Check for updates

Geophysical Research Letters

RESEARCH LETTER
10.1029/2026GL121908

Large (~80 km) Shield Volcanoes on the Moon Possibly Fed by Shallow Magma Reservoirs

Le Qiao[1,2], James W. Head[3], Dengao Qiu[4], Wei Cao[5,6], Luyuan Xu[2,7], Yiran Wang[8], Ruixin Li[1], Jian Chen[1], Jianguo Yan[4], and Zongcheng Ling[1]

[1]Shandong Key Laboratory of Space Environment and Exploration Technology, School of Space Science and Technology, Institute of Space Sciences, Shandong University, Weihai, China, [2]State Key Laboratory of Lunar and Planetary Sciences, Macau University of Science and Technology, Macau, China, [3]Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI, USA, [4]State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan University, Wuhan, China, [5]Planetary Environmental and Astrobiological Research Laboratory, School of Atmospheric Sciences, Sun Yat-sen University, Zhuhai, China, [6]Computer Engineering Technical College (Artificial Intelligence College), Guangdong Polytechnic of Science and Technology, Zhuhai, China, [7]International Institute for Interdisciplinary and Frontiers, Beihang University, Beijing, China, [8]Department of Earth and Space Sciences, Southern University of Science and Technology, Shenzhen, China

Key Points:

- Two ~80 km diameter volcanic domes are identified on the Moon, and their characteristics are similar to large shield volcanoes on Earth
- One of the shields is associated with positive Bouguer gravity anomalies, interpreted as subsurface high-density mafic magmatic intrusion
- The characteristics of these large shields are consistent with shield-building eruptions fed by shallow magma reservoirs

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

L. Qiao,
leqiao@sdu.edu.cn

Citation:

Qiao, L., Head, J. W., Qiu, D., Cao, W., Xu, L., Wang, Y., et al. (2026). Large (~80 km) shield volcanoes on the Moon possibly fed by shallow magma reservoirs. *Geophysical Research Letters*, *53*, e2026GL121908. https://doi.org/10.1029/2026GL121908

Received 16 JAN 2026
Accepted 21 JUL 2026

Author Contributions:

Conceptualization: Le Qiao, James W. Head
Data curation: Le Qiao
Formal analysis: Le Qiao, Dengao Qiu, Wei Cao, Luyuan Xu
Funding acquisition: Le Qiao
Investigation: Le Qiao, James W. Head, Dengao Qiu, Wei Cao, Luyuan Xu, Yiran Wang, Ruixin Li, Jian Chen, Jianguo Yan, Zongcheng Ling
Methodology: Le Qiao, Dengao Qiu, Ruixin Li
Visualization: Le Qiao, Dengao Qiu, Yiran Wang

© 2026 The Author(s). Geophysical Research Letters published by Wiley Periodicals LLC on behalf of American Geophysical Union.
This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

Abstract Large shield volcanoes are among the most prominent volcanic structures on terrestrial bodies. The Moon, while volcanically very active in the past and hosting various volcanic features, seems to lack such large shield volcanoes. Here, we report the identification of two lunar volcanic domes (Prinz-Harbinger and Theophilus) with diameters around 80 km, significantly larger than previously confirmed lunar shield volcanoes (<30 km) and slightly larger than the largest shield volcanoes on Earth. The two domes have circular/elliptical outlines, gentle (<1°) and convex-upward shapes, and summit pits, consistent with the characteristics of large shield volcanoes. One shield exhibits obvious positive Bouguer gravity anomalies, interpreted to represent subsurface (7–32 km deep) magmatic intrusion. These geological and geophysical characteristics are consistent with shield-building eruptions fed by shallow magma reservoirs. Construction of shallow reservoirs is probably enhanced by special geological settings including regions of thin crust and large impact-induced zones of weakness.

Plain Language Summary Large shield volcanoes are the most iconic volcanic landforms on Earth and Mars, like the Hawaiian Mauna Loa (the Earth's largest active volcano) and the Martian Olympus Mons (the tallest volcano in the Solar System). The Earth's Moon, while hosts various volcanic landforms commonly seen on Earth (e.g., lava plains, small domes, and cones), seems to lack these large shield volcanoes due to the low-density lunar crust as a barrier and the mechanism of global contraction. Using high-resolution topography data, we identify two shield volcanoes on the lunar nearside, each having a diameter around 80 km. These are much larger than previously confirmed lunar shield volcanoes and even slightly larger than Earth's largest shield volcanoes. Gravity data suggest that one of the volcanoes was fed by shallow magma chambers, similar to their counterparts on Earth. The construction of shallow magma chambers is likely facilitated by thin crust and huge impact-induced fractures. The two large shield volcanoes represent a new endmember of volcanic landforms on the Moon, demonstrating that the lunar interior is more conducive to deep-to-shallow magma transport than previously thought.

1. Introduction

Volcanism is one of the fundamental geological processes on Earth and other terrestrial bodies, providing important clues to the compositional and thermal properties of the mantle. On Earth, Mars, and Venus, among the most recognizable volcanic landforms are large shield volcanoes, broad (typically >50 km in basal diameter) and generally circular edifices with gentle slopes (<5°), convex-upward shapes (Sigurdsson et al., 2015; Text S1 in Supporting Information S1). The most iconic examples of large shield volcanoes include the Hawaiian Mauna Loa (~65 km wide and ~2.8 km high; Grosse & Kervyn, 2018), the Earth's largest active volcano by volume, and the Martian Olympus Mons (840 × 640 km wide and ~22 km high; Plescia, 2004), the tallest volcano discovered in the Solar System. These large shields are generally interpreted to be constructed primarily by the accumulation of basaltic lava flows (e.g., Macdonald, 1972).

Writing – original draft: Le Qiao, James W. Head
Writing – review & editing: Le Qiao, James W. Head, Dengao Qiu, Wei Cao, Luyuan Xu, Yiran Wang, Ruixin Li, Jian Chen, Jianguo Yan, Zongcheng Ling

Volcanism is also a major geological process on the Moon and has produced various volcanic landforms, including extensive mare plains, and small volcanic domes and cones (e.g., Head & Wilson, 2017). Mare domes have often been interpreted as the lunar equivalent of small terrestrial shield volcanoes, and their basal diameters are generally <30 km (Head & Gifford, 1980; Wöhler & Lena, 2009; Wöhler et al., 2006). Some candidate large lunar shield volcanoes have been previously reported (e.g., Spudis et al., 2013), but their identities as such have been questioned because some diagnostic characteristics (e.g., basal outline and topographic profile) were not observed on these candidates (e.g., Head & Wilson, 2017; Text S2 in Supporting Information S1). The absence of large shield volcanoes on the Moon has been attributed to the unique lunar interior structure with a low-density crust. The feldspathic crust acts as a mechanical barrier for mantle-derived magma ascent. The magmas would only reach the surface if their deep reservoirs became overpressurized, a condition that do not favor the production of shallow near-surface magma reservoirs and large shield volcanoes (Head & Wilson, 1991). In addition, the global contraction of the Moon could also inhibit the formation of large shields, which puts the lithosphere into net horizontal compression, arresting the ascent of magmas (Byrne, 2020; Solomon & Head, 1980). Alternatively, Wieczorek et al. (2001) emphasized the dominant role of magma buoyancy on the lunar magma ascent and eruption, especially at regions of thin crust as the lower portion of lunar crust is denser. Therefore, the presence or absence of large shield volcanos provides critical constraints on the interior structure, thermal evolution, and magma transport mechanism of the Moon.

In this work, we report the identification and definition of two large (~80 km-diameter) shield volcanoes on the lunar nearside. We employ high-resolution orbital data to access their geological characteristics and subsurface structures (Text S3 in Supporting Information S1). These results are then compared with large shield volcanoes on other terrestrial worlds to explore their origin and implications for lunar magma ascent and eruption mechanisms.

2. Results

Using the SLDEM2015 (Kaguya and Lunar Reconnaissance Orbiter (LRO) blended digital elevation model) altimetry, and other new image and spectra data, we conducted a search of candidate large lunar shield volcanoes with similar characteristics of those on other planets (Earth: Grosse & Kervyn, 2018; Mars: Plescia, 2004; Venus: Hahn & Byrne, 2023; Ivanov & Head, 2025), including large basal diameters (>50 km), (sub-)circular or elliptical outlines, convex-upward shapes, and gentle slopes (<5°). We identified two large lunar shields (Figure 1 and Table S1 in Supporting Information S1): one in the eastern Oceanus Procellarum (informally termed the Prinz-Harbinger shield (Jawin et al., 2017)), and another in the southern Mare Tranquillitatis (termed the Theophilus shield). The Prinz-Harbinger shield is centered at 26.79°N, 42.50°W, and has a circular base outline measuring 74 × 72 km in size. It stands 590 m above the adjacent mare and has an estimated volume of ~800 km^3. The Theophilus shield (centered at 6.80°S, 24.58°E) is more elliptical and measures 101 × 75 km in size, 541 m in height, and 1,141 km^3 in volume. The age of the Prinz-Harbinger shield was estimated to be around 3.4 Ga using the crater population technique, close to that of the surrounding mare (Figure S1 and Text S4 in Supporting Information S1). While abundant secondary craters on the Theophilus shield made it challenging to estimate its age. Possible large lunar shields are also observed at other locations, including the ~160 km volcanic rise in Mare Fecunditatis (Qiao et al., 2020) and the ~70 km Gardner "megadome" (Huang et al., 2020; Figure S2 in Supporting Information S1). However, we found that parts of the typical characteristics of large shield volcanoes were not clearly observed in the Fecunditatis and Gardner structures, decreasing the shield volcano identification reliability.

Meter-scale LRO images revealed various volcanic features on the Prinz-Harbinger shield, including one small dome, one cone, grabens, pit craters, pit chains, and sinuous rilles (Figure S3a and Text S5 in Supporting Information S1). The mare dome is ~16 km wide and 270 m high, and the cone is much smaller (~4 km). The linear depression features (grabens and pit chains) are 3–16 km long and 20–280 m deep, most of which lie radial to the shield center. The pit craters are generally rimless and much more elliptical than small lunar impact craters. They are characterized by a median diameter of ~2.2 km and a depth of ~160 m. A specific pit crater, 5.4 × 2.9 km in size and 614 m deep, occurs at the shield center. This central pit is even 24 m topographically lower than the mare surrounding the shield. The sinuous rilles measure 5–92 km long, 0.3–3.1 km wide, and 7–154 m deep. They generally originate in depressions in the shield central portion and extend to the shield edges.

In contrast, the Theophilus shield is populated with much fewer volcanic features (Figure S3b in Supporting Information S1), including 5 grabens (~8–26 km long and ~90–340 m deep), 2 pit chains (~6 km long and

19448007, 2026, 15, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2026GL121908 by TEDA POLYTECHNIC, Wiley Online Library on [04/08/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

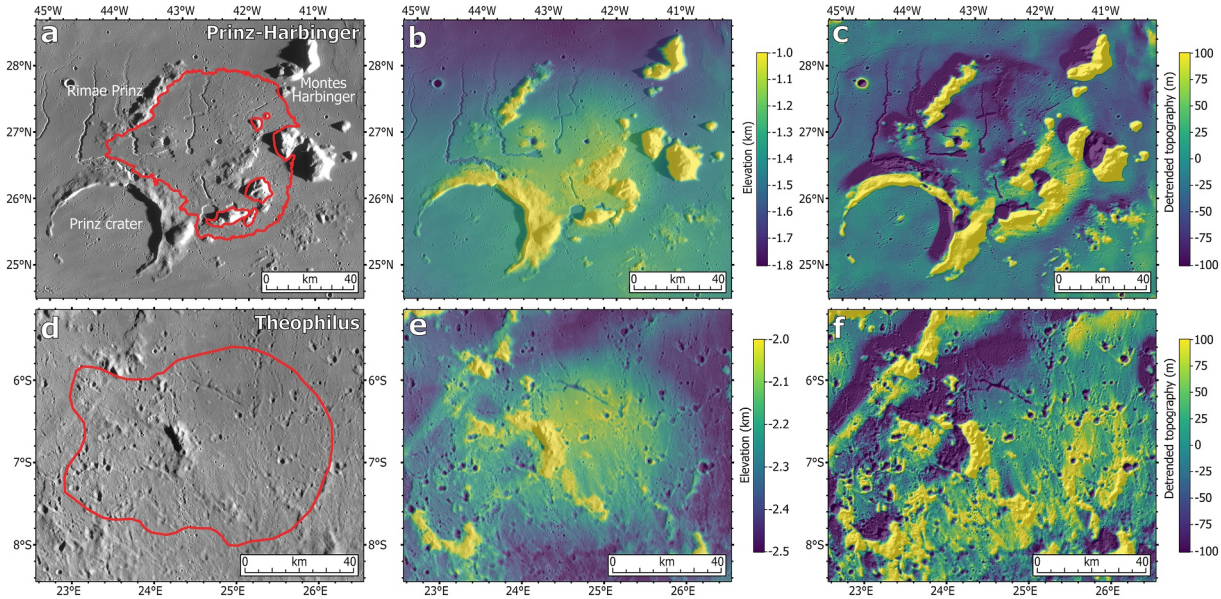


Figure 1. (a), (d) LRO WAC (Wide-Angle Camera) low-sun mosaic, (b), (e) SLDEM2015 topography, and (c), (f) detrended SLDEM2015 topography of (a)–(c) Prinz-Harbinger and (d)–(f) Theophilus shields. The red polygons mark the estimated shield outlines from the surrounding maria. All the maps in this paper are projected into an equirectangular projection with a central meridian of 0°, and north is up.

~155–290 m deep), and 1 pit crater (~4 km diameter and ~330 m deep). Similar to Prinz-Harbinger, a pit crater also occurs at the shield central summit.

We also assess the subsurface (up to ~40 km deep) density structure of the Prinz-Harbinger shield using high-resolution GRAIL (Gravity Recovery and Interior Laboratory) Bouguer gravity data (Figure 2a). The 3D density model (Figure 2b and Figure S4 in Supporting Information S1) reveals a high-density anomaly beneath the Prinz-Harbinger shield. A sharp increase in density (~84 kg/m^3 contrast) is observed at ~4 km depth. The density then increases gradually with increasing depth, reaching a maximum value at ~17 km depth, and then decreases with depth. At 7–32 km depths, the density anomaly values are >150 kg/m^3, consistent with a mafic magmatic intrusion (Kiefer et al., 2012). These data indicate the presence of an intrusive mafic body, broadly ellipsoid-shaped, and measuring 23 × 20 × 26 km (length × width × height) in dimension and 9,693 km^3 in volume. The interpreted mafic intrusion lies beneath the ~18 km dome in the northwest portion of the shield (Figure 2a). A much smaller mafic intrusion, 15 × 7 × 8 km in dimension, is observed at 11–19 km depths beneath the north shield edge (Figure S4b in Supporting Information S1). The Theophilus shield, however, is underlain by a much

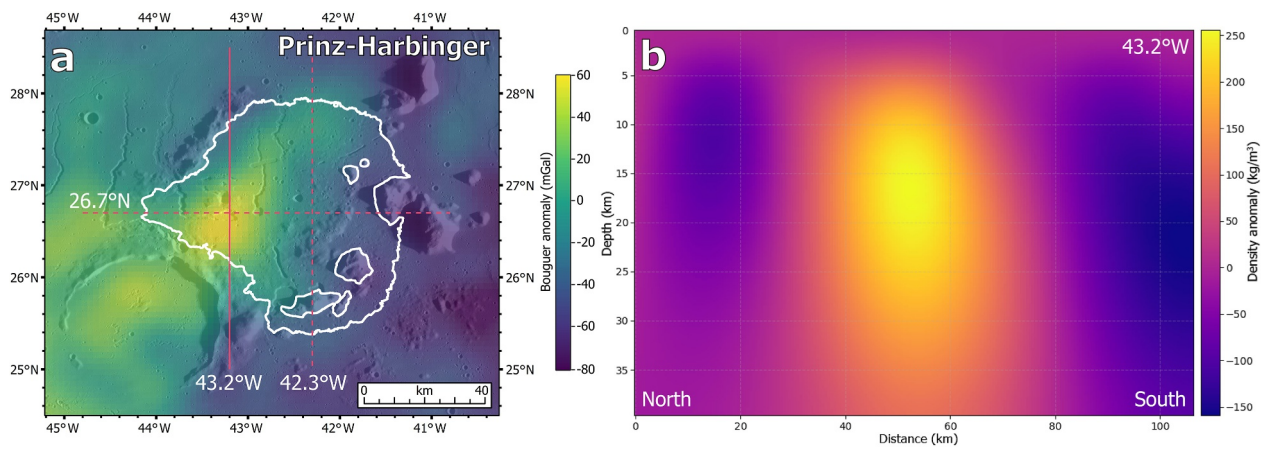


Figure 2. (a) GRAIL Bouguer gravity anomaly and (b) north-south cross section of the 3D density anomaly model along 43.2°W longitude across the Prinz-Harbinger shield volcano. The surface location of the density profile is shown as the solid line in panel (a).

19448007, 2026, 15, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2026GL121908 by TEDA POLYTECHNIC, Wiley Online Library on [04/08/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

19448007, 2026, 15, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2026GL121908 by TEDA POLYTECHNIC, Wiley Online Library on [04/08/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

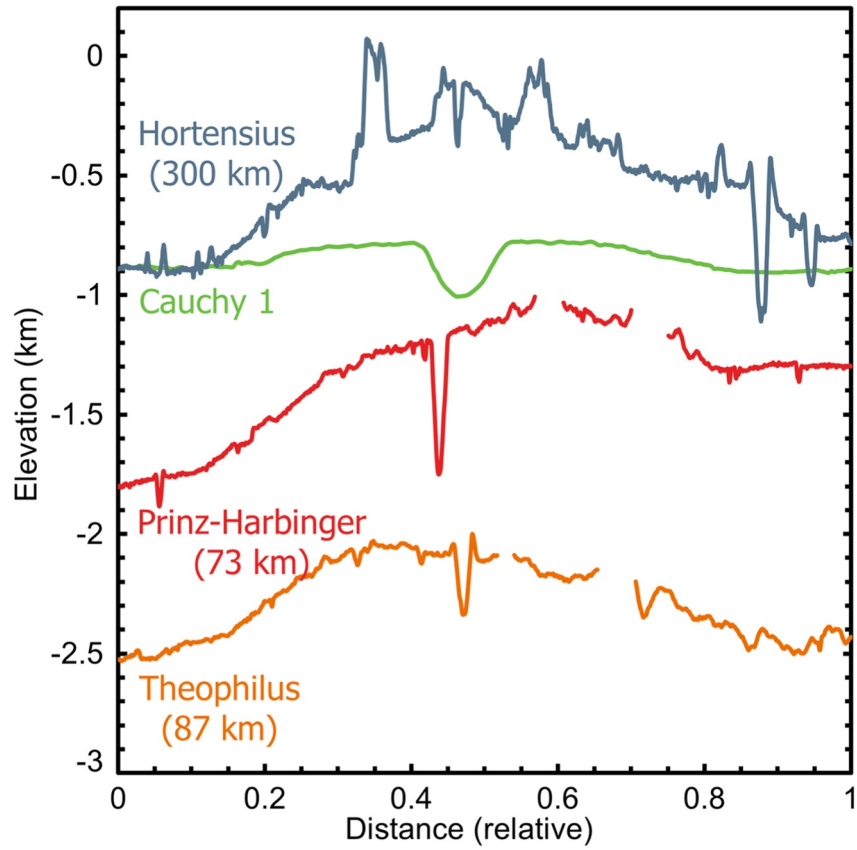


Figure 3. SLDEM2015 topographic profiles across the Prinz-Harbinger and Theophilus shields identified in this work, and comparison with a representative small mare dome, Cauchy 1, and the Hortensius volcanic complex. The locations of the topographic profiles are shown in the Figure S5 in Supporting Information S1. Note that the Prinz-Harbinger and Theophilus profiles were cut off at highland massifs near the shields.

larger (342 km diameter) mass concentration (mascon) associated with a topographically obscured impact basin (Neumann et al., 2015), which may have obstructed the gravity signature of possible subsurface magmatic materials.

3. Discussion

Large shield volcanoes are critical for assessing the interior structure and magma transport mechanism on the parent planets, but their presence on the Moon has been debated (Head & Wilson, 2017; Spudis et al., 2013). Here, we address this issue through comparative investigation of similar volcanic structures elsewhere on the Moon and other planets. We also explore a formation model for these large shields and assess constraints for their magma ascent and eruption mechanism.

3.1. Can They Be Categorized as Shield Volcanoes?

While shield volcanoes are commonly recognized as a specific type of volcano, its definition remains vague (Text S1 in Supporting Information S1). Here, we refer to the literal meaning, also the key criteria and the original definition (Suess, 1904; Whitford-Stark, 1975), of the "shield volcano" term: a volcano (eruptive) shaped like a flat-lying warrior's shield, or scientifically, a convex-upward shape (becoming flatter near the summit) with gentle slopes.

Possible large lunar shield volcanoes have been reported previously, but their identities as such were debated. In particular, Spudis et al. (2013) surveyed eight previously known volcanic complexes, and defined them as large lunar shield volcanoes. To re-assess whether these structures are shield volcanoes, we present high-resolution topographic maps and profiles across them (Figure 3; Figures S5 and S6, and Text S2 in Supporting

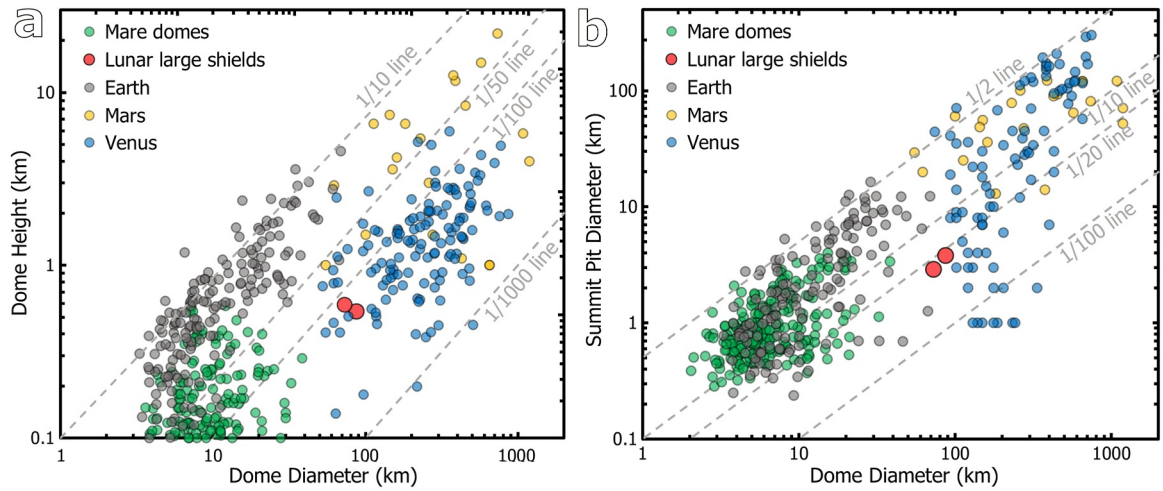


Figure 4. Plots of (a) volcano height and (b) summit pit crater diameter against the shield basal diameter for small mare domes (Lena et al., 2007, 2008; Qiao et al., 2021; Wöhler et al., 2006; Wöhler & Lena, 2009), and large shield volcanoes on the Moon (this work), Earth (Grosse & Kervyn, 2018), Mars (Plescia, 2004), and Venus (Hahn & Byrne, 2023; Ivanov & Head, 2025).

Information S1). We find that, among the eight complexes studied by Spudis et al. (2013), only Hortensius has an approximatively convex-upward profile (Figure 3), but its spatial outline from the adjacent terrains cannot be clearly defined and the map-view outline is irregular. The central volcanic pit (centered at 12.2°N, 26.7°W) identified by Spudis et al. (2013) is characterized by an apparent raised rim and exterior ejecta blanket, indicating that it is more likely an impact crater.

By comparison, the two shield volcanoes identified in this work are both characterized by a generally broad (average slope <0.5°) and convex-upward topographic profile, with an obvious central pit (Figure 3). Note that the Prinz-Harbinger shield is located on a regionally sloping surface. If the regional topographical background is detrended (Figure 1c), the convex-upward nature of the topographic profile is more apparent. The profiles of the two shields are similar to those of many smaller lunar domes, for example, the 9-km-diameter Cauchy 1 (Figure 3; Figure S5c in Supporting Information S1). These small mare domes were generally interpreted as small shield volcanoes built up through multiple low-effusion rate, cooling-limited flows (e.g., Head & Wilson, 2017).

3.2. How Large Is "Large"?

As mentioned above, small shield volcanoes (mare domes) are commonly seen on the Moon, but the presence of large lunar shield volcanoes is debated. Topographical profiles show that the volcanic structures are indeed shield-shaped (Figure 3), but can they be categorized as large shield volcanoes?

To address this issue, we compare the basal diameter and height of the two specific lunar shields with documented small mare domes (n = 380), and shield volcanoes (Figure 4 and Figure S7 in Supporting Information S1) on Earth (n = 182), Mars (n = 21), and Venus (n = 132). The diameter-height plot shows that the two lunar shields are about one order of magnitude larger than the average diameter (~8 km) of small mare domes. The two lunar shields are larger in diameter than the largest terrestrial shield volcanoes (e.g., Mauna Loa (65 km subaerial diameter)). They are also comparable with the low end of large shield volcanoes on Mars and Venus, though still one order of magnitude smaller than the largest shield volcanoes on the two planets, for example, Martian Alba Patera (1,080 km) and Venusian Atanua Mons (863 km). Given that the Moon is much smaller (~1/4 of the Earth radius) and lunar volcanism flux is much lower (Head & Wilson, 1991), we conclude that the two specific lunar volcanoes are indeed massive in terms of both lunar and terrestrial standards, and should be categorized as large shield volcanoes on the Moon.

19448007, 2026, 15, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2026GL121908 by TEDA POLYTECHNIC, Wiley Online Library on [04/08/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

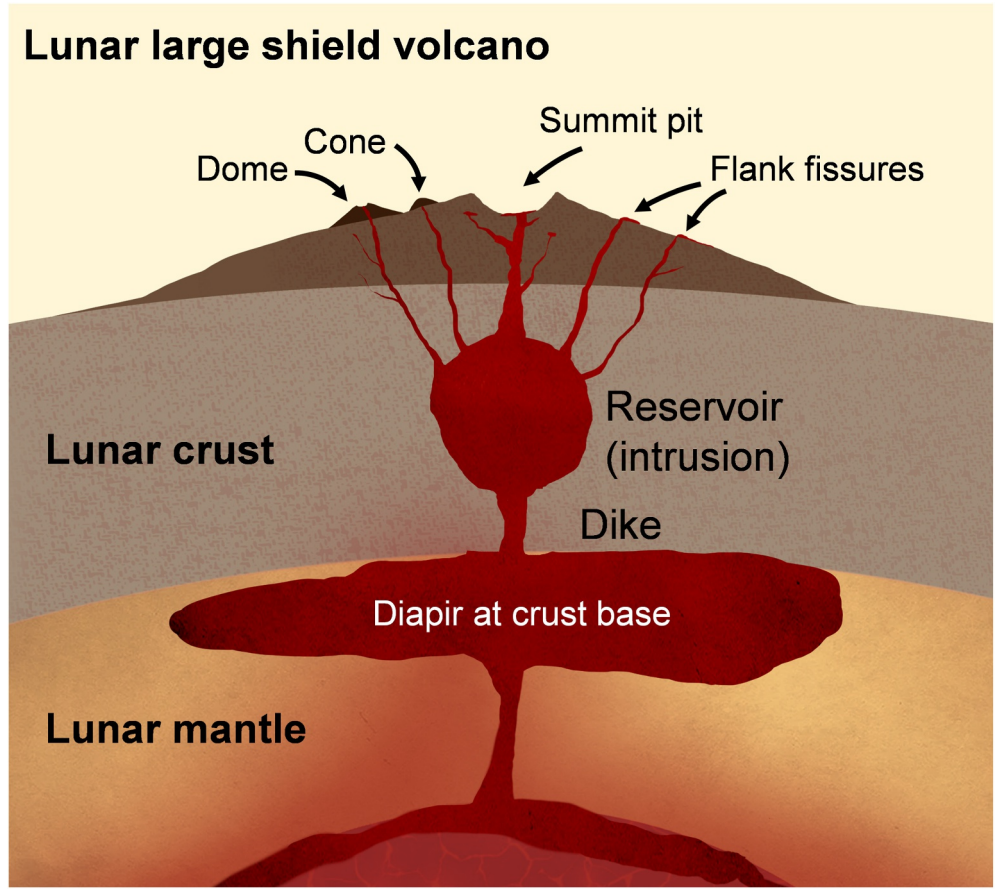


Figure 5. Formation mechanism diagram of the Prinz-Harbinger large shield volcano. During the late stage of low-flux eruptions, the shallow (7–32 km deep) magma reservoir (23 × 20 × 26 km dimension (length × width × height) and ~10^5 km^3 volume) intruded a large number of vertical dikes which formed the summit pit and flank fissures to build up the large shield volcano (74 × 72 × 0.6 km dimension and ~800 km^3 volume). Note that the schematic diagram is not to scale, the surface shield should be much lower, and the diapir at the crust base should be much larger.

3.3. Formation Mechanism of Large Lunar Shield Volcanoes, and Insight Into Magma Transport Mechanism on the Moon

The range of characteristics observed at the two large lunar features interpreted to be shield volcanoes, especially the Prinz-Harbinger, provide an instructive framework for exploring their formation mechanisms (Figure 5). The well-defined circular outline and summit pit crater are common at some terrestrial shield volcanoes (e.g., Hawai'i), and are consistent with central-vent eruptions that supply cooling-limited lava flows to the immediate surroundings and contribute to the shield construction. The production of cooling-limited lava flows is typically dominant in the waning stages of eruptive phases when lava effusion rate is very low (Wilson & Head, 2018).

Alternatively, much smaller lunar domes have been interpreted to be caused by shallow, sill-like formation and uplift (Michaut, 2011; Wöhler & Lena, 2009). In this intrusive origin hypothesis, the central and other pits are interpreted to be the result of magmatic activity after the rise of the domes. However, extensive modeling of lunar magma generation, ascent and eruption (Wilson & Head, 2017) and a comprehensive review of the resulting array of landforms (Head & Wilson, 2017) provide evidence that the vast majority of landforms are of extrusive origin. For example, on the Moon, magma is predicted to arrive at the surface from great depth at initial peak eruption rates, followed by a decrease of the eruption flux (Wilson & Head, 2018). Per this model, the initial high-flux eruptions would have produced relatively extensive lava flows, forming the surrounding mare plains. Some of the long-duration flows would have thermally eroded the substrate to produce sinuous rilles on margins of the Prinz-Harbinger shield (Hurwitz et al., 2012). During subsequent low-flux instances of eruptions, lava flows

19448007, 2026, 15, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2026GL121908 by TEDA POLYTECHNIC, Wiley Online Library on [04/08/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

19448007, 2026, 15, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2026GL121908 by TEDA POLYTECHNIC, Wiley Online Library on [04/08/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

overflowed from the summit vent, which underwent cooling when advancing on the surface, and accumulated on the surrounding terrains, forming the circular shield volcanoes. In addition to the summit pit, dozens of fissures (pit craters/chains and linear rilles) are observed on the Prinz-Harbinger shield flanks. Flank fissure zones are common at large terrestrial shield volcanoes (e.g., Mauna Loa), from which additional flows emanate, and parasitic cone and dome are built, and on this basis, the landforms on the Prinz-Harbinger shield are interpreted to have similar origins as their counterparts on Earth. The one environment in which shallow intrusion and uplift have been convincingly documented to occur on the Moon is in the case of floor-fractured craters (FFCs), where rising magma encounters thick sub-impact crater low density breccia zones, stalling and spreading laterally to uplift and fracture the crater floor (e.g., Jozwiak et al., 2012), creating a sill or laccolith. However, neither the extensive tectonic features in FFCs, nor any evidence of occurrence on a crater floor, are observed at the two large lunar shields, further strengthening an extrusive, constructional origin.

The summit pits of the two large lunar shields (~3–4 km diameter) are smaller than those of large terrestrial shield volcanoes of comparable sizes, for instance, the 65 km Mauna Loa shield has a 6.5 km diameter summit pit. The diameter ratio of the summit pit to the dome (d/D) for the two lunar shields (~0.04) is at the low end of the d/D value range of terrestrial shields (median value 0.18; Figure 4b). The smaller summit pit dimensions for the two large lunar shields and hundreds of small mare domes (Qiao et al., 2021) were attributed to the relatively lower volatile content of lunar magma (Saal et al., 2008). In terrestrial eruptive vents, the subsidence and collapse of the vent floor is often associated with the magma drainage due to degassing (e.g., Tilling et al., 1987). The relatively low volatile contents of lunar magma would minimize such vent floor subsidence and collapse, resulting in smaller summit pits.

The occurrence of large lunar shields provides important insight into magma transport mechanisms on the Moon (Figure 5). The broad (slope <0.5°) convex-upward rise seems to require a broad, flatter magma reservoir at some shallow depth that feeds effusive shield-building eruptions (Wilson & Head, 2023). Such a hypothesized shallow magma reservoir is supported by the subsurface (7–32 km deep) high-density mafic intrusion interpreted from gravity data. We estimated the mafic intrusion to be ~10,000 km^3 in volume, over one order of magnitude larger than the surface shield, sufficient to feed the shield-building eruptions. The ratio between the mafic intrusion to the surface Prinz-Harbinger shield is about 12:1, toward the lower limit of previous estimates (e.g., Head & Wilson, 1992). The presence of a subsurface magma reservoir is further supported by the deep summit pit crater extending below the level of the surrounding mare surface which indicate magma source dikes at depth. We hypothesize that the presence of such a shallow magma reservoir is likely to be the determining factor for the prominent size of the large lunar shields, which feed a large number of lava flows emanating from central vent or flank rift zones to build up the large shields (Figure 5; Head & Wilson, 2020).

The two large lunar shields represent a new endmember of volcanic landforms on the Moon, which involve the intrusion of shallow magma reservoirs. The presence of shallow magma reservoirs on the Moon has been long debated (e.g., Head & Wilson, 1991; Wieczorek et al., 2001), as the great depth of the mare basalt source regions produce individual intrusive episodes that are too infrequent to build up shallow magma reservoirs (Head et al., 2023). The special occurrence of the two large lunar shields is interpreted to be related to their unique geological settings. Both shields are located at sites of relatively thin nearside crust (27 km for Prinz-Harbinger and 14 km for Theophilus; Wieczorek et al., 2013), favorable for deep-sourced magma ascent and eruption on the surface (The low-density crust acts as a density barrier for mantle-derived magma ascent and thinner crust favors magma breaching the surface (Head & Wilson, 2017)). The two shields also sit on the margins of huge impact basins, Imbrium for Prinz-Harbinger and Nectaris for Theophilus (McGovern, 2025). The highland massifs immediately east of the Prinz-Harbinger shield have been interpreted to be remnants of the Imbrium main ring (Strain & El-Baz, 1977). Extensive and deep zones of weakness produced during the catastrophic basin-formation impacts could result in local low-density regions favorable to the shallow crustal stalling and intrusion of magma, enhancing the probability of vertical and lateral magma migration, the buildup of the shallow magma reservoirs, and magma ascent through these fracture networks to the surface. However, the interpreted subsurface magma reservoir at the Prinz-Harbinger shield is not directly beneath the summit pit crater, but below a small (~18 km) dome and the source pit of a long (~90 km) sinuous rille in the northwest portion of the shield. This likely indicates the presence of a complicated magma dike and conduit network beneath the large shield. Alternatively, the Prinz-Harbinger shield may have been fed by lava flows emanating mainly from the pits associated with the small dome and sinuous rilles, rather than the central pit. These unresolved issues, and the specific formation

mechanism of lunar shallow magma reservoirs and shield volcanoes, should be investigated in detail by future landing missions.

4. Conclusions

On the basis of the definition of some fundamental characteristics of shield volcanoes, including circular/elliptical outlines and convex-upward shapes, we conducted a search for large shields across the global Moon and successfully identified two on the lunar nearside: Prinz-Harbinger and Theophilus. Each lunar shield has a diameter around 80 km, comparable with the largest shield volcanoes on the Earth. Gravity analysis reveals a high-density, ellipsoid-shaped anomaly beneath the Prinz-Harbinger shield, interpreted as shallow subsurface magmatic intrusion. These observations are consistent with shield-building eruptions fed by shallow magma reservoirs. The construction of shallow magma reservoirs is probably enhanced by special geological settings, including thin crust and large impact-induced zones of weakness.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

The SLDEM2015 topography, LROC WAC/NAC image, Clementine UVVIS spectrometer, Lunar Prospector gamma ray spectrometer, and GRAIL gravity field data are available at the NASA Planetary Data System Geosciences Node (https://pds-geosciences.wustl.edu/), and Kaguya TC image are archived at SELENE Data Archive https://darts.isas.jaxa.jp/app/pdap/selene/index.html.en).

Acknowledgments
Erica R. Jawin and Lionel Wilson are acknowledged for their works on the Prinz-Harbinger shield volcano. This work is supported by the National Natural Science Foundation of China (42441817, 42578002, 42241107, 42302263, 12303064), State Key Laboratory of Lunar and Planetary Sciences of M.U.S.T (002/2024/SKL), Science and Technology Development Fund of Macau (0012/2023/RIA1), and the Fundamental Research Funds for the Central Universities (501XYGG2026158010).

References

Byrne, P. K. (2020). A comparison of inner solar system volcanism. *Nature Astronomy*, *4*(4), 321–327. https://doi.org/10.1038/s41550-019-0944-3

Grosse, P., & Kervyn, M. (2018). Morphometry of terrestrial shield volcanoes. *Geomorphology*, *304*, 1–14. https://doi.org/10.1016/j.geomorph.2017.12.017

Hahn, R. M., & Byrne, P. K. (2023). A morphological and spatial analysis of volcanoes on Venus. *Journal of Geophysical Research: Planets*, *128*(4), e2023JE007753. https://doi.org/10.1029/2023JE007753

Head, J., & Gifford, A. (1980). Lunar mare domes: Classification and modes of origin. *The Moon and the Planets*, *22*(2), 235–258. https://doi.org/10.1007/BF00898434

Head, J. W., & Wilson, L. (1991). Absence of large shield volcanoes and calderas on the moon: Consequence of magma transport phenomena? *Geophysical Research Letters*, *18*(11), 2121–2124. https://doi.org/10.1029/91GL02536

Head, J. W., & Wilson, L. (1992). Lunar mare volcanism: Stratigraphy, eruption conditions, and the evolution of secondary crusts. *Geochimica et Cosmochimica Acta*, *56*(6), 2155–2175. https://doi.org/10.1016/0016-7037(92)90183-J

Head, J. W., & Wilson, L. (2017). Generation, ascent and eruption of magma on the Moon: New insights into source depths, magma supply, intrusions and effusive/explosive eruptions (part 2: Predicted emplacement processes and observations). *Icarus*, *283*, 176–223. https://doi.org/10.1016/j.icarus.2016.05.031

Head, J. W., & Wilson, L. (2020). Magmatic intrusion-related processes in the upper lunar crust: The role of country rock porosity/permeability in magmatic percolation and thermal annealing, and implications for gravity signatures. *Planetary and Space Science*, *180*, 104765. https://doi.org/10.1016/j.pss.2019.104765

Head, J. W., Wilson, L., Hiesinger, H., van der Bogert, C., Chen, Y., Dickson, J. L., et al. (2023). Lunar mare basaltic volcanism: Volcanic features and emplacement processes. *Reviews in Mineralogy and Geochemistry*, *89*(1), 453–507. https://doi.org/10.2138/rmg.2023.89.11

Huang, Q., Zhao, J., Wang, X., Wang, T., Zhang, F., Qiao, L., et al. (2020). A large long-lived central-vent volcano in the gardner region: Implications for the volcanic history of the nearside of the Moon. *Earth and Planetary Science Letters*, *542*, 116301. https://doi.org/10.1016/j.epsl.2020.116301

Hurwitz, D. M., Head, J. W., Wilson, L., & Hiesinger, H. (2012). Origin of lunar sinuous rilles: Modeling effects of gravity, surface slope, and lava composition on erosion rates during the formation of Rima Prinz. *Journal of Geophysical Research*, *117*(E12). https://doi.org/10.1029/2011JE004000

Ivanov, M. A., & Head, J. W. (2025). Large volcanoes on Venus: Morphology, morphometry, and stratigraphy. *Icarus*, *429*, 116404. https://doi.org/10.1016/j.icarus.2024.116404

Jawin, E. R., Head, J. W., Kreslavsky, M. A., & Wilson, L. (2017). Stealth dome in central Oceanus procellarum: Using detrended topography data to reveal the hidden past of the Prinz-Harbinger region. In *48th lunar and planetary science conference*. Lunar and Planetary Institute. abstract #1184.

Jozwiak, L. M., Head, J. W., Zuber, M. T., Smith, D. E., & Neumann, G. A. (2012). Lunar floor-fractured craters: Classification, distribution, origin and implications for magmatism and shallow crustal structure. *Journal of Geophysical Research*, *117*(E11), E11005. https://doi.org/10.1029/2012JE004134

Kiefer, W. S., Macke, R. J., Britt, D. T., Irving, A. J., & Consolmagno, G. J. (2012). The density and porosity of lunar rocks. *Geophysical Research Letters*, *39*(7). https://doi.org/10.1029/2012GL051319

19448007, 2026, 15, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2026GL121908 by TEDA POLYTECHNIC, Wiley Online Library on [04/08/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Lena, R., Wöhler, C., Bregante, M. T., Lazzarotti, P., & Lammel, S. (2008). Lunar domes in Mare Undarum: Spectral and morphometric properties, eruption conditions, and mode of emplacement. *Planetary and Space Science*, *56*(3), 553–569. https://doi.org/10.1016/j.pss.2007.11.010

Lena, R., Wöhler, C., Phillips, J., Wirths, M., & Bregante, M. T. (2007). Lunar domes in the Doppelmayer region: Spectrophotometry, morphometry, rheology, and eruption conditions. *Planetary and Space Science*, *55*(10), 1201–1217. https://doi.org/10.1016/j.pss.2007.01.007

Macdonald, G. A. (1972). *Volcanoes*. Prentice-Hall.

McGovern, P. J. (2025). Tectonics caused by surface loads. In C. Klimczak, G. C. Collins, & P. K. Byrne (Eds.), *Planetary tectonism across the solar system* (pp. 133–200). Elsevier.

Michaut, C. (2011). Dynamics of magmatic intrusions in the upper crust: Theory and applications to laccoliths on Earth and the Moon. *Journal of Geophysical Research*, *116*(B5), B05205. https://doi.org/10.1029/2010JB008108

Neumann, G. A., Zuber, M. T., Wieczorek, M. A., Head, J. W., Baker, D. M. H., Solomon, S. C., et al. (2015). Lunar impact basins revealed by gravity recovery and interior laboratory measurements. *Science Advances*, *1*(9), e1500852. https://doi.org/10.1126/sciadv.1500852

Plescia, J. B. (2004). Morphometric properties of Martian volcanoes. *Journal of Geophysical Research*, *109*(E3). https://doi.org/10.1029/2002JE002031

Qiao, L., Head, J. W., Wilson, L., Chen, J., & Ling, Z. (2021). Mare domes in mare Tranquillitatis: Identification, characterization, and implications for their origin. *Journal of Geophysical Research: Planets*, *126*(9), e2021JE006888. https://doi.org/10.1029/2021JE006888

Qiao, L., Head, J. W., Wilson, L., & Ling, Z. (2020). Mare domes in mare Tranquillitatis: Identification, distribution, characteristics, and implications for their origin and the oldest lunar volcanism. In *51st lunar and planetary science conference*. Lunar and Planetary Institute. abstract #1798.

Saal, A. E., Hauri, E. H., Cascio, M. L., Van Orman, J. A., Rutherford, M. C., & Cooper, R. F. (2008). Volatile content of lunar volcanic glasses and the presence of water in the Moon's interior. *Nature*, *454*(7201), 192–195. https://doi.org/10.1038/nature07047

Sigurdsson, H., Houghton, B., McNutt, S., Rymer, H., & Stix, J. (2015). *The encyclopedia of volcanoes*. Academic Press.

Solomon, S. C., & Head, J. W. (1980). Lunar mascon basins: Lava filling, tectonics, and evolution of the lithosphere. *Reviews of Geophysics*, *18*(1), 107–141. https://doi.org/10.1029/RG018i001p00107

Spudis, P. D., McGovern, P. J., & Kiefer, W. S. (2013). Large shield volcanoes on the Moon. *Journal of Geophysical Research: Planets*, *118*(5), 1063–1081. https://doi.org/10.1002/jgre.20059

Strain, P. L., & El-Baz, F. (1977). Topography of sinuous rilles in the Harbinger Mountains region of the moon. *The Moon*, *16*(2), 221–229. https://doi.org/10.1007/BF00596727

Suess, E. (1904). *The face of the Earth*. Clarendon Press.

Tilling, R. I., Christiansen, R. I., Duffield, W. A., Endo, E. T., Holcomb, R. T., Koyanagi, R. Y., et al. (1987). The 1972 – 1974 Mauna Ulu eruption, Kilauea volcano: An example of quasi - steady - state magma transfer. In R. W. Decker, T. L. Wright, & P. H. Stauffer (Eds.), *Volcanism in Hawaii, U.S. geological survey professional paper 1350* (pp. 405–469). United States Government Printing Office.

Whitford-Stark, J. L. (1975). Shield volcanoes. In G. Fielder & L. Wilson (Eds.), *Volcanoes of Earth Moon and Mars* (pp. 66–74). Elek Science.

Wieczorek, M. A., Neumann, G. A., Nimmo, F., Kiefer, W. S., Taylor, G. J., Melosh, H. J., et al. (2013). The crust of the Moon as seen by GRAIL. *Science*, *339*(6120), 671–675. https://doi.org/10.1126/science.1231530

Wieczorek, M. A., Zuber, M. T., & Phillips, R. J. (2001). The role of magma buoyancy on the eruption of lunar basalts. *Earth and Planetary Science Letters*, *185*(1), 71–83. https://doi.org/10.1016/S0012-821X(00)00355-1

Wilson, L., & Head, J. W. (2017). Generation, ascent and eruption of magma on the Moon: New insights into source depths, magma supply, intrusions and effusive/explosive eruptions (part 1: Theory). *Icarus*, *283*, 146–175. https://doi.org/10.1016/j.icarus.2015.12.039

Wilson, L., & Head, J. W. (2018). Controls on lunar basaltic volcanic eruption structure and morphology: Gas release patterns in sequential eruption phases. *Geophysical Research Letters*, *45*(12), 5852–5859. https://doi.org/10.1029/2018GL078327

Wilson, L., & Head, J. W. (2023). Formation of magma reservoirs supplying volcanic complexes on the Moon. In *54th lunar and planetary science conference*. Lunar and Planetary Institute. abstract #1453.

Wöhler, C., & Lena, R. (2009). Lunar intrusive domes: Morphometric analysis and laccolith modelling. *Icarus*, *204*(2), 381–398. https://doi.org/10.1016/j.icarus.2009.07.031

Wöhler, C., Lena, R., Lazzarotti, P., Phillips, J., Wirths, M., & Pujic, Z. (2006). A combined spectrophotometric and morphometric study of the lunar mare dome fields near Cauchy, Arago, Hortensius, and Milichius. *Icarus*, *183*(2), 237–264. https://doi.org/10.1016/j.icarus.2006.03.003

References From the Supporting Information

Barker, M. K., Mazarico, E., Neumann, G. A., Zuber, M. T., Haruyama, J., & Smith, D. E. (2016). A new lunar digital elevation model from the lunar orbiter laser altimeter and SELENE Terrain Camera. *Icarus*, *273*, 346–355. https://doi.org/10.1016/j.icarus.2015.07.039

Goossens, S., Sabaka, T. J., Wieczorek, M. A., Neumann, G. A., Mazarico, E., Lemoine, F. G., et al. (2020). High-resolution gravity field models from GRAIL data and implications for models of the density structure of the Moon's crust. *Journal of Geophysical Research: Planets*, *125*(2), e2019JE006086. https://doi.org/10.1029/2019JE006086

Hartmann, W. K. (1984). Does crater "saturation equilibrium" occur in the solar system? *Icarus*, *60*(1), 56–74. https://doi.org/10.1016/0019-1035(84)90138-6

Haruyama, J., Matsunaga, T., Ohtake, M., Morota, T., Honda, C., Yokota, Y., et al. (2008). Global lunar-surface mapping experiment using the Lunar imager/spectrometer on SELENE. *Earth Planets and Space*, *60*(4), 243–255. https://doi.org/10.1186/BF03352788

Herrick, R. R., Dufek, J., & McGovern, P. J. (2005). Evolution of large shield volcanoes on Venus. *Journal of Geophysical Research*, *110*(E1), E01002. https://doi.org/10.1029/2004JE002283

Hurwitz, D. M., Head, J. W., & Hiesinger, H. (2013). Lunar sinuous rilles: Distribution, characteristics, and implications for their origin. *Planetary and Space Science*, *79–80*, 1–38. https://doi.org/10.1016/j.pss.2012.10.019

Kneissl, T., van Gasselt, S., & Neukum, G. (2011). Map-projection-independent crater size-frequency determination in GIS environments—New software tool for ArcGIS. *Planetary and Space Science*, *59*(11), 1243–1254. https://doi.org/10.1016/j.pss.2010.03.015

Kreslavsky, M. A., Head, J. W., Neumann, G. A., Zuber, M. T., & Smith, D. E. (2017). Low-amplitude topographic features and textures on the Moon: Initial results from detrended lunar orbiter laser altimeter (LOLA) topography. *Icarus*, *283*, 138–145. https://doi.org/10.1016/j.icarus.2016.07.017

Li, Y., & Oldenburg, D. W. (1998). 3-D inversion of gravity data. *Geophysics*, *63*(1), 109–119. https://doi.org/10.1190/1.1444302

Michael, G. G., & Neukum, G. (2010). Planetary surface dating from crater size–frequency distribution measurements: Partial resurfacing events and statistical age uncertainty. *Earth and Planetary Science Letters*, *294*(3), 223–229. https://doi.org/10.1016/j.epsl.2009.12.041

19448007, 2026, 15, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2026GL121908 by TEDA POLYTECHNIC, Wiley Online Library on [04/08/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Neukum, G., Ivanov, B. A., & Hartmann, W. K. (2001). Cratering records in the inner solar system in relation to the lunar reference system. *Space Science Reviews*, *96*(1), 55–86. https://doi.org/10.1023/A:1011989004263

Nozette, S., Rustan, P., Pleasance, L. P., Kordas, J. F., Lewis, I. T., Park, H. S., et al. (1994). The clementine mission to the Moon: Scientific overview. *Science*, *266*(5192), 1835–1839. https://doi.org/10.1126/science.266.5192.1835

Oberbeck, V. R., & Morrison, R. H. (1974). Laboratory simulation of the herringbone pattern associated with lunar secondary crater chains. *The Moon*, *9*(3), 415–455. https://doi.org/10.1007/BF00562581

Qiu, D., Yan, J., & Huang, J. (2025). Explosive volcanic eruption at Lassell Massif: Implications for lunar silicic volcanism. *Icarus*, *441*, 116730. https://doi.org/10.1016/j.icarus.2025.116730

Robinson, M. S., Brylow, S. M., Tschimmel, M., Humm, D., Lawrence, S. J., Thomas, P. C., et al. (2010). Lunar reconnaissance Orbiter camera (LROC) instrument overview. *Space Science Reviews*, *150*(1), 81–124. https://doi.org/10.1007/s11214-010-9634-2

Wagner, R. V., Speyerer, E. J., & Robinson, M. S., & LROC Team. (2015). New mosaicked data products from the LROC team. In *46th lunar and planetary science conference*. Lunar and Planetary Institute. abstract #1473.

19448007, 2026, 15, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2026GL121908 by TEDA POLYTECHNIC, Wiley Online Library on [04/08/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License