the IBC, depending on the crystallization sequence, the larger is the amount of IBC that can accumulate at the core-mantle boundary.

**Discussion and Conclusions:** For a reference viscosity of $10^{21}$ Pa s, the value of the activation energy required by the overturn is far lower than the activation energy of peridotite obtained from laboratory experiments. A potential explanation is that the effects of dislocation creep are not considered in our simulations. Christensen [13] suggested that the effective activation energy in the regime of dislocation creep can be obtained multiplying by a factor of 0.3-0.5 the activation energy, depending on whether viscous dissipation is considered or not in the dynamic model. Given the typical activation energy of peridotite in the regime of dislocation creep (~400-500 kJ mol$^{-1}$), the effective diffusion creep activation energy can be determined as about 120-250 kJ mol$^{-1}$. Therefore, the lower activation energy required by the overturn could actually be indicative of the need to account for a non-Newtonian rheology. For a reference viscosity of $10^{19}$ Pa s, the dependence of the overturn on the activation energy is less severe. This value may represent the typical reference viscosity of a wet primitive lunar mantle. Since the level of hydration of the lunar interior can be very significant [14], this could be a potential reason for the occurrence of a global overturn in the early history of the Moon. Additional factors able to lower the mantle viscosity and promote a rapid onset of convection such as the presence of residual melt should be considered in future studies.

GLOBAL SURVEY OF LUNAR WRINKLE RIDGE FORMATION TIMES Z. Yue1, G. Michael2, K. Di1, J. Liu3. 1State Key Laboratory of Remote Sensing Science, Institute of Remote Sensing and Digital Earth Chinese Academy of Sciences, Beijing, China 100101. 2Planetary Sciences and Remote Sensing, Institute of Geological Sciences, Freie Universitaet Berlin, Malteser Strasse 74-100, Haus D, Berlin 12249, Germany (gregory.michael@fu-berlin.de). 3Institute of Geochemistry Chinese Academy of Sciences, Guiyang, China 550002.

Introduction: Wrinkle ridges are a common feature of the lunar maria and an indicator of the post-formational deformation of the mare infill. It is difficult to constrain the timing of wrinkle ridge formation from crater counts because they have limited areal extent, and even over the area which can be mapped, it is difficult to determine whether superposed craters post-date the ridge formation or have merely been uplifted during the deformation. There are, however, parts of the wrinkle ridge structures where it is possible to make such a determination: namely, where the ridge shows a sufficiently steep boundary or scarp that we see whether it deforms an intersecting crater or the crater obliterates the relief of the ridge. Such boundaries constitute only a small component of the wrinkle ridge structures yet they are sufficiently numerous to enable us to obtain statistically significant crater counts over systems of structurally related wrinkle ridges.

We carried out a global mapping of mare wrinkle ridges, identifying appropriate boundaries for crater identification, and mapping superposed craters. Data were analysed using the buffered crater counting method [1].

Method: Image data for the study were drawn from the Lunaserv mapserver LROC NAC overlay [2] at 2048 pixels/degree, equivalent to about 15 m/pixel, to cover the area of the previously mapped ridges [3].

Portions of the ridge boundaries showing scarps or pronounced steep boundaries were mapped with polylines in a GIS system (Fig 1). Superposed craters were mapped using CraterTools to determine the crater [4]. We used a simplified buffering scheme compared to that described by [5], but with the same intent: to reference each crater to a buffer area around the polylines, representing the area where we would have been able to identify other superposing craters of the same diameter, if they were present. Each scarp-intersecting crater was examined and included only if judged to post-date the scarp formation.

Results: Eight aggregated ridge systems (Procellarum, Imbrium, Serenitatis, Crisium, Frigoris, Nubium, Fecunditatis, Humorum) yielded average ages in the range 3.1–3.5 Ga, corresponding to 0.1–0.65 Ga after emplacement of the oldest lavas observed at the surface in each mare [6-10]. Figure 2 shows the result for Mare Crisium, where the ridge systems were split into three spatial groupings to investigate potential timing differences.

![Figure 1. Examples of craters which (a,b) post-date (red circles, 19.1°W 42.6°N, Mare Imbrium) wrinkle ridge formation. Images from Lunaserv mapserver LROC NAC overlay [2].](image1.png)

The ridge system in Tranquilitatis which, notably, is not concentric to the basin as for the neighbouring mascon basins Serenitatis and Crisium, yields a formation time of 2.4 Ga, that is 1.4 Ga after its oldest surface lavas [6].
Figure 2. Sample average model age of wrinkle ridge systems for Mare Crisium (grouped into east, west, central, all-basin systems). Colours correspond to mapped systems in Fig. 3. $\mu$ is a function representing the uncertainty of calibration of the chronology model [11].

Conclusion: We made a global survey of the ages of lunar maria wrinkle ridge systems using the buffered crater counting method. We find that, excepting Tranquilitatis, the ridge systems formed 0.1–0.65 Ga after emplacement of the oldest observable lavas in each mare, but not generally synchronously with one another. This is consistent with the source of stress being local to the maria basins. For those maria where we were not able to measure ages because of insufficient crater statistics, there is nevertheless no indication that the general picture is different.

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Figure 3. Globally mapped wrinkle ridges over LROC WAC mosaic. Separately aggregated systems of ridges marked with distinct colours.
THE ASTROMATERIALS X-RAY COMPUTED TOMOGRAPHY LABORATORY AT JOHNSON SPACE CENTER. R. A. Zeigler¹, D. M. Coleff², and F. M. McCubbin¹.¹NASA, Johnson Space Center, Mail Code XI2, Houston TX, 77058, ryan.a.zeigler@nasa.gov. ²Jacobs Technology, Johnson Space Center, Houston TX 77058.

Introduction: The Astromaterials Acquisition and Curation Office at NASA’s Johnson Space Center (hereafter JSC curation) is the past, present, and future home of all of NASA’s astromaterials sample collections [1-2]. JSC curation currently houses all or part of nine different sample collections: Apollo samples (1969), Luna samples (1972), Antarctic meteorites (1976), Cosmic Dust particles (1981), (4) Microparticle Impact Collection (1985), (5) Genesis solar wind atoms (2004); (6) Stardust comet Wild-2 particles (2006), (7) Stardust interstellar particles (2006), and (8) Hayabusa asteroid Itokawa particles (2010). Each sample collection is housed in a dedicated clean room, or suite of clean rooms, that is tailored to the requirements of that sample collection. Our primary goals are to maintain the long-term integrity of the samples and ensure that the samples are distributed for scientific study in a fair, timely, and responsible manner, thus maximizing the return on each sample.

Part of the curation process is planning for the future, and we also perform fundamental research in advanced curation initiatives. Advanced Curation is tasked with developing procedures, technology, and data sets necessary for curating new types of sample collections, or getting new results from existing sample collections [2]. We are (and have been) planning for future curation, including cold curation, extended curation of ices and volatiles, curation of samples with special chemical considerations such as perchlorate-rich samples, and curation of organically- and biologically-sensitive samples. As part of these advanced curation efforts we are augmenting our analytical facilities as well. A micro X-ray computed tomography (micro-XCT) laboratory dedicated to the study of astromaterials will be coming online this spring within the JSC Curation office, and we plan to add additional facilities that will enable non-destructive (or minimally-destructive) analyses of astromaterials in the near future (micro-XRF, confocal imaging Raman Spectroscopy). These facilities will be available to: (1) develop sample handling and storage techniques for future sample return missions, (2) be utilized by PET for future sample return missions, (3) be used for retroactive PET-style analyses of our existing collections, and (4) for periodic assessments of the existing sample collections. Here we describe the new micro-XCT system, as well as some of the ongoing or anticipated applications of the instrument.

Methodology: We are installing a Nikon XTH 320 micro-XCT system in JSC curation. It has four interchangeable X-ray sources: 180 kV nano focus transmission source, 225 kV reflection source with multi-metal target (Mo, W, Ag, Cu), a 225 kV rotating target reflection source, and a 320 kV reflection source. The system also has a 16-bit, 400 mm² (2000 x 2000 pixel) CCD detector, as well as a heavy duty stage that will accommodate large (up to 30 cm) and heavy (up to 100 kg) samples.

The multiple sources, high-resolution detector, and large stage will allow the flexibility to analyze a wide range of sample sizes. The 180 kV transmission source will allow for high resolution (submicron) scans on small samples (less than ~5 mm), whereas the 225 kV and 320 kV sources will allow scans of larger samples at resolutions on the order of 10s or 100s of microns per voxel depending on the sample size. (The resolution on a scan is largely determined by the diameter of the sample being scanned divided by ~2000.) The maximum size high-density rock sample that can be scanned has yet to be determined, but test scans on basalt samples >15 cm in diameter have been successful.

Discussion: High-intensity XCT scanners have been used to study astromaterials (and other geologic samples) for over 15 years, and the practice is becoming ever more prevalent [3-5]. They have a wide range of scientific uses, including (but certainly not limited to) measuring porosity, determining the modal abundance and 3D distribution of phases inside samples, and identification of fabrics or strain patterns in samples. In addition to their use for research, XCT scans have increasingly been utilized as a part of the astromaterials curation process, beginning with meteorites [6-7], and more recently with the Apollo samples [8].

Their utility in curation lies in their ability to non-destructively map out the phases and voids within a sample. As an example, we have scanned several large Apollo polymict breccias, and we were able to identify and tentatively classify the lithologies in these clasts (Fig. 1). The samples can then be subdivided, either through sawing or careful chipping, and those “new” clasts made available to scientists. Similar reconnaissance XCT scans on igneous samples can find regions of interest, e.g., mafic-rich regions within anorthosites, xenoliths within basalts, or zircons within granites, which again will be cataloged and made available to investigators for more in depth study.

The penetrative nature of the XCT scans allows for astromaterials samples to be analyzed within sealed low density containers, preserving the pristini-
ty of the samples (Fig. 2 – Picture of Apollo samples in Teflon bags, immobilized within cardboard tubes).

The XCT technique is not completely non-destructive, however. A recent study by [9] has shown that XCT scans of meteorites can alter the natural radiation dose of the sample. The number of techniques where this is applicable (e.g., thermoluminescence) is limited, however. Nevertheless, XCT scans could cause damage for other types of studies (e.g., organics), and we plan to undertake extensive studies to fully characterize the impact XCT scans have on the samples [10]. In the meantime, the percentage of any one sample that is studied by XCT will be limited to ensure that no irreparable damage is done to an entire sample.

The use of XCT alone is a powerful tool for curation, but combining XCT with other techniques, such as micro-XRF or confocal laser Raman spectroscopy, will add more quantitative chemical or mineral (respectively) information, and will allow for a more robust classification of new samples. Similarly, we have recently undertaken a project to combine micro-XCT scans with high resolution visual 3D images of the surface of samples into a single integrated data product [11]. This will allow investigators an unprecedented ability to examine samples to determine if they are applicable to their study.

The Astromaterials XCT lab in JSC curation should be online by early Spring 2017, and we expect to begin scanning Apollo and meteorite samples shortly thereafter. These scans will be made available to the scientific public via the curation website, and advertised via newsletters emailed to the community. Additionally, instrument time will be available to investigators funded to do studies on astromaterials where XCT would be of benefit to the study.


Figure 1: Slices of the micro-CT scan of sample 14321,1404. Brightness of the phases are proportional to x-ray attenuation. Yellow arrows highlight interesting feldspathic (top) and mafic (bottom) clasts. Sample is ~ 6 cm in diameter.
THE AMOUNT OF ILMENITE-BEARING CUMULATES PARTICIPATING IN LUNAR MANTLE OVERTURN: A PARAMETER STUDY

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Introduction: The Moon was likely covered with a global magma ocean in its early history [1,2]. Studies of its crystallisation sequence [3,4] show that denser cumulates, with a high Fe content and ilmenite, formed in the latest stages of the crystallisation process, and therefore resulted in gravitationally unstable layering.

An overturn event may have been triggered by this gravitational instability, resulting in the sinking of ilmenite-bearing cumulates (IBC) towards the bottom of the mantle. Since these cumulates are also enriched in radiogenic heat-producing elements, they may temporarily heat up the core [5,6]. This potential impact on the cooling rate of the core is an important factor in studying the existence and duration of the lunar dynamo. Subsequent upwelling may have occurred if thermal buoyancy of the expanding IBC overcame their density. These upwellings would have implications for surface volcanism and the composition of mare basalts. It is therefore important to investigate the likelihood and fashion in which the IBC participate in mantle overturn.

This study investigates the quantity of IBC that sinks into the mantle after magma ocean crystallisation, and its dependence on a range of parameters. The dynamics of the overturn depend particularly on the distribution of buoyancy, related to density contrast between the cumulate layers, and the viscosity. Viscosity depends on temperature and pressure, and is greatly reduced in a partially molten zone. We test the effect of viscosity by varying initial temperature, temperature dependence of viscosity, and weakening by simulation of a partially molten KREEP layer. The effect of different density contrasts is also tested.

Modelling Approach: Modelling experiments are performed on a 2-D cylindrical finite element model. Convection equations are solved using the extended Boussinesq approximation assuming an infinite Prandtl number. Our models start at the end of lunar magma ocean solidification. Stratified crystallisation is modelled by varying density and distribution of heat-producing elements among the layers [7]. Variable thermal conductivity [6] is used. Viscosity is modelled based on the Arrhenius relation in [8]. At a reference depth of 500 km and temperature of 1500 K, the reference viscosity is 1x1021 Pa-s. Composition related buoyancy is modelled by 500,000 active tracers. Mesh refinement is applied near the initial IBC position with nodal point spacing down to 2.5 km. Results were validated by resolution tests.

Figure 1 gives an example of modelling results from Model K4 (Table 1). The left frame is a 2-D snapshot of IBC concentration, in the early stage of the overturn. The right frame is a plot of the vertical distribution of cumulates calculated from the snapshots. In this case, results converge through time within a few hundred Myr, and about 32% of the IBC remain at shallow depth (right frame). Results in the rest of the abstract are presented as the percentage of IBC that participate in mantle overturn (“IBC %”) as a function of various parameters.

**Initial Temperature and Activation Energy:**

**Initial temperature.** The initial temperature used for lunar thermal evolution models, especially in the region of the IBC layer, has a particularly large influence on early model evolution, due to the temperature dependence of the viscosity. In this set of models, initial temperatures are adiabatic in the convective part of the mantle. Both the core-mantle boundary and surface thermal boundary layers are 40 km thick. A series of adiabats (Table 1) are calculated based on lunar parameters using potential temperatures of 1200 to 1800 K, at 100 K intervals. Several of the initial T profiles are shown in the left frame of Figure 2.

**Activation energy.** Experimental results of [9] indicate an E’ value of 300 kJ/mol for dry olivine in diffusion creep. We investigated the effects of contrasting values of 300 and 100 kJ/mol for E’, the latter value recently used in lunar evolution models by [10]. Activation volume is kept at V’=6 cm3/mol [9].

Results of this set of models are shown in Figure 2, and show that overturn is unlikely at initial temperatures that are below the peridotite solidus, when an activation energy of 300 kJ/mol is used in the Arrhenius viscosity model.
KREEP Layer Weakening and Density Contrast: The models of the previous section are based on the assumption that mantle overturn only occurs after the lunar magma ocean is entirely solidified. This section changes that assumption. All models below use $E^* = 300$ kJ/mol.

KREEP layer weakening. The last part of the magma ocean to solidify is the so-called KREEP layer, just below the newly-formed crust. This layer is highly enriched in incompatible elements, including radiogenic isotopes of Th, U and K. It also has low melting temperatures. Therefore it may have been kept in a high-melt-fraction state by its own heat production, even after the rest of the magma ocean has solidified. Such a partially molten layer is weak, and may have acted as a decoupling agent that facilitates mantle overturn.

To simulate decoupling between the crust and the cumulates, a hot layer is prescribed in the initial temperature profile, resulting in a local weak zone due to the temperature dependence of viscosity. The initial temperature is composed of the peridotite solidus and an adiabat whose potential temperature is 1640 K. Figure 2 (left) illustrates two of these initial temperature profiles (K3 and K4 from Table 1).

Figure 2. Initial temperature profiles (left) using adiabats of varying potential temperatures, and resulting IBC % founded in the mantle (right). Also plotted in the left are initial temperatures of Models K3 and K4. Note that K3 only differs from K4 at 40-65 km depth.

Two parameters are tested for the hot layer: layer thickness $h$ and viscosity contrast $\eta = \eta \cdot \eta_{\text{original}}$. When $\eta = 0.1$, for example, the viscosity in the hot layer is one order of magnitude lower than the original. This is achieved by raising temperature of the layer by around 150 K for $\eta = 0.1$ and around 330 K for $\eta = 0.01$ (Figure 2).

The peridotite solidus at the depth of the IBC is comparable to an adiabat of potential temperature 1400 K. As shown in the previous section, if no hot layer is added, this initial temperature would result in a very small IBC %. Results in Table 1 show that overturn is facilitated when the effect of a weak KREEP layer is simulated. Our results show that the hot layer disappears within 10 Myr as its heat dissipates away. This means that even if the KREEP layer solidified relatively fast, it would have played a large role in facilitating mantle overturn.

Table 1. Parameters and results of models testing the effect of a hot layer simulating the molten KREEP layer

<table>
<thead>
<tr>
<th>Models</th>
<th>K1</th>
<th>K2</th>
<th>K3</th>
<th>K4</th>
<th>K5</th>
<th>K6</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h$ (km)</td>
<td>10</td>
<td>10</td>
<td>15</td>
<td>15</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0.1</td>
<td>0.01</td>
<td>0.1</td>
<td>0.01</td>
<td>0.1</td>
<td>0.01</td>
</tr>
<tr>
<td>IBC %</td>
<td>48</td>
<td>59</td>
<td>54</td>
<td>68</td>
<td>56</td>
<td>72</td>
</tr>
</tbody>
</table>

Density contrast. Gravity is the main driving force for the sinking of ilmenite-bearing cumulates, created by the density contrast between the IBC and the pyroxene-olivine-rich layer below. Contrasts ($\Delta \rho$) used in this set of models are in Table 2. The initial temperature of K4 is used in all these models. The results show that higher density results in higher IBC %, but this effect decreases with increasing $\Delta \rho$.

Table 2. Results for several density contrasts between the ilmenite-bearing layer and the layer below.

<table>
<thead>
<tr>
<th>Models</th>
<th>D1</th>
<th>D2</th>
<th>K4</th>
<th>D3</th>
<th>D4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \rho$ (kg/m$^3$)</td>
<td>0</td>
<td>161</td>
<td>323</td>
<td>484</td>
<td>646</td>
</tr>
<tr>
<td>IBC %</td>
<td>56</td>
<td>59</td>
<td>68</td>
<td>75</td>
<td>77</td>
</tr>
</tbody>
</table>

Conclusion: The amount of IBC that participates in mantle overturn is sensitive to the temperature dependence of mantle viscosity and the initial temperature of the IBC layer. Participation is unlikely in a subsolidus mantle when a realistic activation energy of 300 kJ/mol is assumed. A weak KREEP layer simulated by a high initial temperature layer greatly increases the quantity of IBC sinking. Higher density contrasts drive more IBC down, but this effect decreases with increasing contrast.