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Short Communication

Digital and global lithologic mapping of the Moon at a 1:2,500,000 scale

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Scientific knowledge of lunar lithologies was first acquired in the 1960s–1970s. The space race between the United States (U. S.) and Soviet Union has promoted numerous manned and robotic lunar exploration missions. Utilizing datasets from these missions, the first series of lunar geologic maps was prepared and published by the U. S. Geological Survey (USGS). The definition of lunar geological features in these maps was mostly based on morphological characteristics but lacked lithological constraints owing to the incompleteness of the compositional datasets available. After two decades of silence, a new era of lunar exploration began in the 1990s when the Galileo spacecraft flew by the Moon during its gravity-assisted maneuvers. The very successful orbital missions, the Clementine and Lunar Prospector (LP), provided the first global geochemical and mineralogical (multispectral, gamma ray, neutron, etc.) datasets of the lunar surface. The 21st century is an exciting era for lunar exploration. Various missions were carried out by space agencies in Europe, Japan, India, and the U.S. China started its lunar exploration program in 2004 and has already launched two orbital missions (i.e., Chang'e-1 (CE-1) and CE-2). The successful touchdown of the CE-3 lander and release of the Yutu rover in the Guang Han Gong region marks the first "return to the Moon" approximately-four decades after the last visit of Luna 24. The historical landing on the far side of the Moon was realized by the CE-4 mission in 2019. The released Yutu-2 rover is moving and exploring unusual materials exposed in the South Pole-Aitken (SPA) basin. These orbiting, landing, and roving missions collect diverse datasets that enable integrated research on lunar surface materials, improve our understanding of lunar magmatic evolution, and provide primary sources for this lithological mapping effort. In addition to remotely sensed datasets, landing missions during Apollo days returned ~382 kg of lunar samples to Earth. Recently, more lunar samples weighing 1731 g were brought back by the CE-5 mission. Based on the unique properties of lunar materials reflected in the Apollo and Luna samples, >500 meteorites collected on Earth have been confirmed to originate from the Moon. These returned samples and meteorites have allowed scientists to study in great detail the chronology, mineralogy, geochemistry, and petrology of the lunar rocks and soils. Furthermore, the analyses of these returned samples and meteorites provide us with important "ground-truth" for remote sensing studies, allow extended calibrations of other regions that have not yet been sampled, and enable us to interpret lunar global magmatism. The lithologic map of the Moon (Fig. 1) was prepared based on

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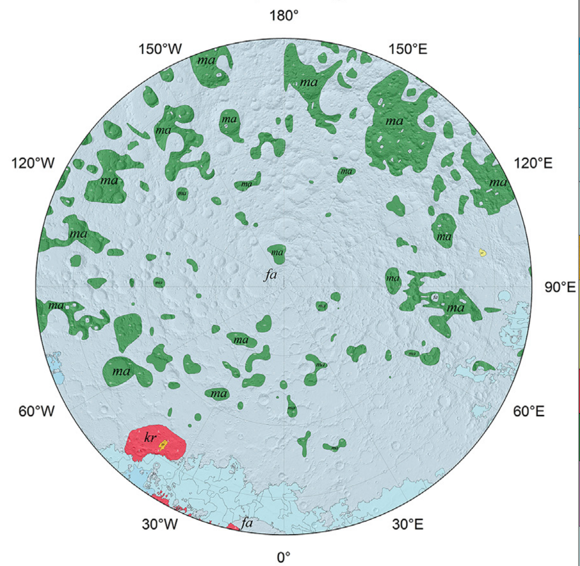
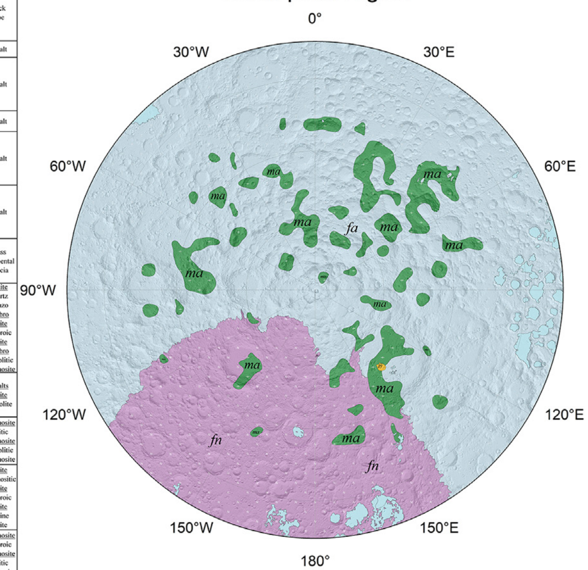


Synthesis of the lunar endogenic lithologies

Lithologic units				Tectonic units								
Symbols	Label	Lithology	Texture	M TU	MHT TU	AH TU	SPA TU	NP TU	Age Method	Magma series	Magma source	Rock type
	vht	Very high-Ti basalt	Poikilitic Equigranular	○					3680–3200 Ma CSFD	Tholeiitic basalt	Mantle	Basalt
	ht	High-Ti basalt	Phyric Subophitic Poikilitic	○	○				3850–1200 Ma Ar-Ar Rb-Sr Sm-Nd U-Pb CSFD	Tholeiitic basalt	Mantle	Basalt
	mt	Medium-Ti basalt	Phyric Subophitic	○	○	○	○	○	3760–1210 Ma CSFD	Tholeiitic basalt	Mantle	Basalt
	lt	Low-Ti basalt	Phyric Subophitic Poikilitic Equigranular	○	○	○	○	○	3900–1650 Ma Ar-Ar Rb-Sr Sm-Nd U-Pb CSFD	Tholeiitic basalt	Mantle	Basalt
	vlt	Very low-Ti basalt	Phyric Subophitic	○	○	○	○	○	3880–1700 Ma Ar-Ar Rb-Sr Sm-Nd U-Pb CSFD	Tholeiitic basalt	Mantle	Basalt
	py	Pyroclastic deposit	Volcanic Vitrophyric	○	○	○	○		3620–3300 Ma Ar-Ar Rb-Sr Sm-Nd U-Pb	Tholeiitic	Mantle	Glass Fragmental breccia
	sr	Silicic dome	Granophyric	○	○				4382–3880 Ma Ar-Ar Rb-Sr Sm-Nd U-Pb	Alkali	Crustal Mantle	Felsite Quartz Monzo Gabbro Norite Gabbroic Norite Gabbro Troctolitic Anorthosite
	kr	KREEP suite	Impact melt breccia Intersertal	○					4309–3820 Ma Ar-Ar Rb-Sr Sm-Nd U-Pb	Tholeiitic	Crustal	Basalts Norite Troctolite
	ma	Magnesian anorthositic suite	Granulitic Blastic Poikilitic	○	○	○	○	○	4330–4080 Ma Ar-Ar Rb-Sr Sm-Nd U-Pb	Tholeiitic	Crustal Mantle	Anorthosite Noritic Anorthosite Troctolitic Anorthosite
	fn	Ferroan noritic suite	Pyric				○		4330–4210 Ma Ar-Ar Rb-Sr Sm-Nd U-Pb CSFD	Tholeiitic	Crustal Mantle	Norite Anorthositic Norite Gabbroic Norite Olivine Norite
	fa	Ferroan anorthositic suite	Cumulate	○	○	○	○	○	4560–4330 Ma Ar-Ar Rb-Sr Sm-Nd U-Pb	Tholeiitic	Magma ocean	Anorthosite Gabbroic Anorthosite Noritic Anorthosite Troctolitic Anorthosite

Note: "○" denotes that the indicated lithologies are exposed in the corresponding tectonic units.



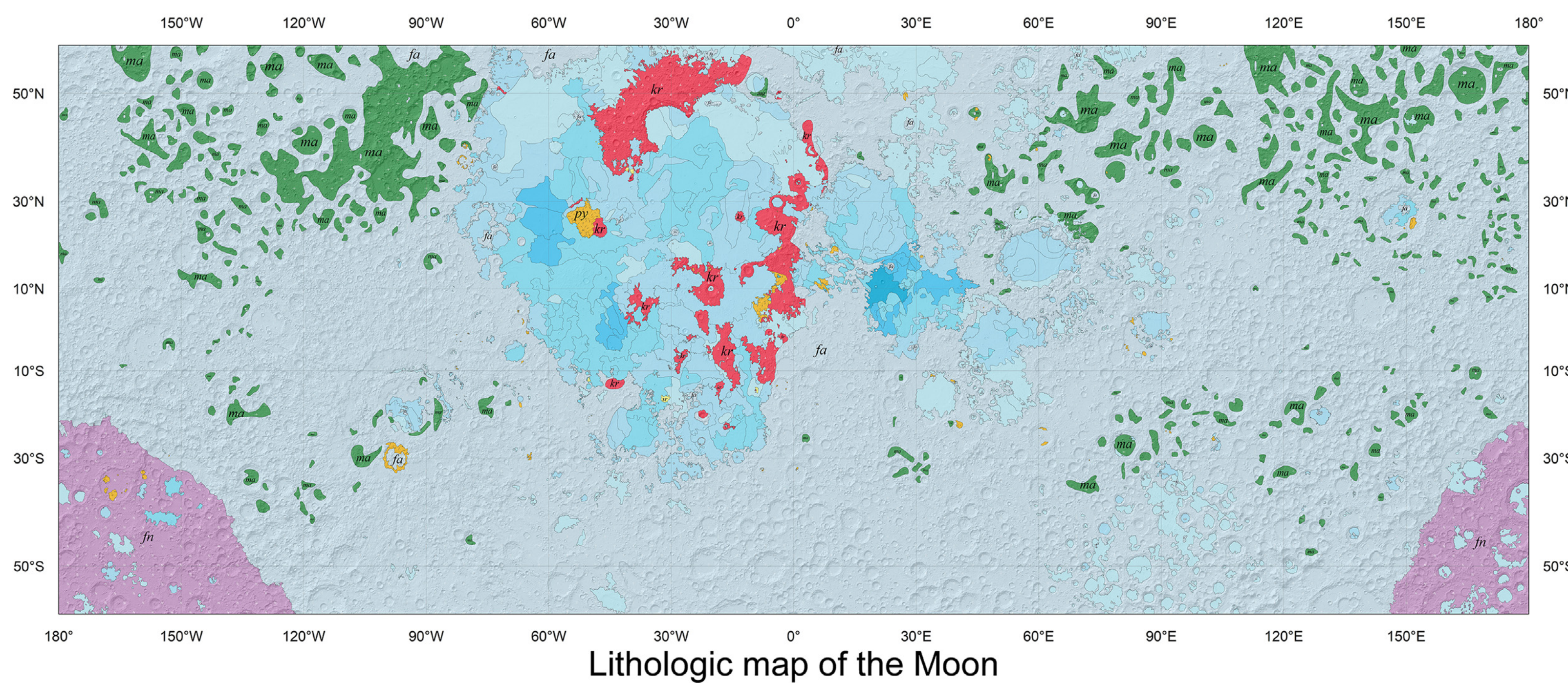


Fig. 1. Thumbnail of the lithologic map of the Moon.

visible and near-infrared, X-ray, and gamma ray spectroscopic datasets of the Chang'e missions. The raw datasets were reduced, vectorized, and integrated with products from international lunar exploration missions and information gained from five preceding decades of lunar sample studies. A systematic classification scheme for endogenic lunar lithologies was reconstructed to map the compositional distribution and magmatic evolution of the lunar surface. The remote sensing datasets were compiled and integrated using Geographic Information System (GIS) software to build a unified database of lunar lithologic distribution, on which subsequent lunar geologic mapping and review of lunar geologic history were based. The lessons learned from this effort are expected to be applied to other planets and small bodies in the future.

As part of the Chinese lunar geologic mapping project (1:2,500,000-scale), the lithologic map of the Moon was prepared based on global products from the CE-1 and CE-2 Digital Orthophoto Maps (CE-1 DOM, 120 m/pixel, CE-2 DOM, 7 m/pixel), Digital Elevation Model (CE-1 DEM, 500 m/pixel, CE-2 DEM, 20 m/pixel), gamma ray spectrometer (CE-1 GRS, 5°, CE-2 GRS, 2°), CE-1 Imaging Interferometer (IIM, 200 m/pixel, Fig. S1 online), regional products from CE-3 and CE-4 visible and near-infrared imaging spectrometer (VNIS), and CE-3 particle induced X-ray spectrometer (PIXS) released by the Ground Research and Application System (GRAS) of the Chinese Lunar Exploration Program (CLEP) [1]. Additionally, we used global products of the Lunar Reconnaissance Orbiter Camera (LROC) Wide Angle Camera (WAC), LRO Lunar Orbiter Laser Altimeter (LOLA), LRO Diviner Lunar Radiometer Experiment (DLRE), Chandrayaan-1 Moon Mineralogy Mapper (M^3), Kaguya Multiband Imager (MI), Kaguya Spectral Profiler (SP), LP Gamma Ray Spectrometer (LP GRS), and Clementine Ultraviolet/Visible (UVVIS) camera, and 1:2,500,000-scale and 1:5,000,000-scale lunar geological maps (Table S1 online) [2–4]. These disparate datasets were combined with knowledge from returned samples and lunar meteorites to characterize lunar surface lithologies originating from endogenic processes and to reveal the magmatic evolution of the Moon.

In the lithologic map of the Moon, polygon features are extensively (>6.25 km^2, corresponding to a 1 mm^2 area on the printed 1:2,500,000-scale map) distributed lithologic units. In contrast, point features have smaller lithologic exposures. In addition, endogenic tectonic features [5] related to lithologic distribution were also included in the lithologic map. In addition to geologic features, annotations, such as nomenclatures, locations of spacecraft landing sites, and elevation points, were also labeled (Table S2 online). The lithological map legend is shown in Fig. S2 (online) [6].

As a result of this mapping effort, we compiled global datasets of lunar surface materials and lithologies, as listed in Table S3 (online).

The rock samples returned by the Apollo and Luna missions can be classified into three distinct groups based on their texture and composition [7]: (1) pristine highland plutonic rocks, uncontaminated by impact mixing; (2) pristine volcanic rocks, including lava flows (basalts) and pyroclastic deposits; (3) polymict clastic breccias, impact melt breccias, and thermally metamorphosed granulitic breccias. The third group (breccia) was mapped as crater materials and basin formations on a geologic map of the Moon. The lithologic map focuses on pristine lithologies.

Most pristine highland rocks formed during the early differentiation of the Moon and can be subdivided into three chemical groups based on the An# (molar Na/(Na + Ca) content) of plagioclase versus the Mg# (molar Mg/(Mg + Fe) content) of mafic minerals [8,9]. The ferroan anorthositic suite (FAS, low Mg#) yields ages in the 4.5–4.3 Ga range; the Mg-suite rocks (high Mg#) are younger (4.43–4.17 Ga) [10]. The alkali suite (low An#) is enriched in alkaline and other trace elements and extends to younger ages (from ~4.3 Ga to ~3.8 Ga) [11].

"KREEPy" rocks are recognized in many returned samples owing to the unique chemical signature [7]. The word "KREEP" is an acronym for K (potassium), rare earth elements, and phosphorous (P). The KREEP component is usually interpreted from the urKREEP reservoir between the feldspathic crust and the ultramafic mantle, which is a residuum from the crystallization of the lunar magma ocean and has played a key role in the magmatic evolution of the Moon. KREEP basalts with enriched concentrations of incompatible elements are thought to have been formed by the remelting or assimilation of the urKREEP reservoir by mantle melts [12]. Mare basalts differ fundamentally from KREEP basalts and are sourced from the partial melting of lunar mantle cumulates. In this mapping effort, we defined the "enriched" urKREEP reservoir as "crustal" reservoir (Table S3 and Fig. S3 online) and the "depleted" reservoirs where mare basalt sourced as "depleted mare basalt mantle".

Lunar meteorites are mostly feldspathic regolith breccia or impact melt breccia and can be classified into five groups based on bulk FeO and Th contents (https://meteorites.wustl.edu/lunar/moon_meteorites_list_alumina.htm): (1) highly feldspathic (noritic and troctolitic anorthosite), thorium-poor breccias; (2) less feldspathic (anorthositic norite and troctolite) breccias with little mare basalt; (3) Th-rich (>3.5 μg/g), moderately mafic breccias; (4) basalt-rich, mafic breccia; (5) largely unbrecciated mare basalts.

Based on a literature review of the classification of returned lunar rock samples, combined with three geochemical provinces of the Moon [13], and integrated with lunar surface lithologies reflected in meteorites and remote sensing datasets, we established an internally related classification scheme of lunar endogenic lithologies, which could reveal the magmatic evolution of the Moon (Fig. 2).

Based on this classification scheme, we summarized the similarities and differences among the returned samples, meteorites, and remote sensing datasets. Combined with the lunar surface chemistry observed by remote sensors, three groups of lithologies (mare basalts, non-mare lithologies, and special outcrops) were chemically classified (Table S4 online) and mapped in the lithologic map of the Moon.

Compared to the previous lithologic maps of the Moon, the main improvements of this map are as follows.

This lithologic map clarified the differences between the magnesian anorthositic granulite and the Mg-suite which are mostly classified as the same lithology in the previous mapping efforts. At present, it is still controversial whether the magnesian anorthositic granulite (proposed in the feldspathic lunar meteorites and remote sensing researches on the lunar highlands) belongs to the same magmatism as the Mg-suite in the Apollo samples or not. In addition, it is unclear whether the petrogenesis of the lunar Mg-suite rocks is necessarily involved with KREEP components. Therefore, they are classified as two lithologies in this map, magnesian anorthositic suite (MAS) and Mg-suite, that further supports the nearside-farside asymmetry of the Moon. The magnesian anorthositic suite is mainly distributed in anorthositic highlands, with low Th contents and no KREEP trace-element-ratio similarity. The newest Mg# maps from CE-1 IIM and LRO DLRE datasets suggest the magnesian anorthositic suite is concentrated at the northern hemisphere of the lunar farside highlands. The Mg-suite is only mapped for the lithologic exposures with similar (i.e., urKREEP-relevant) petrogenesis to those in Apollo samples, which mainly occurs in the Procellarum KREEP terrane on the nearside of the Moon.

The floor of the SPA basin is defined as the ferroan noritic suite (FNS) in this map based on the compositional and mineralogical characteristics in orbital datasets and the latest scientific results from the *in situ* investigations by Yutu-2 rover [e.g., 14]. Although

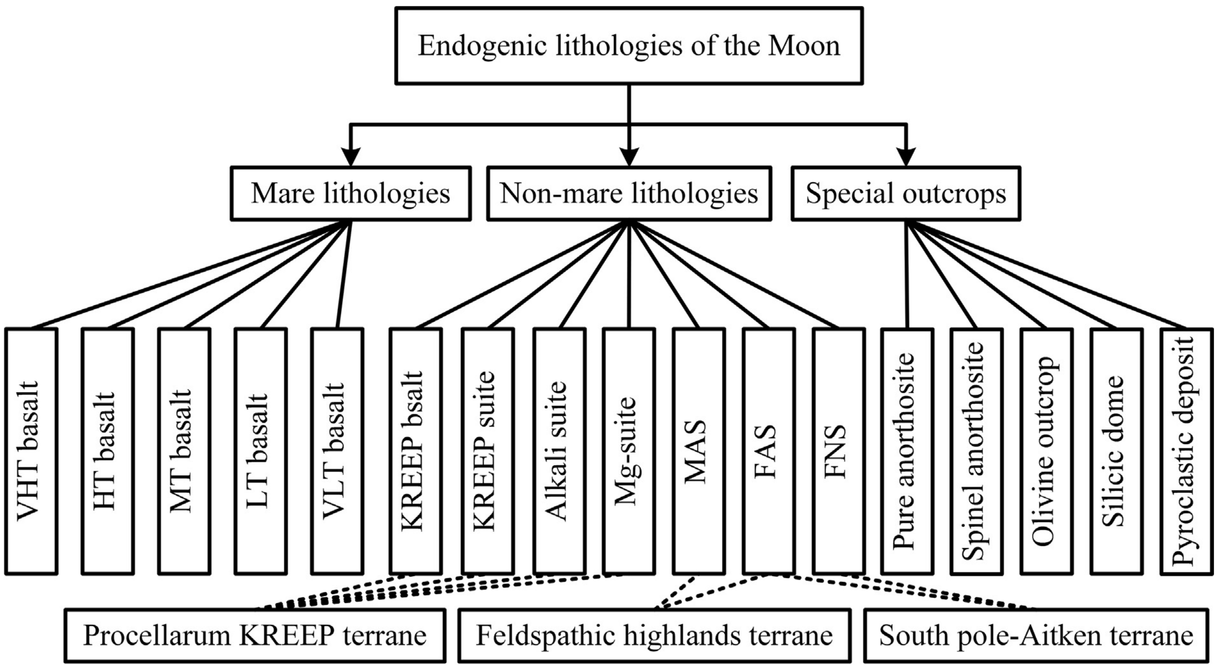


Fig. 2. The classification scheme of lunar endogenic lithologies used in this mapping effort.

the SPA basin floor shares compositional similarities to alkali suite in Apollo samples, the nature of the Th hotspots (KREEP or not) in SPA basin is not clear without returned samples. In addition, there is no evidence that the SPA basin hosts high concentrations of alkaline elements corresponding to the alkali suite. Therefore, the ferroan and mafic anomaly (FeO 10 wt%–15 wt%, Mg# ≤71) in SPA basin is classified as the ferroan noritic suite and distinct from Mg-suite or alkali suite samples returned from the lunar nearside. These analyses highlight the significance of sample return in future explorations of the SPA basin (and the Moon).

The KREEP basalt and Th-rich mare basalts in the Procellarum region are also distinguished in this map. Compared with the Rb/Sr and Sm/Nd values of chondrites, the source regions of high-Ti, low-Ti, and some aluminous mare basalts are consistent with the depleted lunar mantle formed by early lunar (magma ocean) differentiation, while the source region of KREEP basalts has typical enriched characteristics (low Sm/Nd). The petrological and geochemical studies of CE-5 samples returned from the Oceanus Procellarum implies that basalt units with KREEP-basalt-like compositions in orbital datasets could also be derived from non-KREEP mantle source through low-degree partial melting and extensive fractional crystallization [15]. Hence, those Th-rich basalts occurred in the Procellarum KREEP Terrane are classified as (depleted) mare basalts with contamination by materials or gamma ray signals from Th-rich non-mare units. The potential occurrences of (enriched) KREEP basalts with distinct petrogenesis are expressed as point features where sample returns are required to confirm the existence of enriched lava flows.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

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Author contributions

Jian Chen and Zongcheng Ling developed a classification scheme for lunar endogenic lithologies, finished the lithologic mapping of the Moon, and wrote this manuscript. Jianzhong Liu conceptualized this mapping effort. Shengbo Chen, Kai Zhu, and Tianqi Lu contributed to the endogenic tectonic features of the map. Xiaozhong Ding, Kunying Han, Kejuan Xu, Ming Jin, and Ying Wang designed the legend and mapping process for the map. Jianping Chen and Cheng Zhang developed a digital-mapping platform. Weiming Cheng, Yang Song, and Jiayin Deng provided the base maps and annotations of lunar nomenclatures for lithologic mapping. Bo Li, Jiang Zhang, Lingzhi Sun, Changqing Liu, Haijun Cao, Xiangyu Bi, Li Liu, Sheng Wan, Xiaobin Qi, and Zixu Zhao helped with the GIS visualization, reduction of CE-1 IIM datasets, and lithologic mapping of the Moon. Dijun Guo updated the lunar stratigraphic system. Jinzhu Ji, Jingwen Liu, Juntao Wang, Ke Zhang, Jingyi Zhang, Congzhe Wu, and Pengju Sun mapped crater materials and basin formations, which serve as references during the definition of lithologic units. Ziyuan Ouyang contributed to the geologic discussions.

Appendix A. Supplementary materials

Supplementary materials to this short communication can be found online at https://doi.org/10.1016/j.scib.2022.09.015.

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Zongcheng Ling is a professor and a group leader at Shandong University, Weihai. His research interest mainly focuses on remote sensing and laboratory studies on planetary materials employing various planetary spectroscopic methods like Raman, ultraviolet-visible-near infrared, mid-infrared, laser induced breakdown spectroscopy, etc.