



CNSA-ESA WORKSHOP ON CHINESE-EUROPEAN COOPERATION IN LUNAR SCIENCE 16 - 18 JULY 2018

Programme

Time	Duration	Presenter	Title
Day 1, M	onday, 16 J	uly	
09:30	00:05	Welcome and Intr	oductions
09:35	00:15	CNSA Missions ar	nd plans
09:50	00:15	ESA Missions and	plans
10:05	00:10	Discussion	
10:15	00:25	Yongliao Zou	Proposal science goals and its payloads for China future lunar research station
10:50	00:15	Break	
11:05	00:45	Interactive sess infrastructure of	ion: Science, instrumentation and enabling of an international Lunar Research Station
11:50	00:15	Xiaohua Tong	Detecting Hazardous Obstacles in Landing Site for Chang-E Spacecraft by the Use of a New Laser Scanning imaging System
12:05	01:00	Lunch	





Lunar Sample Science Part 1				
13:05	00:25	Wim van Westrenen	New Petrological Views of the Moon Enabled By Apollo Sample Return	
13:30	00:15	Xiaohui Fu	Petrography and mineralogy of lunar feldspathic breccia Northwest Africa 11111	
13:45	00:15	A.C. Zhang	Applications of SEM-EBSD in lunar petrology: 'Cr- Zr-Ca armalcolite' is loveringite	
14:00	00:15	Yanhao Lin	Evidence for extensive degassing in the early Moon from a lunar hygrometer based on plagioclase-melt partitioning of water	
14:15	00:15	Hongping Deng	Primordial Earth mantle heterogeneity caused by the Moon-forming giant impact	
14:30	00:25	Alessandro Morbidelli	The deficiency of HSEs in The Moon relative to The Earth and The history of Lunar bombardment	
14:55	00:15	Romain Tartèse	Recent advances and future challenges in lunar geochronology	

15.10	00:15	Drook
15.10	00.15	DIEak

15:25	00:25	Marc Chaussidon	Lunar soils as archives of the isotopic composition of the Sun and of the impact history of the Moon
15:50	00:15	M. Schönbächler	Tracing the origin of the Moon with isotopes
16:05	00:15	Ian Franchi	New Oxygen Isotope Constraints for the Origin of the Moon
16:20	00:25	Paul Savage	New stable isotope insights into the formation and evolution of the Moon
16:45	00:15	Hejiu Hui	Lunar anorthosites and lunar magma ocean model
17:00	00:15	Z. Deng	Using Titanium Isotopes to Trace Magma Ocean Evolutions of the Moon and Mars
17:15	00:15	Joshua Snape	Secondary Ion Mass Spectrometry (SIMS) Pb isotopic analysis of lunar basalts





17:30	Posters and Reception
19:00	End

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Lunar Sample Science Part 2				
09:00	00:25	L. Qin	Chromium isotope anomalies of lunar rocks	
09:25	00:15	P.A. Sossi	Cold volatile loss from the Moon revealed by chromium isotopes	
09:40	00:15	Ke Zhu	Chromium stable isotopic evidence for the origin of the volatile depletion from Vesta	
09:55	00:25	Mahesh Anand	Laboratory measurements of H, Cl and other volatiles in lunar samples: scientific implications and considerations for future returned samples.	
10:20	00:25	Evelyn Füri	Origin of volatiles (H, N, noble gases) on the Moon: Constraints from analyses of single lunar soil grains	
10:45	00:15	Dayl Martin	Apollo Sample Analysis and Lunar Simulant Curation Activities at ESA ECSAT	
11:00	00:15	Break		
11:15	00:15	Yangting Lin	Proposal for Pre-Chang'e 5 Consortium Study of Lunar Samples	
11:30	00:15	Katherine Joy	Joint Community Report China-European coordination on Lunar Sample Analysis	

11:45	00:45	Discussion: A CNSA-ESA Joint Laboratory for Lunar Samples and Materials	
12:30	01:00	lunch	





Recent A	Advances In	Lunar Science	
13:30	00:25	Ralf Jaumann	Current understanding of the Moon, key questions to address in the future

Recent	Advances	in Lunar Science	1: Landing Sites
13:55	00:25	Jianjun Liu	Study on the landing sites of China's upcoming lunar missions
14:20	00:25	Zhizhong Kang	Geological map and age determination in landing sites of Chang'E missions
14:45	00:25	C. H. van der Bogert	Proposed Landing Sites in the South Pole-Aitken Basin for Upcoming Lunar Missions
15:10	00:15	Break	
15:25	00:15	C. Orgel	Potential Landing Sites for the Chang'e-4 Exploration Mission to the Apollo Basin, Moon
15:40	00:15	Jun Huang	Chang'E-4 Landing site characterization
15:55	00:15	L. Xiao	Geological Characteristics, Proposed Landing/sampling Sites and Anticipated Science Return of the Chang'E-5 Landing Region
16:10	00:15	Z. Yue	High Resolution Mapping and Geologic Analysis of Chang'e-5 Landing Area
16:25	00:15	D. Rommel	Volcanic structures in the von Kármán region inside the South Pole-Aitken basin
16:40	00:15	E. Sefton-Nash	Constraints on lunar polar volatiles from remote sensing datasets
16:55	00:15	J. Flahaut	Lunar polar regions of interest for future exploration





Time	Duration	Presenter	Title
Day 3			

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09:15	00:15	C. Wöhler	New insights into surficial hydroxyl/water on the Moon	
09:30	00:15	S. De Angelis	Planetary surfaces spectroscopy laboratory facilities at INAF-IAPS	
09:45	00:15	S. J. Barber	Lunar Science, Volatiles Prospecting and In-Situ Resource Utilisation: Science-Exploration Synergies at The Open University, UK	
10:00	00:15	T. Liu	Numerical modelling of evolving diffusion of impact melt and its implication on the future sampling work	
10:15	00:15	F. Zhang	Ring-Moat Dome Structures in the Lunar Maria: enigmatic features as potential candidate for future explorations	
10:30	00:15	K. Donaldson Hanna	Remote Sensing Constraints on the Formation and Evolution of the Moon's Anorthositic Crust	
10:45	00:15	M. Martinot	Surveying the lunar crust-mantle boundary with Moon Mineralogy Mapper data	
11:00	00:15	Break		

11:15	00:45	Discussion session: A CNSA-ESA Joint Lunar Research Team Facilitators: James Carpenter and Ruihong Yang
12:00	01:00	Lunch





Exosphere and heliophysics			
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13:15	00:15	M. Y. Wang	Electron Density Profile of Lunar Ionosphere Based on Radio Occultation of the Service Module of Circumlunar Return and Reentry Spacecraft

Physics a	Physics and Astronomy			
13:30	00:15	J. Ping Jointly Promoting Low-frequency Radio Astronomical Detectors in the Earth-Moon between China and Europe		
13:45	00:25	J. Ping	Developing High Precise Laser and Radio Ranging Techniques in Missions for Lunar and Planetary Dynamical Evolution Exploration and General Relativity Test	

Measuring the Lunar interior			
14:10	00:15	T. Kawamura	French-Chinese Collaboration towards seismic observation on the Moon
14:25	00:15	P. Lognonné	The VBB seismometer: From InSight performances to perspectives on Lunar Missions

14:40	00:15	Break

15:55	00:45	Discussion: Request for Information for Payloads and Science Contributions		
15:40	00:20	James Carpenter Meeting outcomes and for and Ruihong Yang	ollow on activities	

	16:00	End
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Posters	
C. P. Tang	A Textural/Mineralogical Gradient Within Vitrophyric Mare Basalt NWA 8632A
J. F. Pernet-Fisher	The hunt for indigenous signatures within Lunar anorthosites
Wei Zuo	CLEP Lunar Science Archive Architecture and Data Management
S. Besse (TBC)	ESA approach to data management and archiving
Xiongyao Li	Indication of lunar soil properties on space weathering
H. Tang	The Characteristics of Water in Plagioclase by Proton Implantation Experiments
M. Formisano	PROSPECTing the Moon: Numerical simulations of temperature and sublimation rate on a regolith cylindric sample
M.C. De Sanctis	A miniaturized spectrometer for surface and subsurface investigations
N. Schnuriger	Long-lived volcanism expressed through mare infilling, domes and IMPs in the Arago region of the Moon
Y. Lu	Young wrinkle ridges in Mare Imbrium: Distribution, morphology and formation times
M. Mokhtari	Experimental determination of the Zinc isotopic fractionation factor during evaporation
Additional posters (TBC)	





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Detecting Hazardous Obstacles in Landing Site for Chang-E Spacecraft by the Use of a New Laser Scanning imaging System

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The mission of hazard detection and avoidance is one of the critical technologies for safe spacecraft landing in deep space exploration. In China's first unmanned landing mission on the moon on December 14, 2013, a new laser scanning imaging system was developed and successfully used in Chang'e-3 lander in the landing stage of so-called hovering and obstacle avoidance above the moon surface. This paper addressed some critical issues of the developed three-dimensional laser scanner system equipped in Chang'e-3 lander for detecting precisely the obstacles such as lunar rocks and craters on the moon surface when the lander hovers 100 m above the moon surface. An empirical experiment was conducted at a specifically designed simulated field. The results showed the high degree of trust in detection of craters and rocks by the use of the new laser scanning imaging system.

New Petrological Views of the Moon Enabled By Apollo Sample Return

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This presentation will highlight some of the main advances in lunar petrology made over the past 49 years since the first Apollo samples were returned to Earth. Emphasis will be placed on advances related to the early history and temporal evolution of the surface and the interior of the Moon, including new sample-driven views of the lunar crust, mantle and core. Key petrological issues that could be addressed by future sample return missions will also be discussed.

Petrography and mineralogy of lunar feldspathic breccia Northwest Africa 11111

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1. Introduction

Lunar meteorites are an important source of material from the Moon. They have greatly increase the diversity of highland materials beyond those collected by Apollo and Luna missions, and present challenges to the Lunar Magma Ocean (LMO) theory ^[1-5]. Northwest Africa 11111 is a new found feldsparthic breccia with gray shock melt veins. The Fe/Mn ratios of olivine in rock clasts and matrix range from 77.77 to 111.3, from 70.9 to 113.5, respectively. The Fe/Mn ratios of pyroxene are in the range of 39.5-80.8 ^[6]. These are the strong evidence of its lunar origin. Based on the petrography and mineralogy investigation of NWA 11111, it was found that this meteorite is mainly anorthositic composition with a limited content of Mg suite lithic clasts. We presumed that the meteorite was derived from lunar farside.

2. Analytical methods

Raman spectra of NWA 11111 were measured by Renishaw inVia® Raman Microscope in Shandong University, Weihai, China. Back-scattered Electron (BSE) image of NWA 1111 section was obtained with FEI SEM in Shandong University. Chemical composition of minerals were determined using an Oxford INCA EDS (IE250X-Max50) with an ultrathin windowed Si (Li) detector.

3. Petrography and Mineralogy

The NWA 11111 section was about 1.5 cm × 2.8 cm in size. This rock has a polymica feldspathic breccia texture mainly composed of anorthosite and various types of Mg suite clasts (gabbro, norite, and troctolite), mm-sized relict crystal clasts (pyroxene, plagioclase, olivine, with minor ilmenite) and impact melts. The dark recrystallized matrix is composed of fine-grained plagioclase, pyroxenes, and minor olivine, ilmenite and glass. No clasts with mare basalt compositions were observed. The fusion crust is absent in this meteorite. And terrestrial alteration products (such as Ba sulfates) are present at the meteorite edges and in penetrating cracks.

The anorthosite clasts are the most aboudant in this meteorite. This lithic clast are composed of plagioclase and minor pyroxene and olivine. Plagioclase (An=95-99) all show irregular fractures. Mafic minerals uneven distributed in this clast. The anhedral olivine (Fo=75) is the main phase of these mafic minerals, indicating late crystallization in the melt. Plagioclase and olivine grains all have well equilibrated. This implies a slow crystallization in an equilibrium system under a certain depth.

Several Mg suite clasts have been found in this meteorite, including gabbro, norite, and trocolite. Gabbro clast consists of plagioclase, pyroxene and olivine (Fo=60-75). All these mafic minerals in them are subheral-anhderal, 10-20 micron in size. Pigeonites in gabbro clasts show very fine-scale exsolution lamellae of augite. In the norite clasts, plagioclase (An=95-99) is 200 μ m in size and show irregular fractures. Raman spectra of this mineral exhibits one broad peak at 508 m⁻¹. This is clearly due to shock effects. However, plagioclases are not totally transformed into maskelynite. The chemical analysis suggests the pyroxenes in this clast are all pigeonites (Fs₃₃Wo₂En₆₅). There are no chemical zoning or exsolution found in the pyroxene. The olivine and pyroxene in these Mg suite clasts range in Mg# from 50 to 75 and 20 to 70, respectively.

4. Conclusions

NWA 11111 contains various lithologies and many minerals fragments. It represents a mixture of pristine anorthositic rocks and various Mg suite clasts. The pyroxene exsolutions are common found in pigeonite as relict crystal fragments and in Mg suite clasts, indicating of complex petrologic history. This meteorite offers an unique sampling of the diversity of lithologies found within the lunar highland (possible derived from lunar farside).

5. References

[1] Korotev et al. (2003) GCA, 67, 4895-4923.

- [2] Korotev et al. (2006) Chemie der Erde, 65, 297-346.
- [3] Day et al. (2006) GCA, 70, 5957-5989.
- [4] Joy and Arai (2013) Astronomy & Geophysics, 54, 4.28-4.32.
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- [6] Meteoritical Bulletin Database, https://www.lpi.usra.edu/meteor/metbull.php?code=64747

Applications of SEM-EBSD in lunar petrology: 'Cr-Zr-Ca armalcolite' is loveringite

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1. Introduction

Armalcolite is a mineral that was first discovered in Apollo samples and named after the three astronauts in the Apollo 11 mission [1]. It is a Ti-rich oxide with an ideal chemical formula (Mg_{0.5}Fe_{0.5})Ti₂O₅. Armalcolite was usually observed accompanied by another Ti-rich oxide, which contains a few weight percent of Cr₂O₃, ZrO₂, and CaO. This Cr-Zr-Ca-rich Ti-oxide was termed as 'Cr-Zr-Ca armalcolite' since then [2-3]. 'Cr-Zr-Ca armalcolite' was also observed in terrestrial rocks. However, armalcolite is an oxide containing small polyhedral sites for Mg and Fe. In principle, cations with a large radius such as Ca²⁺ are not readily to be incorporated into armalcolite [4]. This leads to a puzzle whether 'Cr-Zr-Ca armalcolite' is armalcolite or not. Unfortunately, due to small grain sizes, the 'Cr-Zr-Ca armalcolite' that was described in the literature was not structurally characterized. During detailed petrologic investigation of a lithic clast (Clast-20) from a feldspathic lunar meteorite Northwest Africa (NWA) 8182, we characterized the structure of 'Cr-Zr-Ca armalcolite' with SEM-EBSD technique. The result reveals that 'Cr-Zr-Ca armalcolite' is loveringite, not armalcolite.

2. Results

The lithic clast Clast-20 is a Mg-suite clast of approximately 1.3 mm × 0.7 mm in size. It contains mainly of plagioclase (An=88-91, 55.8 vol%), olivine (Mg#=0.85-0.86, 28.2 vol%), and pyroxene (Mg#=0.87-0.91, 14.4 vol%). Accessory minerals (1.6 vol%) include various Ti-rich oxide minerals, chromite, merrillite, FeNi metal, and Fe-sulfide. Both armalcolite and loveringite were observed as the common Ti-rich oxide minerals in Clast-20. They mainly occur as discrete grains and are closely associated with olivine or pyroxene. Armalcolite is dominated by TiO₂, MgO, and FeO with a Mg# value of 0.58-0.64. The Cr₂O₃, ZrO₂, and CaO contents are 0.86-1.95 wt%, 0.43-0.63 wt%, and 0.35-0.79 wt%, respectively. Its EBSD pattern can be well indexed with a pseudobrookite structure (MAD=0.26). The loveringite grains in Clast-20 contain 67.5-69.7 wt% TiO₂. Their MgO and FeO contents (2.70-3.02 wt% and 8.55-9.36 wt%, respectively; Mg#=0.35-0.38) are lower than armalcolite. They contain high contents of Cr₂O₃ (8.40-10.0 wt%), ZrO₂ (3.65-4.30 wt%), and CaO (3.96-4.21 wt%). Its EBSD pattern cannot be indexed with an armalcolite structure. Instead, it can be well indexed with the loveringite structure (MAD=0.22).

3. Discussion and conclusion

Loveringite in Clast-20 is distinctly different in chemistry from terrestrial loveringite [5] and the loveringite in a chondrules from Allende [6]. Instead, it is similar to 'Cr-Zr-Ca armalcolite' in lunar samples in three aspects: (1) mineral chemistry; (2) mineral assemblage; and (3) lithology of their host rock. Therefore, the phase 'Cr-Zr-Ca armalcolite' that was observed in lunar samples in previous investigations should be loveringite as well. The fact that 'Cr-Zr-Ca armalcolite' is loveringite has two aspects of significance. First, it can perfectly explain the crystallographic puzzle that cations with a large radius such as Ca²⁺ cannot be incorporated into armalcolite. Second, loveringite with large polyhedral sites could be an important carrier of rare earth elements [4], which might play a similar role to merrillite. This would be important for understanding the chemical properties of Mg-suite rocks in the Moon.

4. References

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Evidence for extensive degassing in the early Moon from a lunar hygrometer based on plagioclase-melt partitioning of water. Yanhao Lin^{1*}, Hejiu Hui², Yuan Li³, Yongjiang Xu² and Wim van Westrenen¹

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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 H_2O) in lunar samples [1-4] and experiments [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 partition coefficients for hydrogen are required, with $D_{water}^{plag-melt} = C_{OH}^{plag} / C_{OH}^{melt} = C_{H}^{plag} / C_{H}^{melt}$. Unfortunately, to date, no plagioclase-melt partitioning data for water are available under lunar conditions. In this study, $D_{water}^{plag-melt}$ was measured for the first time at lunar-relevant pressure-temperaturecomposition-oxygen fugacity conditions using highpressure 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.

Experiments produced plagioclase crys-**Results:** tals in equilibrium with quenched melt (Figure 1). The hydrogen concentrations of our samples measured by using a Nicolet IS50 Fourier Transform Infrared Spectrometer (FTIR) range from 42.2±6.6 to 99±36 ppm OH in plagioclase and from 0.13±0.01 to 1.74±0.01 wt.% OH in glass. The corresponding partition coefficients range between 0.002±0.0004 and 0.046±0.0096. 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 $(D_{water}^{plag-melt} = 0.001 - 0.006$ based on Hamada et al. [11]). Our highest partition coefficient is ~10 times higher than previously reported values.



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

Discussion and Conclusions: The recent study published to date of the water content of lunar plagioclase reported ~5 ppm water (H₂O equivalent) in ferroan anorthosite samples [12], thought to be a primary crystallization product of the LMO [9,13]. Our experiments constrains $D_{water}^{plag-melt}$ to 0.002–0.046 under lunar conditions. Using our newly calibrated partition coefficient in combination with the published water contents of lunar plagioclase, we conclude that ~100 ppm H₂O may have been present in the residual magma when 95 % of the initial LMO had crystallized. This is significantly lower than the water content of the residual LMO calculated from crystallization of a closed-system LMO with the initial LMO water content constrained by laboratory high-pressure experiments. This indicates >99 % hydrogen degassing may have occurred during LMO crystallization, suggesting a highly dynamic early volatile cycle on the Moon.

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Primordial Earth mantle heterogeneity caused by the Moon-forming giant impact

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The giant impact hypothesis for Moon formation[1, 2] successfully explains the dynamic properties of the Earth-Moon system but remains challenged by the similarity of isotopic fingerprints of the terrestrial and lunar mantles[3]. Recent work however identified shortcomings in the hydrodynamical method that is routinely used for impact modeling[4]. Using an advanced method, we here show that Moon-forming giant impacts naturally lead to a compositionally stratified terrestrial mantle. The upper layer of the Earth is compositionally similar to the disk, out of which the Moon evolves, whereas the lower layer preserves proto-Earth characteristics. If this predicted compositional heterogeneity is at least partially preserved over the subsequent billions of years of Earth-mantle evolution, the compositional similarity between the Moon's and the accessible Earth's mantle is a natural outcome of realistic and high-probability Moonforming impact scenarios[5]. Such a preservation can indeed provide a unified explanation for a range of previously poorly understood geophysical and geochemical constraints[6–11]. Moreover, considering the preservation of an ancient mantle reservoir, the bulk composition of the Earth-Moon system is systematically shifted toward chondritic values.

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The deficiency of HSEs in the Moon relative to the Earth and the history of Lunar bombardment

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1. Introduction

The timeline of the lunar bombardment in the first Gy of Solar System history remains unclear. Basinforming impacts (e.g. Imbrium, Orientale), occurred 3.9--3.7 Gy ago, i.e. 600-800 My after the formation of the Moon itself. Many other basins formed before Imbrium, but their exact ages are not precisely known. There is an intense debate between two possible interpretations of the data: in the cataclysm scenario there was a surge in the impact rate approximately at the time of Imbrium formation, while in the accretion tail scenario the lunar bombardment declined since the era of planet formation and the latest basins formed in its tail-end. Here, we revisit the work of [1] that examined which scenario could be compatible with both the lunar crater record in the 3-4Gy period and the abundance of highly siderophile elements (HSE) in the lunar mantle.

2. Methods and Results

We use updated numerical simulations of the fluxes of asteroids [2], comets and planetesimals leftover from the planet-formation process. Under the traditional assumption that the HSEs track the total amount of material accreted by the Moon since its formation, we conclude that only the cataclysm scenario can explain the data. The cataclysm should have started 3.95 Gy ago. However we also consider the possibility that HSEs are sequestered from the mantle of a planet during magma ocean crystallization, due to iron sulfide exsolution [3,4]. We show that this is likely true also for the Moon, if one accounts from the bottom-up crystallization of the lunar mantle and the final mantle overturn. Based on the hypothesis that the lunar magma ocean crystallized about 100-150 My after Moon formation [5], and therefore that HSEs accumulated in the lunar mantle only after this timespan, we show that the bombardment in the 3-4Gy period can be explained in the accretion tail scenario. This hypothesis would also explain why the Moon appears so depleted in HSEs relative to the Earth, without requiring ad-hoc size distribution of the projectiles as proposed in [6].

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Recent advances and future challenges in lunar geochronology.

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Geochronological studies of lunar samples seek to address fundamental questions such as: (i) When did the Moon form? (ii) When did major lunar reservoirs (crust, mantle, etc.) solidify? (iii) When were major lunar basins and craters formed? (iv) When was the Moon volcanically active?

The age and early evolution of the Moon remain highly controversial topics despite more than 40 years of investigation of Apollo and meteorite samples. Constraints from the iodine-plutonium-xenon system suggest that the Moon-forming event may have occurred ca. 40 ± 20 million years after the start of the Solar System (at 4.567 Ga) [1]. On the other hand, modelling of the Pb isotope evolution of the Earth mantle seems to point to a much younger Moon-forming event at ca. 4.42 Ga, more than 100 million years after the start of the Solar System [2]. After its formation, it is thought that a globally molten Moon differentiated into major geochemically distinct silicate reservoirs, which include a cumulate mafic mantle, a primary plagioclase-rich crust, and a layer enriched in incompatible elements such as K, REE and P. Mare basalts that cover large areas of the lunar nearside formed through partial melting of the lunar mantle, and, thus, provide constraints on the geological evolution of the lunar interior. Recent Pb isotope data obtained on a range of mare basalts point to differentiation of these major lunar reservoirs at ca. 4.38 Ga [8], suggesting that it took tens to hundreds millions of years for the lunar interior to fully solidify [3]. Obtaining precise crystallisation ages for the global spectrum of lunar basaltic units is also crucial to constrain the timing of volcanic activity on the Moon. While ages derived from sample studies indicate that basaltic volcanism occurred between around 4.3 and 2.9 Ga (see compilation in [5]), remote-sensing studies suggest some basaltic units may be as young as around 1.0-1.5 Ga [4]. Finally, the timing of formation of more than 40 lunar basins is still poorly understood, preventing us to derive firm constraints on the duration, magnitude, and types of impactors delivered to the Earth-Moon system during the basinforming epoch [6-7]. Better constraints on the age of these basins will help understanding the bombardment history of the inner Solar System as a whole, which may have had important implications on the early Earth geological evolution at a time when life started to flourish.

In this presentation, I will highlight some of the recent analytical advances in lunar chronology carried out in labs across Europe that allow tackling these key science questions. Importantly, I will also discuss the limits of our current lunar sample set, which undoubtedly represents a biased collection from a geographically restricted and geochemically anomalous area of the Moon, and how further constraints on these critical science questions will benefit immensely from 'new' samples collected *in situ* from regions of the Moon not visited previously.

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Lunar soils as archives of the isotopic composition of the Sun and of the impact history of the Moon.

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The Sun, because it contains most of the mass of the solar system, has the bulk chemical and isotopic composition of the solar system. While it has been known for long that chondritic meteorites have average chemical compositions close to that of the Solar photosphere, the large variations observed in chondrites for the isotopic compositions of the light elements (C, O, N) have made the isotopic composition of the Solar photosphere with a precision high enough to make these data useful for constraining the early evolution of the solar system and the origin of the first solids and planetesimals.

In the last 20 years in situ techniques using secondary ion mass spectrometry have been developed to determine with high-precision the isotopic composition of solar wind implanted in lunar soils [1-6]. The lunar regolith has accumulated implanted solar wind for exposure ages which can be higher than 1 Gyr. It is thus a very promising archive of the isotopic composition of the Sun. The study of implanted solar wind in lunar soils is however made very difficult by (i) the low concentration of solar wind implanted particles which peak at around 50 nm depth in the lunar grains, (ii) the fact that the lunar grains are poor-collectors because they contain all the elements present in the Moon, and (iii) the presence of other extra lunar components at the Moon surface (e.g. due to impacts). However, careful studies of the variations with depth of concentrations and isotopic compositions of Li, C, N and O have allowed to determine the isotopic composition of the Earth and chondrites. More precise values for these compositions have been obtained from the analysis by ion microprobe of the solar wind collectors of the Genesis NASA mission [7, 8]. These results are of prime importance to unravel the processes by which the first solids were formed in the solar accretion disk.

The study of the variations with depth of the isotopic composition of minerals from lunar soils is also very important because it could potentially constrain the origin and flux of material to the Moon via impacts, in particular the addition of water (and other volatiles) to the Moon by cometary impacts.

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Tracing the origin of the Moon with isotopes

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Due to significant analytical developments, ultra-high precision isotope analyses have become available over the past decade. This triggered the detection of widespread isotopic variations in meteorites, lunar and terrestrial samples at the parts per million level. These variations are generated by different processes such as radioactive decay, galactic cosmic rays or the heterogeneous distribution of presolar dust, produced in different stellar environments, in our solar system (nucleosynthetic variations). These new data provide valuable constraints on the processes involved during accretion and early planetary evolution of the Earth and Moon. The early compositional evolution of the Earth was shaped by accretion, core formation, and the loss/addition of volatile elements. The last large accretion step in the Earth's history is generally attributed to a catastrophic giant impact, in which a large impactor called Theia collided with proto-Earth and which resulted in the formation of the Moon.

The Earth and Moon exhibit an astonishing similarity in isotopic compositions. Nevertheless, a growing number of elements reveal well–resolved, distinct nucleosynthetic compositions for each meteorite parent body (including Mars) compared to the rather uniform Earth-Moon system. This indicates that each planetary body acquired its own dust mixture from the protoplanetary disk. The nucleosynthetic isotope variations mostly occur in refractory elements and include e.g., Ca, Ti, Zr, Mo and Pd. While lighter elements (e.g., Ca, Ti) bear testimony to the heterogeneous distribution of supernova dust in our solar system e.g., [1, 2], heavier elements such as Zr and Pd are best explained by the heterogeneous distribution of *s*-process material formed around AGB-stars [1,3].

The expected nucleosynthetic composition of the impactor Theia can be modelled based on massbalance consideration and todays compositions of Earth and Moon [4]. We considered different dynamical simulations of the giant impact scenario (for details see [4]). The resulting compositions for Theia were compared to those of actual solar system materials.

The outcome of our modelling shows that Theia could not have consisted of carbonaceous chondrite-like material. This conclusion is independent of the chosen giant impact model and is thus a strong constraint. It indicates that volatile-rich material originating from the outer solar system can be excluded for Theia [4]. Moreover, we showed that ordinary chondrite and eucrite-like materials are also rather unlikely for Theia, although material with relatively large isotopic deviations from the Earth-Moon system today can be tolerated as impactor material depending on the considered impact scenario [4]. We propose, however, that it is more likely that protoEarth and Theia shared very similar isotopic compositions [4] in agreement with other studies [2]. This indicates that the inner solar system (or more precisely the accretion region of the Earth, Theia and enstatite chondrites) had very similar isotopic compositions. More samples from the inner solar system, such as Venus and Mercury, would be desirable to better constrain the origin of Theia.

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New Oxygen Isotope Constraints for the Origin of the Moon

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1. Introduction

While there is now general acceptance for the formation of the Moon as a result of a late-stage giant impact involving a Mars-sized planetary object (named Theia) with the Earth (e.g. [1]), confirmation of this event, and key details of the model remain elusive. Isotopic similarities between the Earth and Moon have played a critical role in constraining the nature of the Moon-forming event. Near identical isotopic ratios have been observed for a range of elements, including silicon, titanium magnesium, and initial tungsten (reviewed by [2]). Oxygen, as the major rock-forming element also has a similar isotopic composition. However, whether there is a measurable difference in oxygen with respect to the ¹⁷O excess (termed Δ^{17} O), has received considerable debate over recent years [3-5].

2. Discussion

The Open University pioneered the use of laser fluorination, high-precision, oxygen 3-isotope measurements [3] and has continued to provide input to the definition of the Earth-Moon isotopic composition [4, 5]. Most recently, Greenwood *et al.* [6] provided the definitive measurement of the difference between the Earth and Moon, based on repeated measurements of 17 different lunar rocks that represent all the main lithologies from the 6 Apollo landing sites, together with 14 mineral separates and a further 20 terrestrial samples. In this study we confirmed a statistically resolvable difference of 3 to 4 ppm between the lunar basalts and terrestrial rocks.

Although the aubrites have an oxygen isotopic composition that is closer to the Earth than any other meteorite group, the extremely small, measured Δ^{17} O difference between the Earth and Moon means that much less impactor material could have contributed to the Moon than predicted by typical impact models [6]. Rather, we argued that this small Δ^{17} O difference was consistent with very high energy models of the Moon-forming event that resulted in the development of an extended disk of vapourised rocky material, known as a "synestia", and resulted in virtually complete isotopic homogenisation of the impactor and target [7]. If the system was homogenised with respect to the isotopic composition then the small difference in Δ^{17} O also greatly limits the amount of water that could have been delivered to the Earth during late accretion, as all reasonable source of exogenous water have quite distinct O-isotope compositions. This means that most of the Earth's water was delivered prior to the Moon-forming event.

One of the challenges going forward is to understand how representative the Apollo samples are of the entire Moon. It is clear that the Apollo landing sites are all restricted to a rather anomalous region of the Moon's surface with regards to chemical composition (*e.g.* KREEP-rich). Furthermore, recent Cl isotopic measurements by Barnes *et al.* [8] argued for the urKREEP source region having experienced a specific late-stage impact-driven degassing event, the consequences of which, for the regional bulk composition, have not yet been fully explored. While lunar meteorites appear to have sampled lithologies beyond those present in the Apollo collections, such materials are not ideal for high precision isotopic measurements, having experienced terrestrial weathering, as well as extensive processing on/near the lunar surface. Therefore, efforts to further constraint the isotopic signatures of the Earth-Moon system would be greatly advanced by addition of new materials from lithologies beyond those already sampled.

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New stable isotope insights into the formation and evolution of the Moon

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The continued development of new isotopic analysis techniques, most notably the evolution of MC-ICP-MS technology, has, over the last two decades, opened up the periodic table – providing us with the ability to precisely measure a vast array of isotope systems, in many cases for the first time, across the gamut of geological and extra-terrestrial materials [1]. This has allowed for new insights to be drawn about the processes and physiochemical conditions associated with the formation and subsequent chemical evolution of our Moon.

This talk will attempt to review what are, in our view, the most significant results to be drawn from the analysis of 'novel' stable isotope systems regarding our nearest celestial neighbour. These include Si isotope evidence for the provenance of material which formed the Moon [2] which, along with the similarity of lunar and terrestrial material for isotope anomalies (O and Ti in particular) has led to the so-called 'lunar isotopic crisis' and heavily influenced subsequent models of lunar formation [e.g. 3]. Secondly, the relatively recent ability to analyse to high precision the isotopic composition of more volatile elements, such as Zn, Ga and K, in lunar rocks has provided strong evidence for the violent nature of lunar formation and its early history [4, 5, 6]. Thirdly, more refractory stable isotope systems such as Ti, which do not see the isotopic effect of evaporative loss, can potentially begin to inform us about chemical variations and igneous processes within the lunar mantle [7].

In many cases, these new lunar isotopic analyses have also provided us with new questions and new avenues of investigation. The application of novel isotope systems to our Moon is still in its relative infancy, and with more and more isotope systems being 'added' to our armoury and the promise of new sample return, we are in an exciting time for lunar science.

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Lunar anorthosites and lunar magma ocean model

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1. Introduction

It has been generally accepted that a global magma ocean formed on the very early Moon. By this model, the early Moon was partially or entirely molten. The lunar magma ocean (LMO) crystallized as it cooled. After ~75-80% solidification of the LMO, Ca-rich plagioclase crystallized and floated to form ancient anorthositic crust of the Moon [1, 2], which is generally consistent with anorthositic rocks observed remotely on the Moon's surface and geochemical data of the Apollo samples and lunar meteorites. However, recent studies on lunar samples have shown that the a simple LMO model could not explain the wide ranges of trace element distributions in anorthositic plagioclases [3] and ages of lunar anorthosites and magnesian suite rocks [1]. This indicates that there are at least complexities in the process of lunar crust formation [3, 4].

The simple model of the LMO was proposed based on the Apollo samples, which have only sampled limited regions of the Moon. Meteorites, on the other hand, which randomly sampled the Moon's surface, may be more representative. Therefore, any study of anorthositic clasts in lunar meteorites could bring more insights into the magmatic evolution of the early Moon.

2. Analyses and results

We have studied 53 anorthositic clasts in 10 lunar feldspathic breccia meteorites. Major and trace elements in plagioclase of the clasts were measured using electron probe microanalyzer (EPMA) and laser ablation ICP-MS, respectively. The major element compositions of our plagioclases are similar to those in anorthositic clasts of ALHA 81005 and NWA 2966 [4]. The rare earth element (REE) distribution patterns of plagioclase are generally similar to those of Apollo ferroan anorthosites, Dhofar 908 and Dhofar 081 [3].

3. Discussions and implications

The highest and lowest abundances of REE in our anorthositic plagioclases with similar anorthite contents (An95-97) can differ by more than one order of magnitude, similar to those in Dhofar 908, Dhofar 081, and Apollo ferroan anorthosite [3, 5, 6]. This indicates that at least some anorthosites could have experienced different geologic processes. Furthermore, the REEs in anorthositic plagioclase do not coevolve. They show different evolution trends. This suggests that the anorthosites could have different source regions. The REEs of melts in equilibrium with plagioclases could be explained by LMO-derived anorthosites assimilated/metasomatized by mantle-derived melts and KREEP melts. The alteration may have occurred after the formation of feldspathic crust, which could explain the wide range of ages for lunar anorthosites.

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Using Titanium Isotopes to Trace Magma Ocean Evolutions of the Moon and Mars

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Magma ocean crystallisations during the earliest stages of planetary evolution play a major role in creating the initial compositional heterogeneity in planetary mantles and crusts. For example, the magma ocean differentiation of the Moon has produced an ultramafic mantle and an anorthositic crust. However, the consequences of the magma ocean evolutions in other planets like Mars and Earth can be very diverse due to the different magma ocean crystallization behaviours for varying core-mantle segregation histories and volatile budgets [1]. While large Ti isotopic fractionations have been documented in terrestrial differentiated rocks [2], our recent work demonstrates that, at a typical SiO₂ content, Ti isotope ratios are more fractionated in plume magmas than in island arc magmas [3]. Such a discrepancy arises from the fact that the plume magmas (tholeiitic) are more reduced and less water-rich than the island arc magmas (calc-alkaline), leading to the contrasting crystallization mineral assemblages during magma differentiation [4, 5]. Thus, Ti isotopes are powerful tracers of the fractional crystallization behaviours during the magma ocean stages of rocky planets.

While the initial magma ocean information of the Earth have been obscured by global processes like plate tectonics and mantle convection, Mars and the Moon have preserved some rocky records from the earliest magma ocean stage [6]. We will present Ti stable isotopic data from a large set of lunar samples and Martian meteorites (including the mafic to felsic igneous clasts of NWA 7034 meteorite), and discuss the solidification processes during the magma evolutions of the Moon and Mars.

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Secondary Ion Mass Spectrometry (SIMS) Pb isotopic analysis of lunar basalts

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1. Introduction

Samples of lunar basalt provide a direct record for the magmatic evolution of the Moon. Basalt samples collected during the Apollo and Luna missions have crystallisation ages ranging from approximately 4300-3100 Ma, with the vast majority comprising the mare basalts collected during the Apollo 11, 12, 15 and 17 missions, which have been dated to between 3800-3100 Ma. In the last few years, our group has developed an approach for determining precise crystallisation ages (2σ errors typically within ±15 Ma) and initial Pb isotopic compositions of lunar basalts with *in situ* Secondary Ion Mass Spectrometry (SIMS) measurements [1,2]. Here we present our most recent compilation of basalt ages (Fig. 1), representing the main mare basalt groups sampled during the Apollo missions.

2. Results and Discussion

The eruptive sequences of the Apollo 11 and 17 high-Ti basalts are clearly distinct, with different groups of the Apollo 11 basalts being emplaced over a period of more than 300 million years, from ~3850-3530 Ma, while Apollo 17 basalts were emplaced over a much shorter period (~40 million years) between ~3780-3740 Ma. Crystallisation ages of between ~3250-3130 Ma and 3360-3280 Ma are determined for the Apollo 12 and 15 low-Ti basalts, respectively. The basalts from each of these missions have previously been categorised based on their elemental and isotopic compositions, and our new crystallisation ages are generally very consistent with these classifications.

The initial Pb isotopic compositions determined by this approach have enabled the development of a new Pb isotopic model for the early lunar magmatic evolution [1], describing the formation of distinct mantle reservoirs for the lunar basalts from an undifferentiated bulk silicate Moon. Building on this model, we have begun to integrate our Pb isotopic data with existing data from other isotope systems (e.g. Rb-Sr and Sm-Nd) to examine the evolution mantle sources that resulted in the range of basaltic suites seen, for example, at the Apollo 12 landing site [2].



Figure 1: A summary of new crystallisation ages determined for Apollo mare basalts (error bars represent 2o uncertainties).

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Chromium isotope anomalies of lunar rocks (max. 40 words)

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1. Introduction

It has been favourably proposed that the Moon formed as a consequence of a Mars-sized planetary embryo impacting the Earth late in its accretion and the Moon accreted mainly from the impactor [1]. As the impactor likely had distinct a isotopic composition from the Earth, the Moon is expected to be isotopically different from the Earth. However no isotopic anomalies for Ti and O has been identified for lunar samples [2,3]. Another element that can provide additional constraints is Cr [4]. A recent study found that the Cr isotopic composition of the Moon was compromised by the presence of cosmogenic effects [5]. Mougel et al. [5] tried to correct for these cosmogenic effects by correlating Cr isotopic shifts in lunar samples with variations in ¹⁵⁰Sm/¹⁵²Sm ratio. The issue with this approach is that Sm isotopic variations are produced by capture of secondary thermal neutrons while ⁵⁴Cr is primarily a product of spallation on Fe targets.

2. Samples and Method

In this study, we re-visted the Cr isotopic composition of the Moon by analyzing three lunar samples (Apollo mare basalts 12015, 15499 and 15555) and 13 lunar meteorites. Chromium was extract from the lunar samples using a two-step cation exchange chromatograph, detailed in [4]. The Cr isotopic compositions of the lunar rocks were analysed using the Thermo Fisher Scientific Triton Thermal lonization Mass Spectrometer (TIMS) at Carnegie Institution for Science and the Triton plus at State Key Laboratory of Geological Processes and Mineral Resources, University of Geosciences, Beijing, China. The details of the mass spectrometry procedure can also be found in [4].

2. Results

We found notable excesses in both ϵ^{53} Cr (up to 0.4 ϵ) and ϵ^{54} Cr (up to 1.1 ϵ) for most of our samples. The anomalies of ϵ^{53} Cr and ϵ^{54} Cr in the lunar rocks display a positive correlation. Combining the result from [5], we obtained a slope of 2.65, similar to the slope found for iron meteorites [4], indicating that they have a cosmogenic origin. However the slope is shallower than the latter. This is likely due to the different exposure geometry rather than higher proportion of neutron capture effects over spallation effects in lunar samples. After correcting for cosmogenic effects, we obtained a pre-exposure ϵ^{54} Cr value of +0.02 ± 0.03. This value is in line with the terrestrial rocks and indicates that the moon-forming impactor is Enstatite-Chondrite-like or that the moon is mainly sourced from the proto-Earth.

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Cold volatile loss from the Moon revealed by chromium isotopes

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1. Introduction

Terrestrial and lunar rocks share chemical and isotopic similarities that likely result from vigorous mixing in the aftermath of the giant impact [1, 2]. The depletion of volatile elements in the Moon with respect to the Earth is a notable exception. Within this genetic framework, however, the thermochemical conditions that could engender similarity in refractory lithophile element abundances and isotopes yet strong volatile element depletion in the Moon remain poorly understood.

2. Motivation

The heavy isotope enrichments of Zn, K, Rb and Ga in the Moon compared with the Earth has been taken to imply that evaporation was the driving mechanism for their depletion [3-6]. However, because these elements are all more reduced in the gas than in the melt, both kinetic- and equilibrium evaporation would cause heavy isotope enrichment in the residue. It has therefore been impossible to evaluate whether equilibrium prevailed between the liquid and gas, and, if so, at what conditions (temperature, pressure and oxygen fugacity, fO_2) this occurred. By contrast, chromium has thermodynamically stable gas species in which it is in a higher oxidation state than in the melt, such that equilibrium isotope fractionation between liquid and vapour should uniquely result in an isotopically light Moon.

3. Methods & Results

In order to evaluate whether there are any Cr isotope differences between the Earth and Moon, 17 spinifextextured komatiites and three peridotites were analysed for their Cr isotope composition to determine that of Earth's mantle. Estimates of the Moon's composition were garnered by analysis of six Mg Suite samples, in addition to five lunar mare basalts and lunar green glass. The Cr isotopic data are reported as δ^{53} Cr, the per mille deviation of the 53 Cr/⁵²Cr ratio of the sample from the NIST SRM 979 standard. Following correction for the effects of magmatic differentiation in terrestrial and lunar samples, we show that the Moon is enriched in the lighter isotopes of Cr compared to the Earth's mantle by 0.10 ‰ per atomic mass unit.

4. Implications

This observation cannot be accounted for by core formation and instead implies that Cr was evaporated from the Moon at oxygen fugacities higher than that required to form iron metal, thereby stabilising the oxidised $Cr^{4+}O_2$ gas species, which is isotopically heavy with respect to the $Cr^{2+}O$ component in the silicate melt. In order to reproduce the extent of Cr isotopic fractionation and depletion in the lunar mantle requires temperatures of 1500 - 1800 K during volatile loss, far below peak temperatures reached during a giant impact.

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Chromium stable isotopic evidence for the origin of the volatile depletion from Vesta

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1. Introduction

The howardite-eucrite-diogenite (HED) suite is a family of differentiated meteorites that likely originated from the 4-Vesta asteroid. The HED parent body accreted and differentiated a core and a crust within 5 Myrs after the formation of the Solar System [1]. A striking particularity of the HED parent body is its strong depletion in volatile elements compared to undifferentiated meteorites and the Earth [2]. The origin and condition of this depletion is presently debated.

Stable isotope ratio of moderately stable isotopes can be used to trace the mechanisms of volatile depletion in planetary bodies (e.g. [2]). Chromium is a moderately volatile element with a 50%-condensation temperature of 1296 K [3]. However, it behaves differently from other volatile elements (e.g. Zn, K, Ga, Cl) because it has several stable oxidised gas species. Therefore, during equilibrium evaporation, the residue may be more reduced and therefore enriched in the lighter isotopes compared to the vapor [4]. Hence, Cr isotopes can distinguish between evaporation at kinetic (the residue is heavier) or equilibrium (the residue is lighter) conditions. If at equilibrium, then isotopic fractionation scales with $1/T^2$, and the isotopic fractionation can be used to quantify the evaporation temperature and determine whether evaporation occurred during a giant impact (higher T) or degassing of a magma ocean (lower T).

2. Samples and analytical methods

Eleven eucrites (including 8 non-cumulate eucrites and 3 cumulate), 4 diogenites and 2 terrestrial basalts were studied. The ⁵⁰Cr-⁵⁴Cr double spike were mixed with the samples after complete dissolution. The Cr stable isotope composition of purified samples were analyzed on the Neptune Plus MC-ICP-MS housed at the Institut de Physique du Globe de Paris. The data are reported as the permil deviation of the ⁵³Cr/⁵²Cr ratio from the NIST SRM 979 (δ^{53} Cr), and another standard NIST SRM 3112a is used to monitor the stability of the machine.

3. Results

The δ^{53} Cr values for eucrite samples ranges from -0.13 to -0.25‰, with an average of -0.20 ‰. Most eucrites are characterized by lower Cr content, lower Mg# and lighter δ^{53} Cr than diogenites. The 5 diogenites samples display heavier δ^{53} Cr (mean -0.10 ‰), reaching up to -0.07‰. For comparison, chondrites (and the Earth) have δ^{53} Cr of ~-0.10 ‰, heavier than eucrites but overlapping with diogenites.

4. Discussion

The isotopic variations between eucrites and diogenites reflect the fractionation of Cr between the melt and crystallising mineral phases that incorporate different proportions of Cr^{2+} and Cr^{3+} during differentiation. Diogenites are orthopyroxenites (OPX) ± spinel cumulates and Cr^{3+} is more compatible in OPX and spinel than is Cr^{2+} . Therefore, the diogenites concentrate isotopically heavy, Cr^{3+} -rich orthopyroxene and spinel resulting in their Cr heavy isotope enrichment relative to eucrites.

The normal basaltic eucrites with low Mg# (24~29) best represent the Vesta's primitive melt with δ^{53} Cr of -0.22 ± 0.03 ‰, lighter than ordinary chondrites (OC) (δ^{53} Cr = -0.12 ± 0.03 ‰). This enrichment in the lighter isotopes of Cr in the HED parent body implies that evaporation occurred under equilibrium conditions. Furthermore, the isotopic difference between Vesta and OC, Δ^{53} Cr_{Vesta-OC} = -0.10 ± 0.04, correspond to a fractionation between CrO₍₁₎ and CrO_{2(g)} at temperatures <1800 K. This low temperature range for volatile loss from Vesta suggests evaporation during magma ocean degassing.

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Laboratory measurements of H, CI and other volatiles in lunar samples: scientific implications and considerations for future returned samples.

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Recent sample studies have demonstrated that the lunar interior contains appreciable quantities of water although estimates for the bulk-water content of the Moon vary considerably [e.g. Hauri et al., 2017]. The origin and evolution of this lunar water remain unresolved with a range of possibilities including retention of primordial water during lunar accretion to a late addition of water following the crystallisation of the putative Lunar Magma Ocean [Barnes et al. 2016a; Nakajima et al. 2018]. In addition to water, recent lunar sample investigations for other volatiles, especially Cl, have highlighted some unique aspects of the history of lunar volatiles that require additional processes in order to reconcile an otherwise conflicting evidence for a wet lunar interior [Barnes et al. 2016b; Potts et al. 2018].

For the majority of such studies in lunar samples, the mineral apatite has been the main target on account of its widespread occurrence in lunar rocks and its potential to reveal the volatile inventory of the Moon. Of the three volatiles (F, Cl and OH) present in lunar apatite, it is the abundance of OH and its H isotopic composition that have received most attention followed by abundance and isotopic composition of Cl. We led the development of protocols for measuring H and Cl abundances and their isotopic composition in lunar apatite using a NanoSIMS at the Open University [Barnes et al. 2013; 2016a; Potts et al., 2018; Tartese et al., 2013]. Our work is now being extended to investigate lunar melt inclusions and nominally anhydrous minerals for their volatile contents and isotopic signatures and new analytical protocols are also being developed to measure other volatile elements such as S along with H, Cl and F.

As part of our work, we have investigated volatiles in a range of lunar samples from the Apollo and meteorites collections, representing the ancient highlands, the younger maria, and impact-related rock types. Some major highlights from our work carried out on lunar apatites have been the revelation of significant effects of degassing processes on the initial H and Cl isotopic compositions, and the possibility of a common source of water in the Earth-Moon system [Barnes et al., 2014; Barnes et al., 2016a; Tartese et al. 2013]. The dominant source for lunar water appears to be carbonaceous chondrite-type material with a minor contribution from cometary objects [Barnes et al. 2016b]. However, as we continue to analyse additional lunar samples, a more complex picture is emerging for the history of lunar volatiles requiring considerations of syn- as well as post-magmatic processes, before ascertaining the ultimate origin and source(s) of lunar volatiles. More importantly, it has become apparent that our current lunar sample set represents a biased collection (representing overrepresentation of samples from an anomalous geological terrain on the near-side of the Moon), and, therefore, unravelling the history of volatiles in the Moon will benefit immensely from 'new' samples from regions of the Moon, not sampled previously.

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Origin of volatiles (H, N, noble gases) on the Moon: Constraints from analyses of single lunar soil grains

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1. Introduction

The surface of the Moon has been exposed over billions of years to irradiation by the solar wind (SW) and cosmic rays, and to contributions from extraterrestrial sources. Therefore, the lunar regolith represents a unique archive to study the past and present SW volatile element composition and to identify the source(s) of impactors in the terrestrial planet-forming region. It is important to note that individual lunar soil grains record highly variable H-N-noble gas signatures, implying distinct exposure and irradiation histories due to intense reworking of the regolith by impact gardening [1,2]; therefore, single grain analyses (as opposed to studies of bulk samples) are crucial for quantifying contributions from solar, cosmogenic, meteoritic/cometary, and indigenous volatile sources to the lunar regolith. While noble gases trapped on grain surfaces are exclusively sourced by the SW, coupled nitrogen-noble gas analyses of single lunar soil grains (mineral fragments, glasses, agglutinates) have revealed that nitrogen isotope variations in the regolith result from mixing between isotopically light SW-derived nitrogen and a ¹⁵N-rich non-solar endmember [3-5]. The planetary component is best represented by carbonaceous chondrite-like micrometeorites, whereas a cometary contribution to the nitrogen inventory of the lunar surface appears limited [5]. Similarly, recent analyses of water in individual lunar volcanic glass beads have shown that carbonaceous chondrite-type material contributed to the volatile inventory of the lunar interior [1,6]. The presence of indigenous lunar water [1,6], together with the possible detection of indigenous noble gases [2], in mantle-derived samples demonstrates that the formation and evolution of the Moon involved processes that allowed for the accretion and retention of the most volatile elements in the Solar System.

2. Analytical methods

Volatile element analyses of single lunar soil grains require high-sensitivity (ultra-low-blank) analytical techniques such as secondary ionization mass spectrometry (SIMS) or static noble gas mass spectrometry. SIMS represents a quasi non-destructive method for determining the isotopic composition of indigenous volatiles in grain interiors, away from the outermost rim that contains exogenic components [1,6]. In contrast, step-wise heating static mass spectrometry analysis provides a means for resolving nitrogen and noble gases into constituent components, and, ultimately, for detecting indigenous volatiles in lunar samples. Notably, the CRPG has developed the techniques to analyse very small amounts (10^{-12} mol/g) of nitrogen, together with noble gases, in extraterrestrial samples by CO₂ laser heating [3-5]. Furthermore, noble gas analyses in multi-collection mode using the Helix MC *Plus* noble gas mass spectrometer now allow us to obtain precise isotope ratios for very small-sized lunar samples (i.e., 15-20 µg [2]). Such high-precision, multi-element analyses are key for assessing the exposure history of lunar samples and for understanding their volatile element signature.

3. Conclusions and Outlook

The Chinese Chang'e-5 mission will be the first lunar sample return mission in over 40 years. It is expected to collect up to 2 kg of lunar regolith and drill-core samples from the northern Oceanus Procellarum [7]. *In-situ* SIMS measurements of volatile elements (H, C, N, etc.) – coupled with mass spectrometry analyses of nitrogen and noble gases – in single regolith grains will provide new insights into the origin, abundance, and distribution of volatile elements at the surface of the Moon. These findings will be key for planetary sciences, heliophysics, human exploration, and other applications.

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PROPOSAL FOR PRE-CHANG'E 5 CONSORTIUM STUDY OF LUNAR SAMPLES

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After 47 years of the last lunar sample return mission Apollo 17, the Chang'e 5 will land on the nearside of the Moon, and return about 2 kg samples, including a 2 m long drill core. CNSA and ESA have made agreement on cooperative study on the returned lunar samples, and organized the first "CNSA-ESA workshop on lunar samples" in Beijing in August 2017. In order to promote the cooperation between Chinese and European scientists on the coming lunar samples, it is urgent to grant a consortium study of lunar meteorites and Apollo samples. This consortium study is necessary because of the following three reasons: (1) It is required to determine the analytical protocols available for the laboratories in China and Europe before the lunar sample return. This is hardly to be achieved without analyzing on the same lunar samples; (2) Chang'e 5 will return samples from only one site of the Moon. Hence, study of a set of other lunar samples is critically important to understand the information buried in the Chang'e lunar samples; (3) Efficient cooperative study on the lunar samples is hardly achieved without working together on other lunar samples first.

The Chang'e 5 landing site locates within Oceanus Procellarum KREEP Terrane, hence most of the samples are expected to be KREEP-rich and contain abundant U-Th-bearing minerals (e.g. zircon, baddelyite, phosphates) and K-rich feldspar. The landing region is one of the youngest surface on the Moon, ~2 Ga based on the crater counting method. In addition, the Rumker Mon, locates near the landing site, is a large volcanic complex recording a long history of volcanic activity on the Moon. These features make the Chang'e lunar samples unique to understand: (1) later volcanic activity of the Moon, (2) Reservoir geochemical features of the youngest basalts; (3) impacting flux at about 2 billion years ago, and hence calibration of the crater count dating method.

In order to compare with the Chang'e lunar samples, a set of lunar meteorites for this proposed consortium study may include the KREEP-rich (e.g. SaU 169, NWA 1442, NWA 4472, 6687), and basalts with various Ti-, Al-contents and ages. It would be great helpful if Apollo lunar samples can be analyzed in this cooperative study. The proposal can be discussed in the workshop.

Both CNSA and ESA may supply with their scientists with funds, to support exchanging graduated students and visiting between the partner laboratories, attending related workshops and meetings.

Joint Community Report China-European coordination on Lunar Sample Analysis.

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The future CNSA Chang'e 5 mission will return at least 2 kg of lunar samples to Earth. This will represent the first lunar sample return mission since the Soviet mission Luna 24 in 1974. These new samples will complete the samples already present in the Apollo and Luna collections and permit to better understand the formation and evolution of the Moon as well as its present day composition in the view of future inhabited mission to the Moon. This future return samples offer a unique opportunity to ESA and CNSA to develop a long-term collaboration on lunar sciences that could be extended over the next decade or so. European scientists have a long time expertise in lunar science and many are actively involved in the study of samples returned from the Apollo and Luna missions.

Following, the original CNSA/ESA workshop in Beijing in September 2017, Chinese and European scientists have decided to move forward to combine their strengths to get the full scientific potential of the future lunar sample returned. To reach that goal, we have discussed with a large set of European and Chinese lunar scientists to establish the capabilities in Europe and China and suggest actions to the CNSA and ESA. This includes to:

- Develop existing and create new research collaborations between Chinese and European scientists in lunar sample science to address high priority lunar and planetary science and exploration goals.
- Develop a proposed plan for cooperation in the analysis of samples from the Chang'e 5 mission and other lunar samples (e.g., meteorites).
- Share knowledge and propose cooperation approaches related to analogue materials (including standards) to help maximise science return from laboratory analysis and instrument calibration.
- Further collaborations to plan for next generation of sample return missions and terrestrial samples.

Current understanding of the Moon, key questions to address in the future

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The Moon is key to understanding both Earth and our Solar System in terms of planetary processes and has been a witness of the Solar System history for more than 4.5 Ga. Building on earlier telescopic observations, our knowledge about the Moon was transformed by the wealth of information provided by Apollo and other space missions. These demonstrated the value of the Moon for understanding the fundamental processes that drive planetary formation and evolution. The Moon was understood as an inert body with its geology mainly restricted to impact and volcanism with associated tectonics, and a relative simple composition. Unlike Earth, an absence of plate tectonics has preserved a well-defined accretion and geological evolution record. However recent missions to the Moon show that this traditional view of the lunar surface is certainly an over simplification. For example, although it has long been suspected that ice might be preserved in cold traps at the lunar poles, recent results also indicate the formation and retention of OH⁻ and H₂O outside of polar regions. These volatiles are likely to be formed as a result of hydration processes operating at the lunar surface including the production of H₂O and OH by solar wind protons interacting with oxygen-rich rock surfaces produced during micrometeorite impact on lunar soil particles. Moreover, on the basis of Lunar Prospector gamma-ray data, the lunar crust and underlying mantle has been found to be divided into distinct terranes that possess unique geochemical, geophysical, and geological characteristics. The concentration of heat producing elements on the nearside hemisphere of the Moon in the Procellarum KREEP Terrane has apparently led to the nearside being more volcanically active than the farside. Recent dating of basalts has shown that lunar volcanism was active for almost 3 Ga, starting at about 3.9-4.0 Ga and ceasing at ~1.2 Ga. A recent re-processing of the seismic data supports the presence of a partially molten layer at the base of the mantle and shows not only the presence of a 330 km liquid core, but also a small solid inner core. Today, the Moon does not have a dynamo-generated magnetic field like that of the Earth. However, remnant magnetization of the lunar crust and the paleomagnetic record of some lunar samples suggest that magnetization was acquired, possibly from an intrinsic magnetic field caused by an early lunar core dynamo. In summary, the Moon is a complex differentiated planetary object and much remains to be explored and discovered, especially regarding the origin of the Moon, the history of the Earth-Moon system, and processes that have operated in the inner Solar System over the last 4.5 Ga. Understanding the origin and evolution of the terrestrial planets including Earth requires information about early differentiation, volcanism and related tectonics. However the physics and chemistry of these processes and their chronological sequences are not completely known. The bulk composition of the Moon and its seemingly relatively simple geological history provides insight into planetary processes that are more obscured on other planetary bodies. In particular, Earth and Venus exhibit extremely young surfaces, containing almost no record of their early evolution. Thus, evidence of how planets differentiate, of how early magma oceans operate, as well as of secondary differentiation and initial volcanism, is restricted to the Moon. Earth and Moon form a common planetary system that is unique among the terrestrial planets. Both bodies exchange angular momentum by gravitational interaction. Is there a direct correlation between the origin and evolution of life on Earth and the existence of the Moon? The Moon is thought to be the product of an early planetary collision of a Mars-sized body with Earth. However this model needs to be confirmed by measurable "ground truth". Dating of planetary surfaces and thus of planetary processes such as emplacement of lava, collision events, and breaking of the crust depends on the distribution and frequency of impact craters. As the Moon has no atmosphere, its surface collects impacting particles of smallest scale, with sizes down to the particles of the solar wind and galactic cosmic rays. The surface regolith has thus collected information about conditions in our space environment over time since the beginning of the Solar System. Thus, even today, the Moon remains an extremely interesting target scientifically and technologically because although new data have helped to address some of our questions about the Earth-Moon system, many questions remain unanswered. Returning to the Moon is therefore the critical next stepping-stone to further exploration and understanding of our planetary neighborhood. Working and operating in the complex lunar environment and exploiting the Moon as a platform for scientific research and further exploration poses major challenges. For more information see e.g. [1, 2, 3] and references therein. References

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Geological map and age determination in landing sites of Chang'E missions

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Abstract

Landing site characterization is of great importance to the upcoming Chinese Chang'E missions, for instance Chang'E 4 and 5. For this reason, we conducted a regional geological analysis of the crater fill, including the mapping of stratigraphic units, as well as their age determination with crater-size-frequency distributions (CSFDs) [Neukum, 2001].

1. Impact craters extraction and identification

Lunar impact craters form the basis for lunar geological stratigraphy, and small-scale craters further enrich the basic statistical data for the estimation of local geological ages. Therefore, based on multiple resolutions of real CCD images acquired by the Chang'E orbiters, this paper proposes a coarse-to-fine resolution method to automatically extract small-scale impact craters from CCD images using histogram of oriented gradient (HOG) features and a support vector machine (SVM) classifier. The sample database is updated with the newly extracted small-scale craters for the purpose of the progressive optimization of the extraction.

As secondary craters [Xiao, 2012] likely have a small size, to avoid their negative effect on the craterbased dating, we novelly proposed a method to distinguish secondary craters from primary ones, which utilizes the element iron distribution of lunar regolith and machine learning.

2. Stratigraphic unit mapping and crater-based dating

High-resolution CCD images and relevant data of the China Lunar Exploration Project (Chang'E), Clementine derived mineral maps [Lucey, 2000], Lunar Reconnaissance Orbiter (LRO) Digital Elevation Model (DEM-30m/pixel) and some existent geologic maps [Lunar 5M Geologic Map, United States Geological Survey, 2013], were combined into a unified coordinate system (GCS_Moon_2000). On the basis of Clementine TiO2 and FeO mineral maps, Chang'E-2 Digital Orthophoto Map images (DOM- 7m/pixel) and LRO DEM data, we identified geologic mare units in the landing sites of Chang'E missions.

Base on the primary craters extracted using our proposed method, the CSFDs allowed us to determine absolute model ages for each unit, using the Neukum production and chronology functions [Neukum, 2001]. Our CSFDs show that (taking Sinus Iridum as an example): i) the oldest exposed mare unit in Sinus Iridum dates back to 3.4 Ga ago and hence is Imbrian in age; ii) several younger basalts resurfaced most of Sinus Iridum area during the Eratosthenian, especially between 2.8 to 3.1Ga. iii) according to our CSFDs, very young lava flows (1.2-2.0Ga) with a lower albedo, cover a wide area in the south and east of the crater and are superposed on units with the same age as the oldest infilling (i.e., 3.4 Ga). Comparing with mare unit definition and age determination in Sinus Iridum area from Hiesiger [Hiesinger, 2000] and Qiao [Qiao, 2014], finer stratigraphic units were defined and more complete basic statistical data were acquired for the estimation of local geological ages.

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Proposed Landing Sites in the South Pole-Aitken Basin for Upcoming Lunar Missions

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1. Introduction

Numerous scientific reports (e.g., 1) rate the sampling and exploration of the South Pole-Aitken (SPA) basin as a high priority for a wide range of scientific and technical endeavors. Here, we review our efforts to characterize potential landing sites within the SPA basin for upcoming Chinese and Russian missions, using geomorphological mapping, crater size-frequency distribution measurements, basin ejecta component and compositional analyses, as well as hazard assessment.

2. Chinese landing sites

By the end of 2018, Chang'e-4 will be the first landed mission on the lunar farside to explore the region with a Yutu-heritage rover and an orbital relay satellite [2]. The scientific objectives of Chang'e-4 include studies of: (1) the interaction of the solar wind and lunar surface, (2) the formation mechanism of lunar regolith and dust, (3) lunar-based VLF astronomical potential, (4) the regional geochemistry and subsurface structure, and (5) the recent impact flux of the Moon [2]. Before the selection of Von Karman crater in western SPA [3], a potential landing site for the Chang'e-4 mission was the 538 km-diameter Apollo basin in the NE quadrant of SPA basin. Thus, we assessed its scientific potential, in addition to landing site safety for this region. We prepared a regional geologic map of the northern portion of the SPA basin, including the Apollo basin, for which we also made two higher resolution (1:50,000) geologic maps of the central and southern parts [4,5]. Several regions of interest (ROIs) in the Apollo basin were examined in greater detail. Their relatively high FeO (~14-20 wt%) and TiO₂ (~1-7 wt%) contents make them favorable candidates for in situ resource utilization (ISRU) demonstrations [5]. In addition to the study of the Apollo basin, we are also investigating the Von Karman landing site with the same datasets.

3. Russian landing sites

The Luna-Glob (LG) mission will be the first mission of a series of Russian lunar missions with increasing involvement of ESA. We studies a potential landing zone located close to the rim of the South Pole-Aitken (SPA) basin between 0 and 60° E and 65-85° S [6-8]. Here, predominantly ancient terrains of pre-Nectarian and Nectarian ages are exposed [8]. The pre-Nectarian stratigraphic units are mostly related to the emplacement of SPA ejecta, although post-SPA basins also transported materials across large distances to the landing zone [8,10-12]. Using the model of [13], we assessed the potential local thicknesses of ejecta deposits from several individual lunar basins (e.g., Australe, Nectaris, Schrödinger, Imbrium) to facilitate interpretation of the LG in situ analyses. From these calculations, we find that the SPA basin is the dominant source of materials in the local megaregolith [3,14,15]. The ejecta emplacement model indicates that the average SPA ejecta thickness is ~3.2 km, ranging from ~1.8-5.5 km, depending on the distance from SPA. All other pre-Nectarian basins only contributed ~3.6% to the total ejecta thickness in the landing zone. Australe was the most important secondary source, contributing ~70 m (mean) of ejecta. Nectarian and Imbrian basins delivered only a few meters of ejecta to the landing zone, with Serenitatis and Nectaris being the major contributors.

Future work will include investigations of regions of interest in the vicinity of the South Pole for the Luna-Resurs landers and other upcoming missions to very high latitudes [e.g., 16].

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POTENTIAL LANDING SITES FOR THE CHANG'E-4 EXPLORATION MISSION TO THE **APOLLO BASIN, MOON**

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1. Introduction

As the oldest and deepest impact structure on the Moon, the South Pole-Aitken Basin (SPA) on the lunar farside is a scientifically high priority site for human and robotic exploration [1]. The lunar farside has not been visited by any exploration missions so far, but it is the focus for Chang'e-4 robotic missions planned for the end of 2018 [2].

2. Science rationale

The Apollo basin is one of the youngest basins inside the SPA basin [3]. Based on GRAIL data, the crustal thickness beneath the Apollo basin is less than 5 km [4]. The NE-E rim of the Apollo basin exposes anorthositic material from the highlands along the SPA rim and possibly impact melt and/or mantle material from the SPA interior [5]. The basin floor is mainly covered by four mare basalt provinces (center, south, west, and east), their AMAs ranging from 2.30 to 3.45 Ga [6]. The mare deposits have enhanced FeO and TiO₂ abundances compared to the immediate surroundings [7].

3. Selection of region of interests

To evaluate the potential science return of each proposed ROI, we use all available datasets from previous lunar missions and studies [7]. The terrain traversibility is determined via slope maps, and digital elevation models derived from the LOLA instrument, at resolutions of 60 m/pix. The terrains that compose the Apollo basin are visualized using LRO WAC mosaics of 100 m/pix, and individual NAC images of 1 m/pix, and Kaguya Terrain Camera images of 7 m/pix. We use the Kaguya images as the photobase for geologic mapping and counting craters >50m for crater size-frequency distribution analyses. Geologic maps at 1:50.000 scale are being compiled for the central and southern portions of the Apollo basin, and the FeO and TiO₂ contents are determined using Clementine 100 m/pix global maps [8].

Here, we provide a detailed analysis of three high-priority regions of interest (ROIs) with example rover traverses of 2.5 km, 5 km and 10 km radius from the center of ROIs in the central and southern mare deposits of the Apollo basin. The proposed high-priority ROIs have high scientific interest based on prioritized science concepts defined in the 2007 National Research Council (NRC) report [1] and the scientific objectives of the mission.

4. Conclusion

These high-priority areas could fulfil the general engineering constraints and the scientific objectives, as well as ISRU potential of the mission. In situ observations and sample analyses can help address major scientific questions (NRC concepts:1-3, 5-7) and provide a high ISRU potential at all selected ROIs.

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Geological Characteristics, Proposed Landing/sampling Sites and Anticipated Science Return of the Chang'E-5 Landing Region

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1. Introduction

The Chang'E-5 mission, China's first lunar sample return mission, is scheduled to launch in 2019 and is designed to bring back up to 2 kg of lunar samples. The candidate landing region is designated between 41-45°N in latitude and 49-69°W in longitude within northern Oceanus Procellarum, named the Rümker region [1]. We report on the characteristics of the geological features, produce a large-scale regional geologic map, summarize the nature of the geologic units in the area, propose landing/sampling sites, and evaluate potential scientific outcomes in support of the Chang'E-5 mission [2].

2. Geological characteristics

Topography and geomorphology. The Rümker region is located in the smooth plains in northern Oceanus Procellarum. The average altitude is -1300 m and most of the region has a slope smaller than 2°. There are a variety of landforms that can be identified in this region. Mons Rümker is a circular volcanic complex that is ~70 km in diameter and ~500 m higher than the surrounding mare surface. In addition to the domes developed on Mons Rümker, a small dome centered at 49.85W, 43.68N, ~3 km in diameter and 170 m higher than the surrounding mare surface, is surrounded by mare basalts in the eastern landing region [3]. The Rümker region is crossed by several mare ridges. Rima Sharp, ~1 km in width and 20-50 m in depth, is a sinuous rille in the east part of the landing region.

Composition and mineralogy. Lithology and mineralogy are regionally variable in the Rümker region. The eastern unit has relatively higher FeO (16-18 wt.%) and TiO₂ (6-7 wt.%) contents and a higher albedo, whereas in the western part, FeO (14-17 wt.%) and TiO₂ (1-2 wt.%) abundances are lower. M³ data show that the Rümker region is dominated by pyroxene, whereas the signature of other common lunar minerals such as olivine or plagioclase is not unambiguous. Spectra of the area show that the pyroxene in the western part is of intermediate composition and indicate high calcium abundances in the eastern part. Compared to the surrounding mare basalts, Mons Rümker is characterized by low TiO₂ (~2 wt.%) and FeO (~15 wt.%) abundances, and by a weak pyroxene absorption.

Geologic units. According to the compositional and mineralogical data and spectroscopic observations, the mare basalts in the area can be readily subdivided into 6 geologic units. The model ages of these geologic units were acquired using standard CFSD methods. Results show that the western part of the Rümker region is much older than the eastern part that has an absolute model age of 1.21 Ga, which is the youngest geologic unit in this region, and is one of the youngest mare unit on the Moon [4].

3. Proposed landing/sampling sites

We propose the young high-Ti basalts as a preferred landing site. The possible lunar samples from this region could answer many fundamental questions. For example, 1) the radiometric age of the young basalt could be used to compare with the CSFD ages to constrain the impact cratering flux of the Moon and other planets, 2) the mineralogy and geochemistry could provide information on the mantle properties and thermal state at this time and further constrain the lunar thermal history; 3) volatile components in glass and pyroclastic rocks could provide direct clues of mantle properties; 4) Th contents could improve our knowledge about the role of Th in the late-stage mare basalt petrogenesis [2].

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High Resolution Mapping and Geologic Analysis of Chang'e-5 Landing Area

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1. Introduction

The planned landing area of Chang'e-5 (CE-5) is near Mons Rümker in Oceanus Procellarum [1]. We have created a seamless digital orthophoto map (DOM) of landing area at the resolution of 1.5 m/pixel for detailed morphological and geological analysis. Based on this high resolution DOM, we mapped the central mound craters and then analysed the potential layers in shallow surface. We also made preliminary hyperspectral analysis to this area.

2. High Resolution Seamless DOM Generation

At present, the available lunar global image mosaic products include Clementine global mosaic (100 m/pixel) [2], LROC WAC global mosaic (100 m/pixel), CE-1 CCD camera global mosaic (120 m/pixel) [3], and CE-2 global mosaic (50 m/pixel released) [4], and so on. These maps may not be sufficient for detailed analysis and mission planning of CE-5 for their low resolutions. In this research, we have produced high-resolution seamless DOM of CE-5 landing area using 765 LROC NAC images base on planar block adjustment and thin-plate-spline based registration techniques. Meanwhile, the DOM is tied to the widely used reference DEM - SLDEM2015.

3. Central Mound Craters Mapping and Analysis

With laboratory experiments, Quaide and Oberbeck [5] confirmed that impacts on weak-over-strong layers could produce craters with the central mounds. This type of craters is subsequently used to derive the thickness of lunar regolith [6]. To analyse the variation of the thickness of lunar soil or shallow layers, currently we have mapped more than 500 central mound craters and derived the depth of the layers. Preliminary results indicate that there is a layer about 50 m sub-surface.

4. Hyperspectral Analysis of CE-5 Landing Area

Spectral ratios of hyperspectral data from MI/Kaguya are generated to delineate geological units in the landing area, and the iron and titanium abundance are derived, the optical maturity (OMAT) [7] also is estimated in this area. Distinct geological features are selected (e.g. fresh craters) based on the above information for further geogogic analysis (e.g., crater dating).

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Volcanic structures in the von Kármán region inside the South Pole-Aitken basin

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1. Introduction

The South Pole-Aitken (SPA) basin on the lunar farside has a diameter of more than 2000 km and was formed probably more than 4 Ga ago [2]. In this work, we investigate traces of basaltic volcanic activity in and around the crater von Kármán located inside SPA, relying on LRO WAC mosaic [6] and NAC [4] images, Moon Mineralogy Mapper (M³) hyperspectral images [3] and GLD100 topographic data [5].

2. The craters von Kármán and von Kármán M

Fig. 1a shows a petrological map of the region around von Kármán (44° S, 176° E), constructed using the framework of [7]. The lava-flooded floor of von Kármán exhibits lobate flow structures of 16 x 33 km² size and 115 m height (Fig. 1b). On the lava-flooded floor of von Kármán M, a slightly elliptical dome structure of 15 x 17 km² size and 100 m height is situated (Fig. 1c). Both structures show sharp demarcations with respect to the underlying surface, indicated by white arrows in Fig. 1b and c. The occurrence of such effusive volcanic structures in mare areas is commonly explained by lavas erupting in the final phase of a long-lasting basaltic eruption, forming cooling-limited flows [1].



Figure 1: (a) Petrological map overlaid on LRO WAC mosaic of the von Kármán region (red: basalt; green: Mg-rich rock; blue: anorthosite). (b) LROC NAC image of the volcanic flow structure on the floor of von Kármán and (c) of the volcanic dome on the floor of von Kármán M.

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Constraints on lunar polar volatiles from remote sensing datasets

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The inventory of lunar volatiles as a function of location is poorly constrained with respect to the needs of future science and exploration targets. The wealth of remote sensing data in recent years from missions such as NASA's Lunar Prospector, JAXA's Selene (Kaguya) [1, 2], NASA's Lunar Reconnaissance Orbiter (LRO) and LCROSS impactor [3], have shed light on evidence for volatiles on the surface and at depth.

In this presentation I will summarize the main lines of evidence in various datasets that have led to our present understanding of the lunar volatile inventory that is potentially accessible to future missions, focussing principally on the south polar region. Datasets analysed in efforts to understand the lunar volatiles distribution include visible observations [e.g. 1, 2], neutron flux measurements [4], thermal infrared observations (LRO Diviner Lunar Radiometer Experiment [5, 6]), IR spectra (Chandrayaan-1 M3 [7]) radar reflectivity and polarisation (LRO Mini-RF [8]), ultraviolet spectra [9, 10], laser altimetry and reflectance (LRO LOLA [11]).



Figure 1: Example of analyses to assess presence of surface water ice signatures using multiple lunar remote sensing datasets. Comparison of UV and IR data indicating surface water ice at the lunar south pole. Left – Figure 14. From Hayne et al. (2015) [10], Locations of anomalous UV albedo measured by LRO LAMP instrument consistent with surface water ice. Right – Figure 11. From Fisher et al. (2017) [11]. Cyan areas are brighter 1064nm reflectance than 2-sigma from the mean in areas within 125–175 K, with maximum temperatures less than 110 K and slopes less than 10°. These areas are unlikely to be part of the background ice-free population and thus represent compelling locations for surface water frost, however they do not always spatially coincide with other lines of evidence.

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Lunar polar regions of interest for future exploration

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1. Introduction and Scope

The last decades have been marked by increasing evidence for cold trapped volatiles at the lunar poles [1-3]. Orbital measurements reveal an enhancement in hydrogen at both poles, which is interpreted as evidence for surface or subsurface water ice [4]. In addition, recent Moon Mineralogy Mapper (M3) data reveal hydroxylation of the lunar surface [5]. Lunar hydroxyl and water are targets of interest both as scientific repositories and for exploration purposes. Determining the exact nature, extent and origin of the volatiles at and near the surface of the lunar poles requires *in situ* analyses via lander or rover missions. A number of upcoming projects and missions will address these by obtaining new in situ data or return of lunar surface or shallow subsurface samples, and hence rely on the selection of optimal landing sites (e.g., [6]).

2. Identifying Regions of Interest

Several recent studies have focused on the identification of regions of interest (ROI) in the vicinity of both lunar poles, in preparation for future missions (e.g., [7,8]). ROI are accessible regions where water ice and other volatiles should be present and could be extracted and analyzed on site, but where additional science benefits have also been identified. Of particular interest are highly illuminated areas that would provide almost continuous power supply for lunar landers or permanent bases (e.g., [9-12]). The present paper established a list of possible ROI at both poles based on various selection criteria, including illumination, enhanced detection of volatiles, surface temperature, proximity of cold traps, terrain characteristics and the presence of geological features of interest. We will also discuss the available datasets for remote characterization and existing knowledge gaps. An example of ROI for the south pole is given in figure 1. Downselecting from ROI to candidate landing sites is specific to a mission; examples based on given scenarios will be presented.



Figure 1: South pole ROI for volatile investigations above 80° in latitude (green circles). Background: Diviner average temperature map (white = low). Blackened areas = Diviner avg T >110K, Orange areas = Diviner avg T <54K, S Pole stereographic projection.

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The potential constrains for the vertical variation in rock abundance of the moon by Chang'E microwave radiometer (MWR) observations

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1. Introduction

The mapping of rock abundances, i.e., cohesive materials, scattered across the lunar surface is key to the understanding of its evolution and impact history. Global rock abundance of lunar surface has been derived from the Diviner observations [1]. However, the vertical variation of the rock abundance is still uncertain. By virtue of its longer wavelength in comparison to UV-VIS-IR, global lunar microwave radiation obtained by the Chang'E missions (CE-1 and CE-2) carries thermal radiation from deeper into the surface and can extend to several times the observation wavelength. These data can be employed to model and constrain the distribution of rocks with depth. Here we preview the results from a new rock model of the brightness temperature (TB) from the lunar surface [2], which match the CE MRM observations closely. The TB model includes the rock effect that focuses on the difference in the thermal properties between lunar rock and regolith, based on a previous model that included the topographic effect (shadowing and slope effects). Comparing these results to the Diviner observations put constrains on the vertical variation in rock abundance refining our understanding of regolith development and overturn rates.

The Level 2C Chang'E-2 (CE-2) Microwave RadioMeter (MRMs) data [3] were used in this study, following system calibration and geometric correction with Planetary Data System. The MRM underwent onboard adjustments to ensure its reliability and accuracy using a two-point calibration method (for details see [3]). We chose 37GHz single-track observations to highlight the topographic effect on TB and avoid modifications in the MRM data (averaging the data over local time and MRM shots). The rock abundance (RA) data applied for the model is calculated by Bandfield et al. [4], which is the averaged surface rock fraction over the field of view (FOV) of the Diviner Radiometer onboard LRO, representing the meter-size and larger rocks [4]. To account for the rock effect on the TB of the lunar surface, a mixed layer made up of rocks and the lunar soil (dust and regolith) has been proposed (Fig. 1). Only the meter-size and larger rocks are considered in simplified mixed layer in Fig.1. The thicknesses of the mixed layer over all the selected sites can be assumed to be 1 m, which is deep enough to cover the penetration depth at 37GHz.



Figure 1: The schematic diagram of the rock model. Meter-size and larger rocks within a lunar regolith matrix constitute the mixed layer.

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New insights into surficial hydroxyl/water on the Moon

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1. Introduction

It is well known that near-infrared reflectance spectra of the lunar surface exhibit an absorption band near 2.8-3.0 µm, which is commonly interpreted as being due to surficial hydroxyl (OH) and/or water (H₂O). The latitudinal dependence and temporal variations of the 3-µm band depth were analysed using hyperspectral image data of the Moon Mineral Mapper (M³) instrument [3] on-board Chandrayaan-1 and during the Cassini mission [5], respectively. Recent analyses of M³ data provided global maps of the H₂O content [2] and demonstrated the importance of surface roughness for thermal emission removal [1]. This contribution summarises our analyses of spatial and time-of-day-dependent variations of the 3-µm band depth [6, 7].

2. Variations of the 3-µm band depth with location and time of day

We constructed M³-based global maps of the integrated 3-µm band depth (OHIBD) (Fig. 1), relying on a refined analysis framework [6, 7] which performs a correction for the thermal emission component using a physically-based method extending the approach of [4], where also the surface roughness is taken into account. In the lunar morning and afternoon, the OHIBD increases with latitude, but much less strongly than found in [3]. The OHIBD amplitude in the course of the lunar day is higher for maria than for highlands, whereas the absolute OHIBD level is lower for maria. High-Ti maria exhibit the lowest OHIBD level. In the highlands, the 3-µm band is only slightly less pronounced at midday than in the morning and afternoon. Our results are generally consistent with OH/H₂O being formed by adsorption of solar wind protons, but they also suggest that in particular in the lunar highlands a strongly bounded surficial H₂O/OH component is present, which is stable against diffusive loss and photolysis.



Figure 1: OHIBD maps of the western hemisphere of the Moon, overlaid on M³ 1.579 µm reflectance. Left: morning (07:00-08:00 local time); middle: midday (12:00-14:00); right: afternoon (16:00-17:00).

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Planetary surfaces spectroscopy laboratory facilities at INAF-IAPS.

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1. Introduction

Laboratory investigation of rocks analogues and meteorites, by means of reflectance spectroscopy in various environmental conditions, is a valuable tool to support the interpretation of data from both telescopic observations and planetary missions, carrying remote-sensing instruments as well as landers/rovers. Here we present the laboratory facilities that are in use at the INAF-IAPS (Rome), devoted to the study of spectroscopy of Planetary Surfaces analogues and meteorites.

2. The Spectral Imaging facility (SPIM): imaging spectrometer @0.2-5.1 μm

The spectrometer installed in SPIM [1], which is a spare of the VIR instrument [2] on board Dawn mission, is an imaging spectrometer characterized by high spatial and spectral resolution. It covers the 0.22-5.05 μ m spectral range, with 38x38 μ m of spatial resolution on the target. Two bi-dimensional focal plane arrays, a CCD for the visible between 0.22 and 1.05 μ m (spectral resolution of 2 nm) and an MCT for the IR between 0.95 and 5.05 μ m (spectral resolution of 12 nm) allow to obtaining the spectral coverage. Thanks to the alignment of the bi-dimensional focal planes with the spectrometer's 9 mm slit axis, it is possible to acquire the target's image of 0.038x9 mm at different wavelengths. The spectrometer and the IR detector need to be cooled at 130K and 80K, respectively, in order to reduce the background noise due to thermal emission. To avoid vapour condensation when at the operative temperature, the spectrometer has been installed inside a thermo vacuum chamber (TVC) chilled by liquid nitrogen. The optical layout of the spectrometer is based on an Offner configuration. SPIM acquires hyper-spectral cubes observing the target moving on a scanning sample holder. Two lamps provide the light sources for the VIS channel (a QTH lamp, 120 W) and the IR channel (108 W).

3. The FieldSpec Pro: spectrometer @0.35-2.5 µm

The spectral range of this commercial spectrometer is $0.35-2.5 \ \mu\text{m}$; the detection system is divided into three separate channels, VIS ($0.35-1.0 \ \mu\text{m}$), using Si diode, and SWIR1 ($1.0-1.8 \ \mu\text{m}$) and SWIR2 ($1.8-2.5 \ \mu\text{m}$), using InGaAs detector. The spectral sampling is 1-2 nm, while the spectral resolution is in the range 3–12 nm. A QTH lamp is used as light source to illuminate the sample, with a 5 mm spot thanks to an optical fiber plus collimator. A fiber optics bundle recollects the reflected signal (5 mm spatial resolution) and transfers it to the spectrometer.

4. The Environmental P-T cell

Infrared spectra of minerals and rocks acquired in the laboratory are often dominated by the presence of absorption features due to adsorbed water. Water molecules from ambient vapor, at standard P-T conditions, are subject to physical adsorption: the molecules quickly attach between the surface grains of the materials (mainly powders) during the preparation, storage and measuring phases. These absorptions can mask diagnostic bands of the host materials, and this can also be problematic when using laboratory spectra to compare with data from planetary missions. In order to overcome these issues, we designed and developed an environmental cell [3] to acquire IR reflectance spectra of materials at controlled pressure and temperature. The vacuum chamber was realized custom by Vacom, other parts were realized at INAF-IAPS. The sample to be measured is placed in a copper sample holder, in contact with a ceramic heater, allowing to warm up to 400 °C. A PID controller permits the temperature control. The cell consists of a UHV stainless steel cube: a primary membrane pump and a secondary turbomolecular pump in the current version permit to reach a vacuum of about 10⁻⁵ mbar. A 3-mm thick CaF₂ viewport allows acquiring spectra in the visible-infrared range.

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Lunar Science, Volatiles Prospecting and In-Situ Resource Utilisation: Science-Exploration Synergies at The Open University, UK

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1. Introduction

The Open University (OU) has been a key player in lunar science since the Apollo era, with activities spanning from analysis of returned samples to in-situ instrumentation, and from scientific- to exploration-motivated research in volatiles and other potential resources in and on the Moon [Anand, 2010; Anand et al., 2012; 2014].

Initial interests were in the development and application of specialised mass spectrometers for stable isotopic studies of Apollo, Luna and meteorite samples. Some of the recent analytical research on lunar samples being carried out at the OU are summarised at this workshop by Anand et al. and Franchi et al.

OU has developed a suite of space instruments for missions including Rosetta and ExoMars. These are now being applied to lunar science and exploration, through the miniature science laboratory ProSPA [Barber et al., 2018a] for the prospecting and analysis of lunar ices and volatiles within the PROSPECT package for the Luna-27 lander (Roscosmos/ESA). Further instrument and mission concepts are in development for science and resource prospecting from rovers [Biswas et al., 2018] and penetrators [Barber et al., 2018b].

OU is also preparing for the transition from prospecting for lunar resources, to developing a new sustainable mode of space exploration based on the utilisation of local resources (ISRU). Activities in this area range from chemical processes for the extraction of oxygen from lunar regolith [Sargeant et al., 2018] to microwave processing for additive manufacturing (3D-printing) of lunar materials [Lim et al., 2017; Srivastava et al., 2016].

This presentation will describe the OU's capabilities, interests and aspirations in the field of lunar exploration. It will also explore the synergies between in situ science and laboratory analysis of new returned samples, and how science and exploration can be advanced together for mutual benefit.

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Numerical modelling of evolving diffusion of impact melt and its implication on the future sampling work

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1. Introduction

Impact cratering has been the primary process to alter the distribution of lunar highland materials since the formation of a crust. The impact history is recorded in the radiogenic clocks of produced impact melt which are accessible to study in lunar samples. However, emplaced impact melt is exposed to a long-time gardening process (i.e. re-melting, excavation, burial, and re-excavation) by the subsequent impacts resulting in a complex spatial distribution. To investigate the diffusion behavior of impact melt, a model tracing the evolving distribution of melt laterally and by depth within a narrow band is built by means of a Monte Carlo approach. The lateral melt diffusion for three mid- to late-forming basins (Serenitatis, Crisium, and Imbrium) are obtained based on the model.

2. Results and relation to the lunar bombardment history

The present-day distribution of impact melt by depth for three basins is obtained. The quantitative abundance of basin melt at Apollo-Luna sampling sites is estimated and compared with the radiometric datings. For the relatively young Imbrium and Crisium melt, the simulated results are consistent with the radiometric datings [1]. The older Serenitatis melt at the near-surface is strongly dependent on the subsequent impact events. Its content is only statistically predictable at specific sites.

In spite of the high impact flux, the lateral transportation efficiency of impact melt by impact gardening is not high as expected. The great volume of melt generated by the giant basin-forming events survives until the present day, which is consistent with the radiometric datings from highland samples. If the estimated basin age is close to the true value, it thus supports the nearby basin origin explanation for the grouped isotopic datings around 3.9–4.0 Ga of Apollo-Luna highlands samples rather than the cataclysm scenario [1], [2].

3. Implication on the future sampling work

Our simulation found that the area within a basin should possess a high fraction of basin melt, particularly for younger basins (neglecting the presence of mare flooding). The surficial layer might have the great volume of basin melt, but could be seriously affected by the local impacts, and the pulverized materials with fine grain size are difficult for radiometric dating using the current techniques. Pure basin melt is expected at greater depths within basins. Higher melt abundances may be expected to be sampled from low-lying outcrops within a basin. Therefore, in this year's Chinese CE-4 mission that aims to find the old mantle material on the lunar far side, deep-lying material should be preferentially sampled. The old materials excavated by SPA might be found in or around the later-formed big impact crater like the Apollo basin and Von Kármán Crater, that likely re-excavated buried material from the SPA event.

4. Acknowledgments

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Ring-Moat Dome Structures in the Lunar Maria: enigmatic features as potential candidate for future explorations

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On the Moon, ring-moat structures are typical small flow features standing not more than 20 meters higher than surrounding mare surface. Mapped using orbital Apollo photography, they were initially interpreted as remnants of flow topography associated with mare emplacement [1]. After 30 years, global high-resolution mapping of the lunar surface has allowed re-investigation of these elusive features. Recent studies [2, 3] have produced large scale maps of these subtle positive topographies, renaming them as Ring-Moat Dome Structures (RMDSs) and showing that to be characterized by: a generally circular shape and dome-like morphology, a surrounding moat, a relatively small diameter/height compared with other lunar and planetary volcanic features, concentrated in clusters, associated with lunar maria, but only found in certain mare regions, and with a composition similar to the surrounding lava plains.

Lunar mare surface morphologic structures/features represent important keys in the understanding of the nature of basaltic lava flow emplacement [4], which carries important information on the deep mantle interior [5]. Small domical features in volcanic fields on Earth are commonly associated with the emplacement of lava flows on the surface [6], which is directly linked to physical and chemical properties and behaviours of the original magmas.

At present, the most plausible interpretation on the formation of RMDS, based on occurrence and morphology, favours a mechanism linked to extrusion of lava foams and loading of the crust (thus forming the characteristic encircling moats).

We employed Lunar Reconnaissance Orbiter images and NAC-based DEMs to analyse the RMDSs distribution and morphological characteristics, along with compositional mapping of the flow field using Clementine and Moon Mineralogy Mapper spectral data. This should provide the opportunity to associate lava emplacement mechanisms models to flow morphology. The result and analysis will enhance our understanding of the complex interactions (processes that have shaped the lunar RMDSs) between the solids, liquids, and gases that comprise these basaltic lava flows..

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Remote Sensing Constraints on the Formation and Evolution of the Moon's Anorthositic Crust

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1. Introduction

The formation of the Moon's primary anorthositic crust is still an outstanding science question as two major hypotheses have been suggested, a lunar magma ocean [e.g. 1,2] and serial magmatism [e.g. 3,4]. Examining the local and global distribution of anorthosite across the lunar surface and estimating its compositional variations is significant for better discriminating between these two lunar crustal formation processes. In this work we combine the strength of identifying Fe-bearing minerals in near infrared (NIR) remote sensing data with the strength of determining plagioclase composition using remote thermal infrared (TIR) observations to characterize the distribution of pure anorthosite (PAN) and determine the composition of the PAN units.

2. Results

Analysis of Moon Mineralogy Mapper (M³) NIR observations identified pure crystalline plagioclase (~99-100% plagioclase) widely distributed across the lunar surface. Spectrally pure, crystalline plagioclase was identified in the walls and ejecta of simple craters and in the walls, floors, central peaks, and ejecta of complex craters; most in association with the inner rings of near- and far-side impact basins [5]. While many of the anorthosite identifications are concentrated on the far-side and around impact basins, regions with the highest crustal thickness values [6], anorthosites are also identified within craters with intermediate and lower crustal thickness values [5]. Thus, pure anorthosite is found across large-scale surface features and throughout the crustal column suggesting large coherent zone(s) of anorthosite. To better understand the compositional variability of plagioclase distributed across the lunar highlands, estimated Diviner Christensen Feature (CF, an emissivity maximum diagnostic of silicate mineralogy [7]) values were analyzed. A single distribution of CF values is observed with a mean CF value of 7.91 \pm 0.05 μ m suggesting that the average composition of plagioclase identified across the lunar highlands is similar [5]. The mean Diviner CF value can be compared to the wavelength position (7.84 µm) of the CF of high-Ca anorthite (An₉₆) measured under simulated lunar conditions to estimate the An# for the observed pure plagioclase units [5]. The mean Diviner CF value suggests the plagioclase composition across the highlands is relatively uniform in composition, highly calcic (An_{>06}), and is consistent with plagioclase compositions found in the ferroan anorthosites (An₉₄₋₉₈) [e.g. 1-2] and feldspathic meteorites (An₉₅₋₉₇) [e.g. 4]. However, shorter CF values are observed in several craters, including Jackson crater, suggesting some anorthositic units may have less calic plagioclase corrobating earlier Diviner observations [8].

3. Conclusions

The global nature of anorthosite identifications and the scale of the impact basins require a coherent zone of pure anorthosite of similar composition in the lunar crust. These remote sensing observations along with others including the (1) range in the ferroan anorthosites ages [e.g. 9], (2) geochemical differences observed in Apollo ferroan anorthosites and feldspathic meteorite anorthosites [e.g. 4, 10-11], and (3) the remotely observed differences in the Mg# on the near- and far-sides [e.g. 12-13] are important constraints to be considered in any model for the formation and evolution of the Moon's anorthositic crust.

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Surveying the lunar crust-mantle boundary with Moon Mineralogy Mapper data M. Martinot^{1,2*}; J. Flahaut^{3,4}; S. Besse⁵; C. Quantin² and W. van Westrenen¹

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1. Abstract

Detailed knowledge of the lunar crustal composition and stratigraphy is crucial in order to understand the thermal and magmatic evolution of the Moon, *e.g.*, [1]. The Lunar Magma Ocean (LMO) concept predicts the formation of an anorthositic (> 90 % plagioclase-rich) upper crust formed by floatation on a magma ocean, *e.g.*, [2,3]. On the contrary, denser minerals such as olivine and pyroxene are expected to sink to the bottom of the LMO, forming the lower crust and mantle, *e.g.*, [4,5]. Spectroscopic datasets allow for a global study of the lunar crust, and provide insight into its composition and lateral variations. Tompkins and Pieters [6] studied the mineralogy of lunar crater central peaks with Clementine data, and suggested that there is an increase of mafic content with depth. More recently, multiple surveys have highlighted evidence for both lateral and vertical variations in the crustal composition [7,8].

In this study, the high spectral and spatial resolution data from the Moon Mineralogy Mapper (M³) instrument was used in order to provide mineralogical information over a selection of > 30 impact craters' central peak and/or peak ring sampling material from the crust-mantle interface. The aim of this survey is to characterize the crust-mantle interface, and its lateral and vertical evolution. The depth of origin of the crater's central peak and/or peak ring was calculated, and compared to the GRAIL crustal thickness estimates. The selected craters' central peak and/or peak ring mineralogical signatures show that the crust-mantle interface is marked by broad lateral heterogeneities. Plagioclase is widely detected, even in the central peak and/or peak ring of craters allegedly sampling lower crustal to mantle material. An evolution of the pyroxene composition is observed with depth.



Figure 1: Global distribution of plagioclase (blue stars in a), pyroxene (purple pentagons in b) and olivine and spinel (respectively, green and pink pentagons in c) in the central peaks of our selected craters. The craters with a darker coloured symbol sample above the crust-mantle interface, whereas the craters with a lighter coloured symbol sample below the crust-mantle interface. The transparent pink and blue circles outline the selection of craters with the different GRAIL models (model 1 in pink, model 3 in blue). The crossed crater indicates the absence of a distinct mineralogical signature. The detections are overlain on the global LRO WAC mosaic, and the red outline highlights the limit of the South-Pole Aitken basin.

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The Advanced Small Analyzer for Neutrals (ASAN) on the rover of Chang'E-4 M. Wieser^{1*}; X.-D. Wang¹

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1. Introduction

The Chang'E-4 mission to the Moon will be the first to land on the lunar far-side and of 2018. Chang'E-4 carries on its rover the Advanced Small Analyzer for Neutrals (ASAN), an energetic neutral atom (ENA) instrument built at the Swedish Institute of Space Physics in Kiruna, in collaboration with the National Space Science Center (NSSC) of the Chinese Academy of Sciences in Beijing, China.

2. Science background

The surface of the Moon is covered by regolith, a layer of finely powdered rock [1]. As the Moon only has a very tenuous atmosphere (or exosphere), the solar wind precipitates directly onto the surface where permitted to do so by magnetic fields. The solar wind interacts with the regolith by creating a zoo of secondary particles by different mechanisms that are then emitted from the surface: electrons, positive and negative ions and ENAs. The ENA emissions from the lunar surface have been characterized by the Sub-keV Atom Reflecting Analyzer (SARA), built by the Swedish Institute of Space Physics in Kiruna [2]. It opened a new field in remote sensing of the solar wind surface interaction. However, a ground truth measurement was missing.

3. Science objectives

The primary task of ASAN is to measure in-situ at the surface the energetic neutral atom and ion fluxes backscattered from the lunar surface. This will allow investigating the following high-level objectives:

- 1) The microphysics of the solar wind-surface interaction processes that result in the emission of ENAs and ions: An important process resulting in ENA production is direct backscattering of the precipitating solar wind. The SARA experiment revealed that the reflection coefficient for the solar wind protons neutralized on the surface is around 20% at the Moon [3]. This high ENA reflection yield from regolith and how it relates to the emission of ions is poorly understood.
- 2) The formation and maintenance of lunar exosphere: Sputtered ENAs may serve as a source for the tenuous but dynamic lunar exosphere [4]. Both the ions coming directly from the solar wind as well as energized lunar ions precipitate on Moon's surface, resulting in sputtering. Measurements of these ENAs are crucial for understanding the contribution of sputtering to the formation of Moon's or similar other solar system bodies' exosphere.

Since it is difficult or impossible to reproduce the lunar surface conditions in the laboratory, instrumentation placed on lunar landers is the only option to investigate these processes. Placed on the Chang'E-4 rover, ASAN will perform the first ENA measurements directly at the lunar surface.

4. Instrument status

On April 7, 2017, the Swedish Institute of Space Physics successfully delivered the flight model of the ASAN to NSSC. For a brief episode in January and February 2018, ASAN returned to IRF for additional environmental tests and recalibrations and was redelivered end of February 2018 to NSSC and has been reintegrated onto the spacecraft.

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Electron Density Profile of Lunar Ionosphere Based on Radio Occultation of the Service Module of Circumlunar Return and Reentry Spacecraft

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Since 1960s, radio occultation has been used in planet exploration to detect vertical changing of temperature, pressure and electron density of atmosphere and ionosphere. In 1966, the radio occultation experiment of Pioneer-7 proved the existence of Lunar ionosphere which is very thin (electron density is about 4*10⁴ el/cm³)^[4]. In Apollo 14 mission, the electron density detected by the Charged Particle Lunar Environment Experiment (CPLEE) was 10⁴ el/cm³ at several hundred meters high during lunar day time^[7]. In Luna-19 & 22 mission, the electron density profiles were detect and the peak densities were about 10³ el/cm³^[6]. In the last decade, European mission SMART-1 and Japanese mission SELENE also performed radio occultation experiment for Lunar ionosphere^[1,2,3,5].

The circumlunar return and reentry spacecraft is a Chinese precursor mission for the Chinese lunar sample return mission. It was launched on 23 October 2014 and nine days later the return vehicle landed at Inner Mongolia successfully. The service module performed a divert maneuver to avoid re-entry and to go to the Earth-Moon L2 (EML2) point. The service module stayed at EML2 until 4 January 2015 and then conducted a departure maneuver to leave EML2 and begin a transition into a Lunar Orbit. It arrived on 11 January 2015 in a 200*5300 km lunar orbit. Finally its orbit would be lower to ~100 km to image the target landing zone for the Chinese lunar sample return mission. During this period, we performed the radio occultation experiment to detect the Lunar ionosphere.

The service module provides a stable and reliable frequency source for both X-band and S-band signal. The signals transmitted from the spacecraft in S and X band passed through lunar ionosphere, interplanetary plasma, Earth ionosphere and atmosphere, finally received by the ground tracking stations. According to the coherent ratio of the S/X signal, we convert the phase information of S-band signal to the frequency of X-band signal and calculate the difference of these two signal. Then, the extrapolation algorithm was used here to deduct the interference error of the earth ionosphere and the interplanetary plasma. Based on the above work, the electron density profile of lunar ionosphere was explored preliminary. The peak of electron density profile are two times of the maximum result from Luna 19/22, are 1~2 orders higher than the SELENE result, but well-matched with the result from CPLEE. These results show that the lunar ionosphere is clearly exist and much stronger than we expected. The result here gives a positive support and some dynamical constrains for the scientific objective of the very low frequency radio astronomical payload onboard the Chang'E-4 lander mission.

Acknowledgements

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Jointly Promoting Low-frequency Radio Astronomical Detectors in the Earth-Moon Space between China and Europe

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1. Introduction

Lunar far-side can escape from the radio noises of the Earth and the Sun, gives a unique place for lowfrequency (less than 30MHz) radio astronomical observation, so as to uncover the evolution features of the universe. Setting such kind of a facility on the lunar far-side surface, has been a hot scientific topic for many years globally. To promote this work, Chinese lunar mission Chang'E-4 will send 4 units to the lunar space as a path finder mission. One of the mission NCLE, is set on the relay satellite, developed under the support by the Netherlands Space Office and China National Aerospace Administration. Beyond these missions, colleagues from multi-sides like to promote the 2nd stage of space low frequency radio astronomical constellations, before finally setting instruments on the surface of the lunar far-side surface.

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2. Chang'E-4 and the Low-Frequency Exploration

Chang'E-4 lunar exploration project is a back-up lunar landing project of Chang'E-3. After the successful work of Chang'E-3, the Chinese scientists and engineers like to send the backup lander to the lunar farside. And also, a relay communication satellite will be launched also in this project. To take the advantage of this chance, radio astronomy society together with lunar society in China suggested to set a pair of lowfrequency radio detectors on the lander and relay-satellite separately. Additionally, university side also prepared a pair of micro satellites for similar work. To make this radio astronomical path-finding mission more meaningful, a Dutch team has been invited to develop and set one of the payload unit NCLE on board the relay communication satellite. The flight mode of NCLE has been tested and integrated on the relay satellite for launch in May. The join China-Dutch team are preparing the mission operation for this mission now. The 4 units will focus on detecting type II and III solar burst, Earth AKR emission, Jovian radio burst, Earth-Moon radio environment, and Earth-Moon VLBI test at HF and VHF frequency.

3. NCLE-2

Beyond the first mission of Netherlands-China Low-frequency Explorer in Chang'E-4 lunar exploration project, the scientists and engineers like to extend the collaboration for the second stage: using cube satellite constellations and state-of-art EMC clean technique on cube satellite, to detect the cosmic low frequency radio emission in the Earth-Moon space again. Cube satellite mission concept will reduce the cost largely, the state-of-art EMC clean technique will reduce the EMC effects from S/C bodies dramatically, and the constellations will give the chance to map the radio sky with nice spatial resolution never being done at the low frequencies. This kind of mission also can be developed in a very short period. Hope the suggestion can be considered and approved by multi space agencies.

Developing High Precise Laser and Radio Ranging Techniques in Lunar and Planetary Dynamical Evolution Exploration and General Relativity Test

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1. Introduction

High precision laser and radio ranging between the Earth and other bodies in solar system, like the Moon and Mars, give a large chance to study the dynamical evolution and interior structure of the bodies. Also, give a large chance to test and develop the general relative in the inter-planetary scale directly. In the Chinese lunar missions, a new kind of lunar radio phase ranging method has been develop for these target. A new kind of laser retro reflector also is brought to Earth-Moon L2 point to improve the concept of LLR. We are looking forward to making more joint studies in the near future joint lunar and planetary missions.

2. Lunar and radio phase ranging

In planetary radio science experiments of lunar and planetary missions, usually the radio Doppler method for S/C carrier wave and/or residual carrier wave have been heavily used for various scientific studies in planetary space of the solar system. Following the technique development of software radio and time-frequency methods, the radio phase of S/C carrier wave or residual carrier wave can give more chance for planetary radio science studies. In Chang'E-3 lander mission, we developed and tested this kind of new technology. This technique can benefit the precise orbit determination of Chang'E-4 relay satellite. We will also try to test it for Martian missions in the near future.

3. Promoting the joint Lunar laser ranging

Lunar laser ranging has been developed and used nearly 50 years. French scientists and engineers developed the 1st generation laser retro-reflector, set it on the moon by using Luna landers and rovers, also has been tracked it for many years. In China, we are also developing the LLR technique by all means of ground telescope system, retro-reflector, IR laser, data analysis system, partly with supports from European colleagues. Also, we are discussing the possibility of setting new generation retro-reflector(s) developed by European colleagues on lunar surface, with Chinese lunar missions. And then, to do the relevant study together, by means of tracking them and merging the LLR with LRR for lunar dynamical studies and for test the general relatives.

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French-Chinese Collaboration towards seismic observation on the Moon

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1. Introduction

Seismic observation is a powerful tool to explore the internal structure of the planet and satellites. For the Moon, Passive Seismic Experiment of Apollo observed the lunar seismic activities with 4 seismic stations and provided about 7 and a half years of seismic data stream on the Moon. Internal structure of the Moon was studied with the data and since 1980's to today and it has been one of the most important to data sets to uncover the lunar interior [e.g. 1,2,3,4]. However, since the termination of Apollo observation on September, 1977, no seismic observation was made for the Moon. After decades of seismic investigations on the Moon, there is still remaining questions to be answered and there are strong demands for new seismic observation on the Moon from lunar science community. Following the termination of the Internal Space Station, international community has started to aim for the Moon as the next step. Various national space agencies started studies for the lunar missions including landing mission. Chinese Chang'e mission will be a great opportunity to deploy a broadband seismometer on the Moon.

No seismometers have been planned in the landing Chang'e missions, despite an offer of China to CNES to embarque a VBB on Chang'e 4, which was incompatible with the InSight VBB activities. New perspectives are however forseen with continuous construction of permanent station at South Pole-Aitken, within 2020-2030, which might enable to provide a new view angle besides the Apollo observation and to explore the seismisity at far side. The water-ice would also be detected in situ on the permanently shadowed area. As the expected missions might re-use both the soft landing technology and the radio-isotopic sources developed during the Chang'e program, these opportunities might allow the deployment of one, possible two VBBs for long term operations. A scientific working group lead by Institute of Geology and Geophysics from CAS and Institut de Physique du Globe de Paris has been initiated, together with several French and Chinese laboratories.

2. Current Collaboration between France and China

We have started the discssion with our chinese colleagues in 2017 and exchanged a memorandum of intent in September 2017 (see Appendix) to continue the collaboration on the development of lunar and martian seismometer. We have agreed that we will take advantage of the experience in IPGP for the development. We will work in collaboration to be ready to propose the seismometer to Chinese follow-up lunar missions from 2020-2030. In the latest article submitted to ISSI-BJ Taikong, it was mentioned that the first mission in the follow-up mission will be a landing mission to the South Pole and a seismometer will be used to obtain information on shallow to deep structure. It is now well accepted within the Chinese lunar exploration community that seismometer is one of the key scientific instrument in the near future lunar missions. It is of urgent need that we launch the discussion to be ready for the launch opportunity.

The first collaborative work we will carry out with the Chinese teami will be the performance test of lunar VBB in Wuhan. The VBB to be tested will follow a basic design developed for InSight and will be modified to lunar configuration. The Moon is seismically very quiet compared to the Earth. This mainly due to the lack of atmosphere and ocean on the Moon. Thus the noise requirement for lunar seismometer is so severe that little test facility is capable of testing the instrument. Seismic vault of Huazhong University of Science and Technology (HUST) in Wuhan, China is one of the few candidates. HUST has a seismic vault under clean condition which enables us to instruments to be installed on spacecrafts under extremely low condition. The vault is already used to test accelerometers for Earth orbiting spacecraft or making high precision measurements of absolute gravity and gravity constants. The facility is well equipped to carry out tests and is a perfect candidate to test our lunar VBB.

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The VBB seismometer: From InSight performances to perspectives on Lunar Missions

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1. Introduction

The VBB InSight sensors [1] have been developed for the InSight mission. The VBB component has demonstrated during qualification and acceptance tests an improvement of about 2500 at 1Hz and 200 000 at 0.1 Hz with respect to Viking. With respect to Apollo seismometer, the improvement is about 5 at the 0.5 Hz peaked resolution of Apollo. How much further improvements can we achieved for a VBB on the Moon and what will be the associated science achievements?

2. VBB instrument performances and Science perspectives

The VBB InSight sensor performances have been tested for both the Flight Models, Spare Models and



Figure 1: Performances of the VBB as compared to other space qualified seismometers. Viking, Apollo are in black and blue respectively. InSight SP is in long dashed green. VBBs VEL and POS are in green continuous and dotted for InSight and red for Lunar version. Noise are rms in m/s² in a 1/6 decade bandwidth, while in LSB for Apollo and Viking. The black arrow shows an improvement of 20. Resolution better than 10⁻¹¹ m/s2 will be achieved for long period waves of a Lunar VBB.

Earth model. By design and for the same feedback and sensing electronic, these performances depend on the gravity of the planet with a scaling factor related to the ratio between earth and the target planet gravity. Performances down to 5 x 10⁻¹⁰ m/s²/Hz^{1/2} have been achieved in the long period body waves bandwidth (0.1-1 Hz) as well as a validation of the instrument noise model during tests made on Earth and where the seismic vault noise is in addition likely responsible for a large part of this noise, especially at long period. With the same feedback and detection electronics, noises are expected to be better by 2.65 and 6.95 for Mars and Lunar conditions. Several environmental differences between Mars and the Moon will in addition allow further improvements. One is obviously related to the free vacuum of the Lunar environment and a second is the temperature stability of the Moon in the seismic bandwidth. This is a major difference with Mars, especially if RTG technology is used, as done for the Apollo ALSEP and possibly considered for post Chang'E missions. This will allow thermal regulation of the instruments. Preliminary analysis show that simple tuning of the VBB feedback can be done for improvement better than 20x with respect to the Apollo performances at the 0.5 Hz peaked frequency (Figure 1). Improvement by 15x will also be achieved at 20 sec periods, while those at 1 Hz are almost 100x. The mass of such VBB instrument with its electronics and surface protection is estimated to about 15 kg and will request to be deployed at lunar surface in the vicinity of the lander. Such improvements will allow major steps and breakdown in all science goals of lunar interior determination, by giving access to long period surface waves much less sensitive to scattering, to the core

phases of the lunar core [2,3] on individual records, and lunar normal modes from shallow moonquakes [2]. In additions, Deep Moonquakes [4] and Impacts [5] will be detected with a frequency one order of magnitude higher than on Apollo, with multi-daily and daily rate respectively. If combined with flash observations [6], this will provide hundreds of located seismic sources. This will enable the exploration of a new area of Lunar interior structure and, for seismic stations located near sample returns, a 3D detailed view of the crust and upper mantle from where samples are originating.

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A TEXTURAL/MINERALOGICAL GRADIENT WITHIN VITROPHYRIC MARE BASALT NWA 8632

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1. Introduction

The 24-gram meteorite Northwest Africa (NWA) 8632 has been described as a rare lunar vitrophyric basalt devoid of plagioclase [1,2]. For most of the rock's volume, this characterization is valid. The rock consists of early phenocrysts of olivine with microphenocrysts of Cr-spinel, a later generation of pyroxene (px) phenocrysts, and a groundmass of (partially devitrified) aluminous glass with minor ilmenite, and no plagioclase (plag). However, we have found that a corner of rock has a holocrystalline texture, where the groundmass, instead of being dominantly glass, is dominated by roughly equal proportions of plag and px (caveat: we say "holocrystalline" and "plag" in reference to the original rock; launch off the Moon may have altered the plag to maskelynite). Px within the holocrystalline zone is compositionally distinctive.

2. The plag-rich zone

The plag-rich zone occupies one corner, accounting for ~ 10 % of our 155 mm2 thin section (manifestly from the same rhomb-shaped slab as the sample studied by [2]). Fig. 1 shows a backscattered electron (BSE) image of typical plag-zone groundmass. The dominant groundmass phases are plag and px, clustered into sheaf-like bunches of elongate, subparallel to slightly radiating platy crystals, with typically about 10 grains of each (plag and px) per sheaf. Directional crystallization within the sheafs was influenced by surrounding phenocrysts, but sheaf orientations are near-random; they seldom pass through large phenocrysts and show little or no long-distance foliation. Groundmass

grain sizes for plag are up to $130 \times 12 \ \mu m$ (px is similar), although conceivably long grains in BSE are not single crystals. Grain sizes generally decrease with distance away from the tip of the plag-rich corner, and give way to glass at about 4-5 mm. In the x-ray map (Fig. 2) the upper left corner is near the outer boundary of the plag-rich zone.

3. Pyroxene element compositions

Pyroxene major-element compositions are shown in Fig. 3. In the plag-free vitrophyric portion of the rock px compositions are restricted to moderate mg and moderate-to-high Wo. Pyroxene in the plag-rich zone is more diverse, as the groundmass px is distinctly Ferich and Ca-poor (some of the lowest-Ca, highest-Fs "pyroxene" is conceivably pyroxferroite). The FeO that (unlike MgO) remained largely still in melt and quenched into glass in the vitrophyric zone, instead yielded high-Fs px in the holocrystalline zone. The plag-rich zone's pyroxenes also show less development of compositions near Fs50Wo30, which formed in the vitrophyric zone by late plag-absent extensions onto rims of phenocrysts.

Pyroxene minor-element compositions also show effects of cocrystallizing plag. In the absence of plag (vitrophyric zone), minor elements became enriched in late, relatively low-mg px. A similar pattern occurs in the analogously plag-free Apollo-15 vitrophyre 15597 [3,4]. The anticorrelation between mg and AI (mirrored by Ti) is striking. To allay concern that the trend might be a trivial side-effect of major-element variation, Fig. 4 shows instead the similar pattern from Al/Ca. In the plag-rich zone, the groundmass px shows Al/Ca lower by a factor of close to 5 in relation to the low-mg end of the vitrophyric anticorrelation trend. The AI that partitioned mainly between melt (glass) and late px in the vitrophyric zone was instead incorporated into plag in the holocrystalline zone.

The px (both zones) shows a typical mare-basaltic trend [5] of anticorrelation between mg and the ratio "ti" [=molar Ti/(Cr+Ti)]. The mg = 50 intercept of this trend at ti ~ 0.78 implies [5] an initial magma TiO2 content of ~ 3.4 wt%, high in comparison with a bulk analysis (from only 64 mg) result of 2.5 wt% [1]. However, "initial" in the case of an olivine-phyric rock may best be viewed as representing the magma at onset of ti-mg fractionation, i.e., px crystallization.

Oceanus Procellarum and Mare Imbrium Volcanism: Lunar volcanic history and diversity ready to be explored

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1. Introduction

Numerous scientific instruments are of critical interest for investigations of the lunar surface and the selection of areas to further explore. Instruments onboard the "recent" Chandrayaan-1, Lunar Reconnaissance Orbiter, Grail, and Chang' E missions provide digital terrain models, interior properties, mineralogical maps and geological context to assess the interest of possible landing site.

2. Near Side volcanism from remote mineralogical investigations

Oceanus Procellarum and Mare Imbrium correspond to vast region with valuable information on lunar volcanism, its evolution and nature. From olivine-rich to olivine-poor units [1,2], volcanism exhibits the million years of evolution of the early Moon to the end of its thermal activity. The volcanic complex of Marius Hills [3] is gathering in only few tens of kilometres the long and complex volcanic evolution of the lunar mantle with effusive and explosive volcanism mineralogically distinct.



Figure 1: Mapping of mineralogical units in Mare Imbirum [1] and Flamsteed.

Explosive volcanism is also widely represented on the lunar surface and today's instrumentations onboard the spacecraft allow identification of these pyroclastic deposits, and their composition often rich in volcanic glass [4]. In fact, mineralogical variations at local scale [5] can also relate to the eruption mechanism and the complex evolution of the lunar near-side.

3. Lunar Volcanism exploration, still a high priority target

Various landing site of high scientific values could be extracted from the latest mineralogical investigations of the lunar surface. The Yutu rover exploration should be expanded to investigate mineralogical units [2] of effusive volcanism. Volcanic domes and cones (e.g., Rumker, Mairan, Gruthuisen) are of great values, together with the Marius Hills, which may combine different volcanism style and composition in a single localized place [2].

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The hunt for indigenous signatures within Lunar anorthosites

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1. Introduction

Noble gases, while chemically inert, are important tracers of physical processes across the Solar System [1]. Here we present noble-gas (Kr, Xe) isotope systematics of a suite of 10 Apollo highland anorthosites (FAN suite) in order to investigate the physical history of these samples. Canonical interpretations of the FAN suite state that they have been shielded from the effects of lunar 'surface' solar wind and cosmogenic implantation processes for the majority of their history [2]. Indeed, pristine anorthosites typically only display short near-surface residence times (<20 Ma based on ³⁸Ar and ⁸¹Kr systematics [3]). Therefore, anorthosites are ideally placed to investigate the 'indigenous' (i.e., the noble-gas signature present since the formation of the Moon) volatile signatures of the Moon. The composition of which, has yet to be fully constrained in lunar samples [4, 5].

2. Results and Discussion

We investigated 10 Apollo anorthosites (65325, 62275, 67635, 60135, 69955, 60015, 60515, 62236, 67215, 15415). To liberate the Kr and Xe gas, we step heated ~10 mg sample chips using a diode laser (λ = 900 nm). In total 4 heating steps was undertaken. Two steps were con-ducted at low power (15, 25 W, < ~1000°C), a third over the melting point of the sample (35 W), and a fourth final high temperature (45 W) to ensure the liberation of all gas from the samples. The extracted was measured on a Thermo Helix MC using peak jumping mode.

Four samples (62236, 62275, 67635, 15415) display clear evidence of spallation reactions induced by galactic cosmic rays. However, most samples cluster around the composition of solar wind/air. Previous investigations of lunar FANs have concluded that chemisorption of terrestrial atmospheric xenon (rather than physical adsorption) have comprised the Xe isotope systematics, accounting for the measured airlike light Xe-isotope ratios (¹²⁴⁻¹³²Xe) [4]. Thus, it is likely that the Xe-isotope systematics reported here reflect a mixture of both solar and adsorbed terrestrial air components.

Recent Xe isotope studies of lunar FANs [5] have reported evidence of a depletion in the heavy Xe isotopes $(^{134,136}$ Xe) relative to terrestrial air ($[^{136}$ Xe/ 132 Xe]_{air} = 0.98 ± 0.01 1 σ) in one sample. We also observe similar depletions in 7 of the anorthosites investigated here. Our observed depletions are much greater than those reported by [5] ($[^{136}Xe/^{132}Xe]_{air} = 0.94 \pm 0.04 (1\sigma)$, to 0.67 ± 0.12 (1 σ)). Bekaert et al. [5] concluded that these signatures could represent a contribution from U-Xe mixing with a small cosmogenic and contaminated air contribution. The U-Xe component is thought to represent the precursor to modern terrestrial atmosphere [6]. Whereas it has been debated if U-Xe represents a tangible component, recently studies have modelled that U-Xe represents a mixture of chondritic, solar, and cometary Xe [7]. This has led to suggestions that the observed ^{134,136}Xe depletion in sample 65315 is the result of cometary addition to the Moon [5]. It is notable that both low and high temperature steps from this study display these depletions, indicating that these signatures are indeed a trapped component within minerals, rather than the result of surficial implantation. It is possible that icy bodies including cometary material was delivered to the Moon during the late veneer, prior to anorthosite crystallization. In this scenario, the observed ^{134,136}Xe depletions would represent a true lunar indigenous component. Overall, whereas the observation of ^{134,136}Xe depletions in some lunar anorthosites reveals a tantalizing insight into indigenous lunar noblegases, it is currently unclear to what extent processes, such as impact metamorphism or recent (< 20 Ma) additions to the lunar regolith act to mask the indigenous lunar Xe signature.

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CLEP LUNAR SCIENCE ARCHIVE ARCHITECTURE AND DATA MANAGEMENT

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1. Introduction

The Lunar Science Archive (LSA) is China's Lunar Exploration Program (CLEP) repository of science data from all Chang'E missions. First released in 2008, it went through a completely renewed user interface and system architecture, with the "new" LSA v3.0 released early 2017 and can be accessed at http://moon.bao.ac.cn

The LSA is being developed and operated within the Ground Research&Application System (GRAS), which located at the National Astronomical Observatories of Chinese Academy of Sciences in Beijing.

2. LSA content

The LSA is a multi mission archive containing science datasets from Chang'E missions (CE-1, CE-2, CE-3) and will include science data holdings from future Lunar and Mars missions (CE-4, CE-5, HX-1).

All data sets are compliant with the Planetary Data System (PDS) standards. From LSA v3.0 early 2017, the archive can ingest datasets from PDS3 and PDS4 and offer them to scientists through common interfaces.

3. LSA interfaces

The primary way to access CLEP planetary science data holdings is through the LSA GUI, which offers a powerful and user friendly faceted search web interface. Lots of work has been done to ensure homogenous metadata across the many instruments, to enable science driven searches across instruments across missions.

Login is required for proprietary data download for users, but most of the data is public and accessible without requiring to login. Although planetary scientists represent the main users of the LSA, there are many spectacular images that can also be of interest of the general public and the media. To facilitate access to these, an archive image browser is also available to quickly search and visualize Rosetta browse products. Plans for a map browser using GIS technologies are on-going, based on a still to be defined uniformed geometry information across mission's datasets.

4. LSA Architecture

The LSA is based on a modular and flexible 3-tier architecture. The storage layer consists of a data repository (around 35TB) and a RDBMS (Oracle). The Client layer offers the main interfaces to scientists, either through a thin web client or through command line interface. The Server layer takes care of handling all database queries, data distribution services and all archive administrative services (ie user login and authentication, usage statistics).

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Indication of lunar soil properties on space weathering

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1. Introduction

Since 3 billion years ago, there was few strong tectonic activity on the Moon. Space weathering becomes the main geological process in this period. Micrometeorite bombardment and solar wind implantation lasted the whole period and changed the lunar soil properties. That is, the properties of lunar soil record lots of information of space weathering. In macroscale, there is distinct change in spectrum characters, such as weakening absorption strength, decreasing reflectivity, and smoothening spectrum continuum [1]. However, which properties indicates the lunar space weathering process in microscale? In this study, the relationships between micro-properties of lunar soil grains and lunar space weathering will be described.

2. Microstructure and Nanophase Iron (npFe⁰)

In lunar space weathering, both of the micrometeorite impact and solar wind implantation can destroy the mineral microstructure. Different characters of mineral microstructure have been found in Apollo lunar samples [2]. To investigate the characters of mineral microstructure destroyed in space weathering processes, we simulate micrometeorite impact and solar wind implantation by pulse laser irradiation and ion implantation, respectively. Based on these experiments, some results are obtained [3,4].

- Multi-layers structure is usually formed in mineral subsurface in micrometeorite impact process, and double layers structure is formed in solar wind implantation process;
- In micrometeorite impact process, much more npFe⁰ particles are produced in high-Fe content mineral subsurface and the particle size is relative large;
- For plagioclase, npFe⁰ inclusions presented in outmost layer usually relates to the micrometeorite impact process, and no npFe⁰ inclusions layer is formed by solar wind implantation process;
- In solar wind implantation process, the destruction of mineral microstructure mainly depends on the implanted ion dose and crystal structure.

3. Hydroxyl

Except destruction of mineral microstructure, solar wind proton implantation can formed "water" in silicate minerals. That is verified by detecting the absorption of H_2O and OH at 3μ m and near 2.8μ m in recent lunar explorations, such as Cassini, Deep impact, and Chandrayaan-1 missions [5]. To investigate the hydroxyl characters induced in solar wind proton implantation, some experiments are made. And we get some primary results as following:

- The water can be formed in all silicate minerals after H⁺ implantation, and is mainly hydroxyl;
- OH shown different thermal stability, one of them is little affected by lunar day-night alteration;
- The hydrogen isotope reserves the information of solar implantation process.

4. Summary

Mineral microstructure, npFe⁰, and hydroxyl in lunar soil grains contain lots of information of lunar space weathering process. With the analysis of lunar samples returned by Chang'E-5 mission, the space weathering will be comprehended furtherly.

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The Characteristics of Water in Plagioclase by Proton Implantation Experiments

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1. Introduction

The absorption characters at about 3 μ m and near 2.8 μ m on the almost entire lunar surface have been detected by the infrared spectrometers of Cassini, Deep Impact and Chandrayaan-1 missions [1-6], which indicated the presence of H₂O and OH, respectively. The widespread OH/H₂O on the lunar surface is thought to result from the interaction between the solar-wind proton and the oxygen in the regolith. However, the formation mechanism, states, abundance and stability of solar wind induced water are still ambiguous. Here the formation and thermal stability of water in plagioclase by H⁺ implantation will be presented.

2. Experiments

An ion implanter is used to simulate the process of solar wind implantation. The plagioclase sample is irradiated with 5 keV H^+ at dose of 10^{17} ions/cm². We use micro-FTIR with Temperature Controlled Stages to analyse the water content and the change of water with temperature.

3. Results

After H^* implantation, the peak intensities of OH and H_2O in the plagioclase sample are obviously increased (Fig. 1). The absorption peaks at 3621 and 3436 cm⁻¹ represent OH and H_2O , respectively. Based on the Beer-Lambert law, the water content in the plagioclase is calculated. The increase of water content after H^* implantation is about 215±45 ppm.

We also analyse the thermal stability of the water with temperature in the plagioclase ample after H⁺ implantation. As the temperature increases, the water content decreases gradually (Fig. 2). H₂O content decreases obviously than OH content, and there is rarely H₂O content above 300°C. The change of the water content with temperature is similar to that in the lunar surface. The results imply that the H₂O formed by solar wind is hardly to be stored in the lunar equatorial region. In the middle and high latitude of the lunar surface, more OH and some H₂O induced by solar wind could be reserved.





4. Conclusions

After H⁺ implantation in the plagioclase, the water content remarkably increases, and the change of water content with temperature is obvious. The research of solar wind induced water in Chang'E-5 lunar samples is important to well understand the origin, characteristics, storage and migration process of the solar wind induced water in the lunar soil.

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PROSPECTing the Moon: Numerical simulations of temperature and sublimation rate on a regolith cylindric sample

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1. Introduction

The goal of the PROSPECT mission [1] is to extract and characterize a regolith sample from the lunar south polar region, by studying its physical and chemical properties, in particular the abundance and distribution of water ice and other volatiles. In order to evaluate the expected water ice sublimation rate during the drilling transfer and analysis, we applied a 3D thermophysical model [2] to a cylindric sample of lunar regolith. Numerical solutions have been used to inform the system's development.

2. Numerical method

The numerical model is based on a 3D finite element method (FEM) [2] which solves the classical heat equation plus a term linked to the energy subtracted by the water ice sublimation (see e.g.[3]). Ice diffusion is treated by using a mass conservation equation where the diffusion coefficient is set according to the kinetic theory of gases [3]. The water vapor is treated as an ideal gas and the local thermodynamic equilibrium is assumed [3]. The lunar sample consists in a cylinder of 3 mm of diameter and 6 mm in height and it is covered by a triangular mesh of about 1000 elements. The loss of water ice is allowed only through one open space of the cylinder. In the models we have simulated, the boundary temperatures ranges from 148 K to 223 K, while the initial temperature of the sample is always at 123 K. The water ice content of the sample ranges from 0.1% to 10%.

3. Results

We obtain a significant loss of ice only in the case of high temperatures on the side (223 K) while the water ice is preserved if the gradient between the sides ad the interior of the sample is small. As an example, we report in Fig.1A the case in which the sides are at 148 K and the initial volume percentage of ice is 10%, corresponding to about $2x10^{-6}$ kg: the water ice is preserved during all the simulation (about 100 minutes). If the boundary temperature is set at 223 K and the volume percentage of ice is set at 10%, the complete loss of the water ice occurs after 30 minutes from the beginning of the simulation, as we can see in Fig.1B.



Figure 1: Ice loss [kg] vs simulated time [min] with boundary temperature at 148 K (panel A) and at 223 K (panel B). The intersection between the red line (the initial vol.% of water ice) and the sublimation curve gives an estimation of the preservation time of the water ice.

4. Future works

Future simulations will explore different physical situations (different sample size, thermal/chemical properties) and will support the evolving PROSPECT development.

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A miniaturized spectrometer for surface and subsurface investigations.

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1. Introduction

Here we describe the concept of a miniaturized spectrometer like the Ma_MISS (Mars Multispectral Imager for Subsurface Studies [1]) hosted by the drill system of the ExoMars 2020 rover [2]. It will perform spectral reflectance investigations in the 0.4–2.2 μ m range to characterize the mineralogy of the excavated borehole wall at different depths (≤2 m). The spectral sampling is 20 nm while the spatial resolution is 120 μ m. Such kind of instrument is suitable also for the investigation of the surface and subsurface (if hosted in a core/drill device) of the lunar surface.

2.Ma_MISS instrument aboard of EXOMARS rover

The Ma_MISS instrument main requirement is miniaturization because it is embedded within drill of the ExoMars Rover. It relies on the usage of optical fibres to illuminate the target and to collect the signal. The spectrometer is placed in a box on the side wall of the drill box. The spectral range is 0.4–2.2 µm, with a spectral resolution of 20 nm and SNR~100. The light from a 5W lamp is collected and carried, through an optical fiber bundle, to the miniaturized Optical Head (OH), hosted within the drill tip. A Sapphire Window (SW) with high hardness and transparency on the drill tip protects the Ma_MISS OH allowing to observe the borehole wall. Different depths can be reached by the use of 3 extension rods, 50 cm long, each containing optical fibers and a collimator. The first extension rod is connected to the non-rotating part of the Drill, hosted on the rover, through a Fiber Optical Rotating Joint (FORJ), that allows the continuity of the signal link between the rotating part of the drill and the spectrometer. The instrument spectral range and sampling capabilities are suited to map the composition of the borehole in terms of both minerals and ices before the collection of samples by the drill. Moreover, Ma_MISS will be able to produce a stratigraphic column and contribute to assess the geological processes that shaped the subsurface.



Figure 1: left. Artistic view of the ExoMars Rover with instruments allocations. Ma_MISS is integrated within the deployed drill (from [2], modified). Right. Ma_MISS instrument schematic concept. The light/signal link is shown from the TIP to the spectrometer.

Given the reduced dimension and the modular concept, Ma_MISS is a versatile instrument to study the mineralogy of the Moon.

3. References

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Long-lived volcanism expressed through mare infilling, domes and IMPs in the Arago region of the Moon

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1. Introduction

Recent studies find that the geological features and volcanic history of the Moon are far more complex than previously thought. This complexity is well illustrated by the diversity of volcanic landforms that are observed in the vicinity of the Arago crater, located in the western half of Mare Tranquilitatis. Eight volcanic domes and around 40 Irregular Mare Patches (IMPs) have previously been reported [1,2]. The domes were previously separated into two classes, based on their morphologic and spectral characteristics. Both classes have low slopes, and were likely emplaced by extrusive, effusive volcanism [1]. The IMPs were identified based on their low density of craters and tentatively interpreted as recent mare volcanism on the lunar nearside [2], although this interpretation is debated [3]. The present study describes the characteristics and relative timing of these various features using a variety of high resolution datasets.

2. Datasets and Methods

All the datasets available between 18 to 30°E and -2 to 12 °N were downloaded, processed, and integrated into a Geographic Information System. Our data collection includes : Kaguya TC images and associated DTM (spatial resolution 10m/px), LROC WAC (100m/px) and NAC imagery (<1m/px), LOLA topography (100m/px), GRAIL gravity, Lunar Prospector GRS (15 km/px), and Clementine global maps. Kaguya MI data (resolution 10 to 62 m/px) were also used to build a false-color map mimicking the Clementine RGB color composite with the following bands: R = 750/415 nm, G = 750/950 nm, B = 415/750 nm. Finally the Moon Mineralogy Mapper (M3) VNIR hyperspectral data (140 to 280 m/px) were used to derive mineralogical information over the study area.

3. Results and Discussion

Nine candidate volcanic domes were identified using the TC DTM [4]. Their dimensions range from 4.8 to 24 km in diameter, 40 to 400 m in height and 0.8 to 3 degrees in slope. All of the eight Arago domes are located onto two specific mare units: domes A2 and A3 are located in the Tr3 unit (dated at 3.67 Gy), whereas domes A1, A4, A5, A6, A7, A8 are located within the Tr4 unit (youngest regional unit dated at 3.59 Gy) [5]. Crater counts reveal three groups of ages for the domes: 1) domes A1 and A8 (small-scale, intermediate slope) dated at 3.7-3.8 Gy, 2) domes A4 to A7 (smallscale, low slope) dated at 3.3-3.5 Gy, and 3) domes A2 and A3 (large-scale, steeper slope, more silica-rich?) dated at 2.7-2.9 Gy. M3 spectral data reveal no major compositional difference between the domes and the surrounding mare units, which are dominated by high calcium pyroxenes (HCP) signatures. All IMPs are located in the Tr4 unit, and some on the top of dome A6, making them younger features. Both the domes and IMPs are aligned, and are perpendicular to some grabens, suggesting a strong relationship to tectonics. These observations allow us to reconstruct part of the geologic history of Mare Tranquilitatis, which started with the emplacement of mare basalts > 3.85 Gy (regional unit Tr1), followed by the emplacement of more mare units, volcanic domes and IMPs, that spread over more than 1 Gy [4]. The Arago region is located outside of the Procellarum KREEP Terrane, but it is associated to a positive thorium anomaly, which could explain its exceptional volcanic history and complexity. Its peculiar geologic record could therefore hold clues to the Moon thermal and magmatic evolution.

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Young wrinkle ridges in Mare Imbrium: Distribution, morphology and formation times

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1. Introduction

Wrinkle ridges are common tectonic features widely distributed in the lunar maria. Lunar wrinkle ridges were considered to be rather old, formed close to emplacement of mare plains [1, 2]. Many young wrinkle ridges were found inside Mare Imbrium using Lunar Reconnaissance Orbiter Camera Narrow Angle Cameras high-resolution images (Fig. 1A). The crisp morphology and crosscutting relations with fresh craters indicate that wrinkle ridges may be still forming within the past 50 Ma [3], and suggest that the Moon's tectonic activity continues until today [4, 5]. Here we show the distribution, morphologies and formation ages of young wrinkle ridges inside Mare Imbrium, and further discuss their possible formation mechanism.

2. Location and morphology

Figure 1B shows the two sites where they were found. Some of the young ridges are located to the north of the CE-3 landing site. The others are close and nearly parallel to the Eratosthenian lava flow fronts. They are mainly distributed on old Imbrian basalts.

The young wrinkle ridges can be a few hundred meters to several kilometers long and are usually less than 300 m wide. They are sinuous (Fig. 1C), with a bend every few hundred meters. The bend angles are large, sometimes more than 90°. The young wrinkle ridges are arched or dome-shaped (Fig. 1C), but show no steep ridges or scarps.

3. Time of formation

The spatial boulder density method [6] applied to four small fresh craters crosscut by young wrinkle ridges was used to derive the maximum ages of the ridges. According to the density to time calibration equation from [6], the ages of four small craters were estimated to be $<3.2^{+9.0}_{-7.3}$ Ma, $48.0^{+14.5}_{-11.7}$ Ma, $79.8^{+18.4}_{-14.8}$ Ma, and $<17.7^{+10.8}_{-8.7}$ Ma, respectively, indicating that some of the discussed ridges are even younger than 10 Ma.



Figure 1: Young wrinkle ridges in Mare Imbrium.

4. Possible formation mechanism

Young wrinkle ridges in Mare Imbrium are not evenly distributed but concentrated at the inner region of the basin. It seems that global compression [4] is not the only source of stress, and may suggest the thermal and structural evolution of the inner region of Imbrium basin was protracted.

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