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Short Communication

The 1:2,500,000-scale global tectonic map of the Moon

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The tectonic evolution of the Moon is driven by both endogenic (e.g., magmatism) and exogenic (e.g., meteorite impact) forces. A tectonic map of the Moon provides key information about the spatiotemporal distribution of structures and tectonic units. Although the Moon has no plate tectonics, its surface can be divided into different terranes due to the uneven evolution [1]. We define these terranes as tectonic units. Structures, such as craters and faults, are the basic elements of the tectonic units. As a synthesis of current knowledge on lunar tectonics and evolutionary history, lunar tectonic maps are a fundamental resource for scientific research, exploration planning, and landing site selection [2]. From the 1960s to late 1970s, the classification schemes of lunar structure, published in 79 regional geologic maps of the Moon at different scales by the United States Geological Survey [3], were not consistent [4]. One or more sets of data from ground-based telescopes, lunar exploration satellites and field surveys of the Apollo program were used to complete these maps. Their classifications of lunar structures were mainly based on topographic and geomorphic features. Additionally, different mapping personnel have different understandings of the structures in their mapping areas at different scales. It often results in the situation of the same structure with different names or the same name with different meanings, which leads to confusion and misunderstanding [5]. In 2020, six 1:5,000,000-scale quadrangular maps were stitched together and released a globally consistent geologic map [6]. This map focuses on the crater materials and basalt, and only a few types of structures were represented (e.g., wrinkle ridge, rille, graben and lineament of ambiguous origins). It lacks a demonstration of the structure's origin and does not express mascons or deep faults from the gravity field [7]. Additionally, it does not express lobate scarps, which are thought to be the young thrust faults and could provide the recent stress state of the Moon [8]. To date, there has been no recognized and comprehensive classification system of the global lunar structure. A global tectonic map of the Moon was not released until we initiated the 1:2,500,000-scale lunar global tectonic map.

The exploration datasets and products from China's Lunar Exploration Program (CLEP) [9] are used as the primary data (Table S1 online) for mapping the tectonic map. As vital Supplementary materials, high-quality datasets and products from international exploration missions (Table S1 online) were collected.

The geologic time scale is the foundation for a tectonic map. Currently, the lunar geologic time scale of five periods [10] does not emphasize the importance of the South Pole-Aitken (SPA) impact basin in the evolutionary history of the Moon. The formation of the oldest SPA basin (~4.3 Ga) [11] not only established the framework of three first-order tectonic units but also indicated a dynamic transition. Additionally, this event indicated that the lunar crust had cooled and consolidated to sufficient rigidity, and traces of structures could be preserved. In this map, "three Eons-six Periods" [12] were adopted for the compilation of the global tectonic map (Fig. 1). The Eolunarian Eon indicates the initial phase, which was dominated by endogenic processes; the Palaeolunarian Eon indicates a phase when endogenic and exogenic

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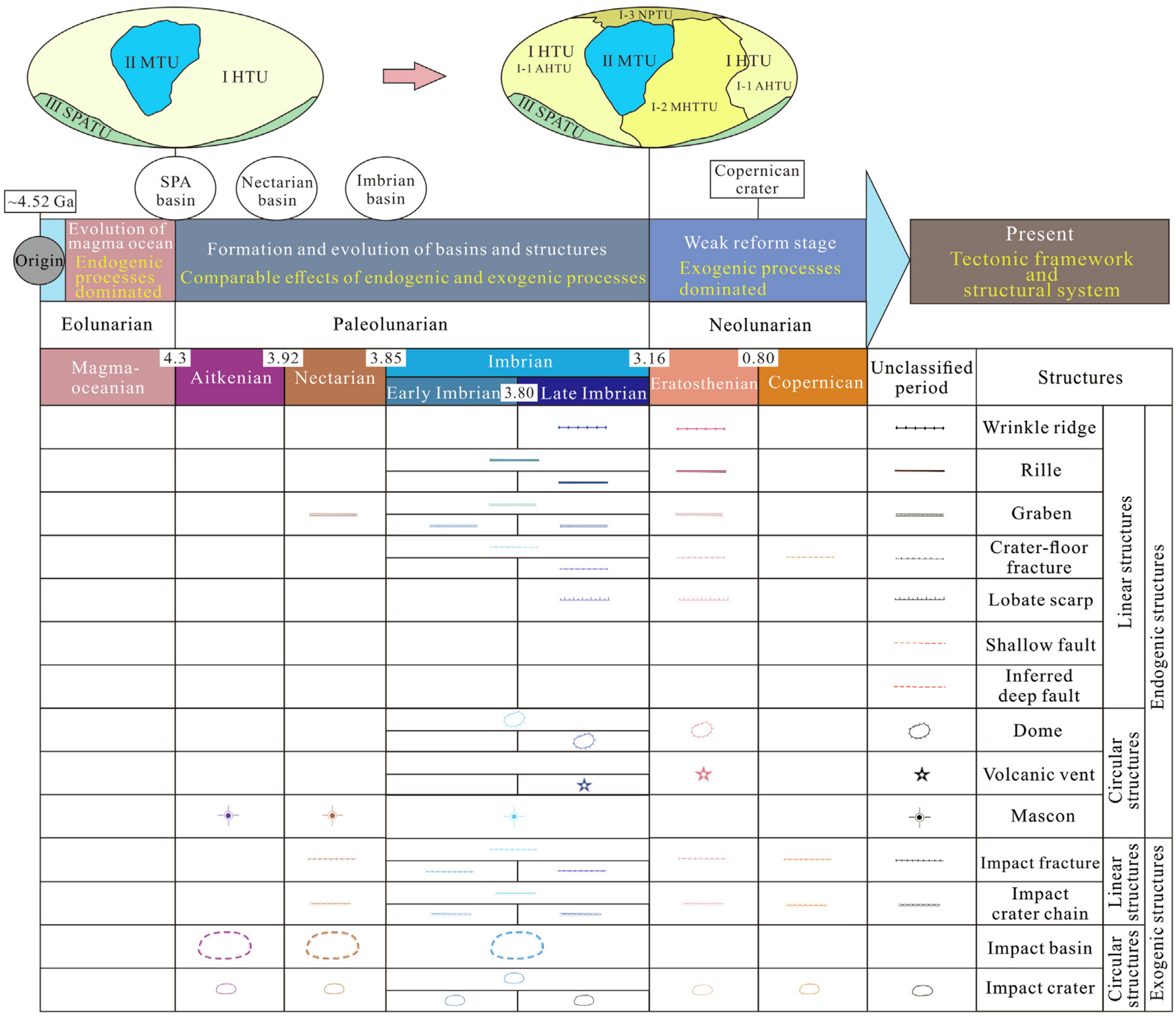

Fig. 1. Schematic diagram of tectonic evolution of the Moon. The right side is the classification system of the lunar structure, the top two ellipses are the schematic diagram of tectonic unit evolution, the colored rows are the updated lunar time scales, and the following table shows the legend used in the 1:2,500,000-scale tectonic map.

processes were both active; and the geological process during the Neolunarian Eon was dominated by exogenic dynamics, and they were obviously weaker than other phases (Fig. 1). The updated lunar time scale scheme shows a great advantage in highlighting the dynamic evolution of lunar structures and tectonic units.

Based on the genetic mechanism and morphology, the characterization and interpretation of the structural signatures were determined (Table 1), and then the global structural classification system was established (Table S2 online). According to genetic mechanisms, lunar structures are divided into 10 endogenic and 4 exogenic types, and they can be further subdivided into linear and circular structures based on geometric features.

Density slicing was used to enhance the differences in topography (Fig. S1 and Table S3 online), geophysical field (Figs. S2 and S3, and Tables S4 and S5 online), and geochemical composition (Figs. S4 and S5, and Tables S6 and S7 online). On this basis, combined with the characteristics of the structural distribution (Table S8 online), the lunar crust was divided into three first-order tectonic units: Highland Tectonic Unit (HTU), Mare Tectonic Unit (MTU) and South Pole-Aitken Tectonic Unit (SPATU). The HTU can be subdivided into three second-order units: the Northern Plain Tectonic Unit (NPTU), Anorthosite Highland Tectonic Unit (AHTU) and Mare-Highland Transition Tectonic Unit (MHTTU) (Text S1 and Fig. S6 online).

After referring to the specification of the Earth's geological maps at each scale, we determined the minimum scale of mappable features on the 1:2,500,000-scale tectonic map (Table 1). Volcanic vents and mascons are represented by points, and others are represented by lines. Generally, this map only displays structures whose diameter or length is greater than 2.5 km (equivalent to 1 mm on the map). For some sparse or dense structures, these indicators can be appropriately regulated. The lunar surface hosts numerous and dense small impact craters. If all craters with diameters greater than 2.5 km were represented on the map, they would mask evolutionary information revealed by endogenic structures. Therefore, only craters with diameters greater than 25 km were displayed [13] (Fig. 1).

This mapping work was performed on the ESRI (Environmental Systems Research Institute) ArcMap platform in Mollweide projection. Eventually, 9 types of linear structures, including 18,976 elements (358 inferred deep faults, 1335 shallow faults, 11,046 wrinkle ridges, 474 rilles, 816 grabens, 2583 crater-floor fractures, 227 lobate scarps, 1882 impact fractures and 255 impact crater chains), and 5 types of circular structures, including 2501 elements (271 volcanic vents, 47 domes, 46 mascons, 3460 impact craters and 81 impact basins) were mapped. Additionally, special features, such as toponyms, mountains and landing sites, were represented

Table 1
The classification system of the lunar structure and the scales on the 1:2,500,000-scale tectonic map.

Structures			Origin and characteristics	Scales (km)
Endogenic structures	Linear structures	Wrinkle ridge	Wrinkle ridge results from faulting of volcanic rocks by contractional forces; it is characterized by linear to sinuous asymmetric topographic highs in mare basalt	≥2.5
		Rille	Rille is the remnant of shallow lava channels or collapsed subsurface lava tubes; it exhibits varying degrees of sinuosity while maintaining the parallel-striking, laterally continuous walls	≥2.5
		Graben	Graben results from localized tensional stress fields associated with basin formation and subsequent mascon-related lithospheric loading or from near-surface dike emplacement; it is characterized by long straight or arcuate, narrow trough	≥2.5
		Crater-floor fracture	Crater-floor fracture is formed by intrusion of bedrock/rock cap under crater floor; it is fracture at the bottom of crater	≥10
		Lobate scarp	Lobate scarp is interpreted as shallow, low-angle thrust fault scarps with hanging walls moved up relative to footwalls; it is characterized by relatively small-scale asymmetric landform that is often segmented with lobate margin	≥2.5
		Shallow fault	Shallow fault is caused by the deformation of the shallow crust by faulting; it exhibits linear extension on the lunar surface	≥10
		Inferred deep fault	Inferred deep fault is interpreted to be ancient vertical tabular intrusions or dikes, and it is formed by magmatism in combination with extension of the lithosphere; it exhibits probable linear gravity anomaly	≥10
	Circular structures	Dome	Dome is interpreted as volcanic shield or caused by laccolith intrusion; it is characterized by circular to somewhat irregular outline, generally convex shape	≥2.5
		Volcanic vent	Volcanic vent is the vent of magma and pyroclast that rises to the lunar surface; it is generally in the form of collapse	all
		Mascon	Mascon is formed by isostatic adjustment and cooling and contraction of a voluminous melt pool; it displays high positive free-air gravity anomaly and thin crust	all
Exogenic structures	Linear structures	Impact fracture	Impact fracture is formed by impact action, including pitted and radial fractures	≥2.5
		Impact crater chain	Impact crater chain is produced by impact action; it is characterized by beaded secondary craters	≥2.5
	Circular structures	Impact crater	Impact crater is formed by meteorite impact; it is typically less than 200 km in diameter	≥25
		Impact basin	Impact basin is formed by large meteorite impact; it is generally ≥ 200 km in diameter	≥200

on the map for easy searching. The completed global tectonic map of the Moon is shown in Fig. 2.

The tectonic map is not only an integration of lunar tectonic units and structures but also a microcosm of tectonic-thermal evolution. Most researchers have reached a consensus on the origins of HTU and SPATU, and the origin of MTU is the focus of controversy. The HTU is mainly composed of anorthosite, which was formed by the crystal fractionation of the magma ocean. The SPATU is consistent with the SPA basin, which was formed by meteorite impact. The Oceanus Procellarum is a major part of the MTU, and it is the key to resolving disputes on the origin of the MTU. Many hypotheses have been proposed to explain the origin of the Oceanus Procellarum, such as continuation of primitive asymmetry, asymmetric evolution of the magma ocean, impact origin, or byproduct of the SPA basin [14]. According to the different origins of Oceanus Procellarum, the lunar tectonic framework has a different evolutionary path. If the Oceanus Procellarum was originated from continuation of primitive asymmetry or asymmetric evolution of the magma ocean, the HTU and MTU formed at the same time. If it resulted from impact action, it would be an impact basin (Gargantuan basin) that is older than the SPA basin. The shock wave caused by giant impact may converge at the antipodal point and result in a fracture zone at the antipodal region. Therefore, the framework of the SPATU and MTU may be formed by the same impact events. In either case, the formation of the SPA basin is the event that established the framework of three first-order tectonic units. Since then, endogenic and exogenic structures have been preserved. Meteorite impacts ran through the whole evolutionary history of the Moon, and early impacts were larger and more frequent. Therefore, impact structures began to be preserved on the lunar surface after crust solidification. Shallow and inferred deep faults are the oldest endogenic linear structures, and they resulted from regional tectonic movement. Late Heavy Bombardment (LHB) and basalt flooding are the major geological events after the formation of the SPA basin. The ages of 80 impact basins expressed on the map suggested that the LHB may be a continuing process rather than concentrated at approximately 3.8 Ga. It is generally believed that mantle uplift associated with mascon is caused by large impacts, and later basalt flooding also contributed to the formation of mascon. Volcanism should be very active after the formation of the SPA basin, but there is less ancient (>4.0 Ga) volcanic rocks have been found on the Moon. Traces of ancient volcanism may have been eliminated by later geological events. Most volcanic structures (e.g., volcanic vent, dome and rille) observed on the Moon were formed during the basalt flooding. Some other structures, such as wrinkle ridges, grabens and crater-floor fractures, were also products of tectonothermal movement during basalt flooding, and they are closely associated with basalt. Because the lunar morphology and elemental distribution were reformed by the LHB and basalt flooding, the HTU can be further divided into three second-order tectonic units: MHTTU, NPTU and AHTU. The AHTU has the thickest lunar crust and hosts most ancient basins. The NPTU hosts only one non-mascon basin and few basalts, which suggests that the LHB and basalt flooding had the least effect on the NPTU. Impact basins in the MHTTU are generally younger than those in the AHTU, and most of them are filled by basalt. The endogenic and exogenic processes weakened rapidly after basalt flooding. The later weak volcanism and impact action had few effects on the framework of tectonic units. Structures formed in this period are relatively small, such as middle and small craters, as well as lobate scarps. A series of geological events of the Moon formed what we see today.

The first 1:2,500,000-scale global tectonic map of the Moon provides a state-of-the-art illustration of various structures and tectonic units of the Moon, which reveals the lunar tectonic-thermal evolution. The maps were compiled in both Chinese and English, which will be published in hard copied by the Geological Publishing House; meanwhile, the digital version will be released as well. For further investigation and best utilization of the maps, the geodatabases of the maps will be made publicly accessible. As the

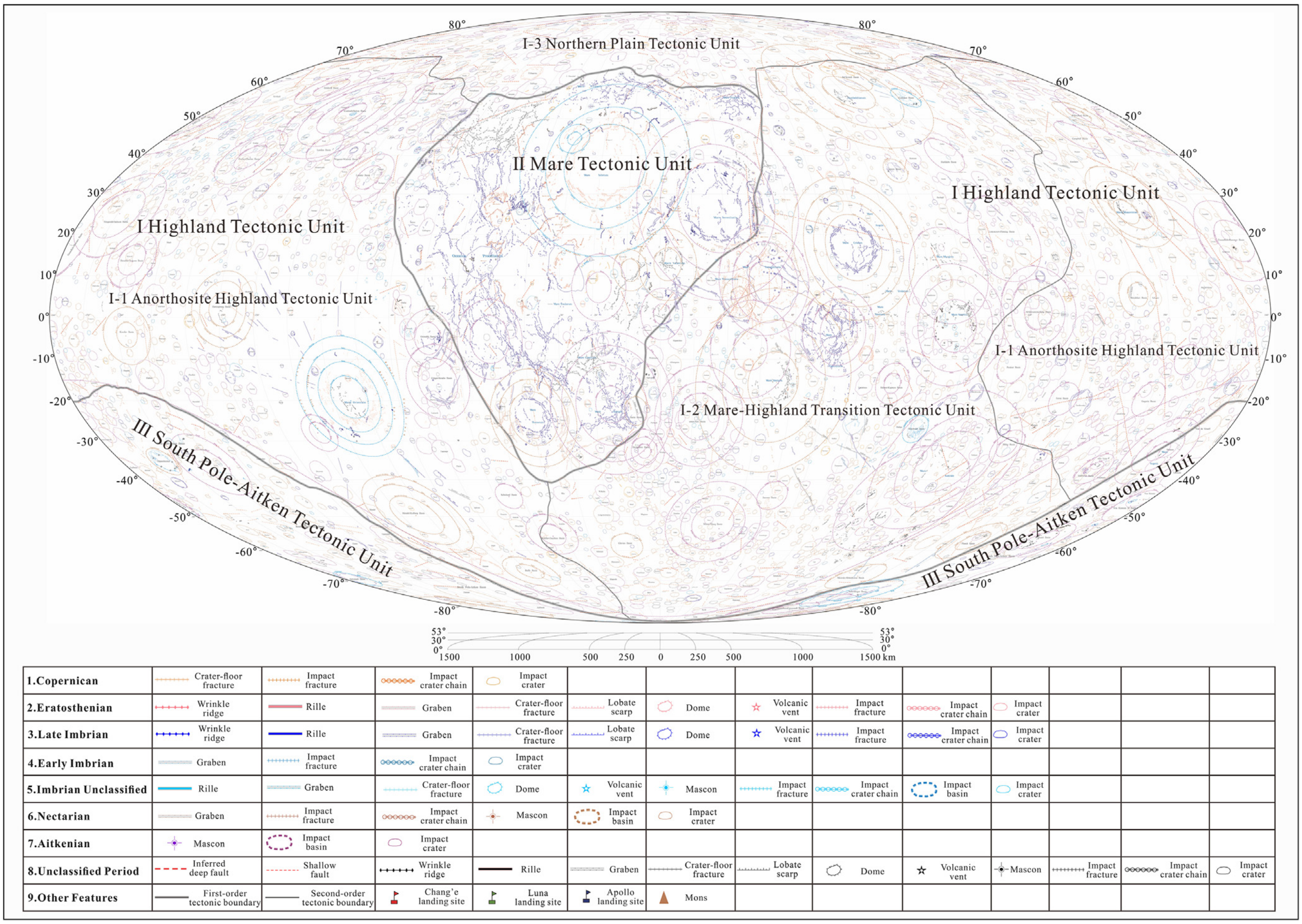

Fig. 2. Thumbnail of the 1:2,500,000-scale global tectonic map of the Moon. The map is presented with Mollweide projection.

unprecedented integrative product of lunar exploration structural achievement, the 1:2,500,000-scale lunar tectonic map will play important roles in lunar scientific research and exploration in the future. After a decade of efforts, the experience learned from this lunar mapping project lays the foundation for mapping other planets.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

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Author contributions

Shengbo Chen, Jianzhong Liu, and Ziyuan Ouyang conceptualized this work. Tianqi Lu and Kai Zhu wrote the manuscript and performed the analyses. Shengbo Chen, Tianqi Lu, and Kai Zhu established the classification system of lunar structure and divided the tectonic units. Tianqi Lu, Kai Zhu, Yongling Mu, and Anzhen Li mapped the tectonic map of the Moon. Zongcheng Ling and Jian Chen completed the global lithologic map. Xiaozhong Ding and Kunying Han designed the legend and map layout. Jianping Chen contributed to creating the geodatabase. Weiming Cheng contributed to map pre-publish editing. Danhong Lei revised the expression of the manuscript. All authors contributed to discussions on many aspects of the tectonic map of the Moon.

Appendix A. Supplementary materials

Supplementary materials to this short communication can be found online at https://doi.org/10.1016/j.scib.2022.08.017.

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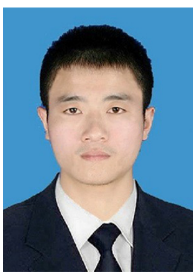

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