DOI: 10.46299/979-8-90214-588-2.3

# 3. Volcanic activity of the Moon in the historical past: manifestations, research methods and evolution

## Introduction

The Moon is a differentiated body consisting of geochemically distinct layers: crust, mantle, and core. This structure is thought to be the result of fractional crystallization of a global magma ocean that existed shortly after its formation approximately 4.5 billion years ago. The formation of the Moon is often associated with a hypothetical giant collision between the proto-Earth and another planetary body, followed by repeated accretion of material into Earth's orbit. During this formation, the heaviest materials, such as iron and nickel, settled toward the center, forming the core, while the lighter minerals, such as plagioclase, rose to the surface, forming the crust. The study of lunar volcanism [17, 20, 24, 25] is of paramount importance for understanding the thermal and geological evolution of the Moon. Volcanic activity serves as a direct indicator of the internal thermal state and dynamics of planetary bodies [18, 19, 24, 26, 27, 28]. Analysis of the distribution, composition, and age of volcanic rocks allows us to reconstruct the thermal history of the Moon, the processes of its differentiation, mantle convection, and depletion of internal heat sources [38].

The internal structure of the Moon, which is the result of these early processes, is crucial for understanding its volcanic history. The lunar crust has an average thickness of about 50 km, but its thickness is globally asymmetric, varying from about 60 km on the near side to 100 km on the far side. It is composed mainly of anorthosite rocks, rich in plagioclase, in the upper part and norite or gabbro-norite rocks in the lower part. The Moon's mantle extends approximately 1,350 km beneath the crust [31] and is composed primarily of the minerals [23] olivine, orthopyroxene, and clinopyroxene. It is more ferruginous than Earth's mantle and is at least 70% depleted in thorium and uranium compared to Earth. At the center of the Moon is a small, iron-rich metallic core with a radius of about 350 km or less, which is about 20% of the Moon's diameter. Current studies, based on reanalysis of Apollo data, indicate a solid inner core with a radius of

240 ± 10 km and a liquid outer core with a radius of 330 ± 20 km, surrounded by a partially molten lower mantle layer about 150 km thick. The liquid outer core may contain up to 6% sulfur by weight.

The Moon's initial differentiation into distinct layers (crust, mantle, core) is a direct consequence of its formation (Fig. 3.1). The composition and thickness of these layers, especially the crust and mantle, directly control where and how magma can form and erupt.

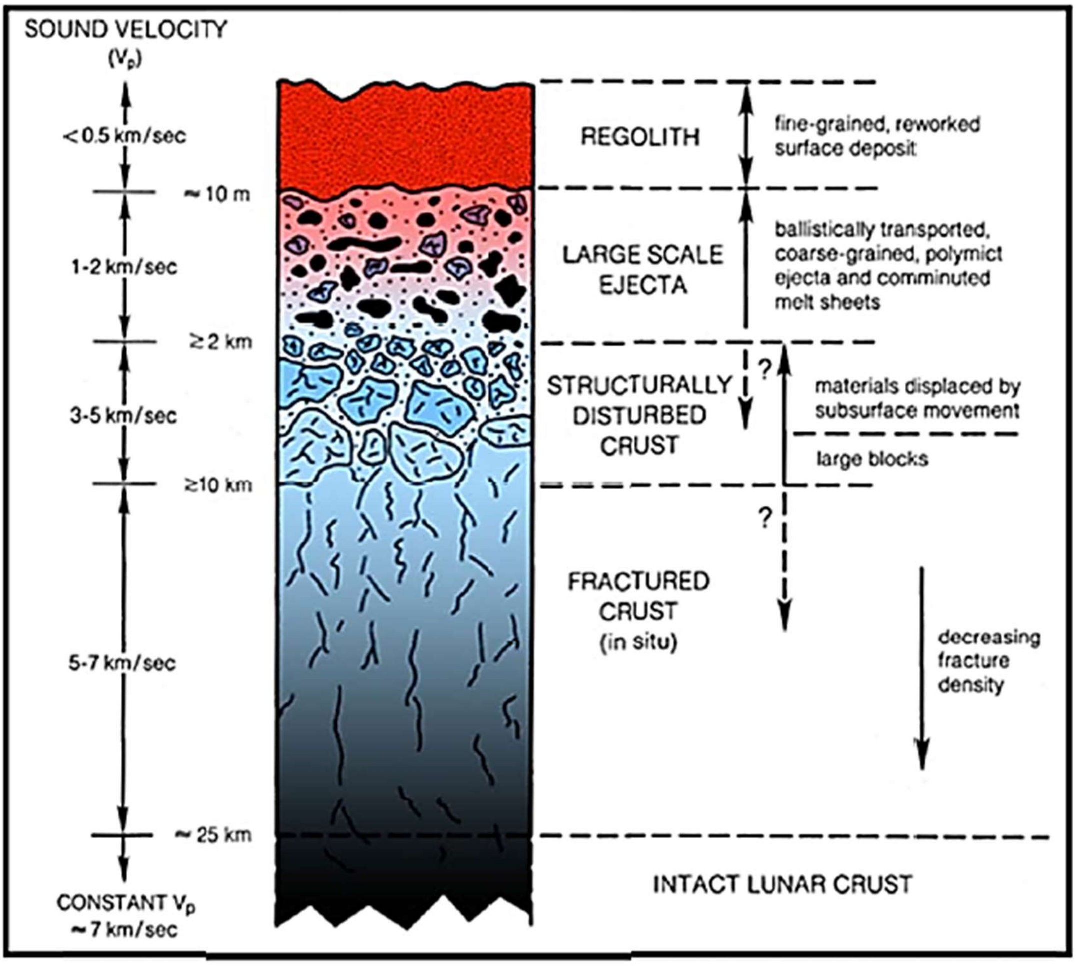


**Fig. 3.1.** Schematic cross-section of the upper 25 km of the lunar surface, illustrating the effect of large-scale cratering on the structure of the lunar crust [30]

For example, the thinner crust on the near side of the Moon provides an easier path for magma to the surface, which affects the distribution of basalts in different parts of the seas [11]. The presence and distribution of radioactive elements in the mantle is the main internal source of heat that fuels volcanism over geological timescales. The state of the core (partially molten) and the mantle (partially molten layer) further determines the thermal state of the Moon and its seismic activity, which in turn reflects the potential for current or past magmatic activity. Therefore, understanding the layered structure and its compositional variations is fundamental to interpreting the observed volcanic forms and their distribution. This emphasizes that lunar volcanism is not a surface phenomenon, but a deeply rooted process linked to the fundamental internal evolution of the Moon.

### 3.1. Sources and mechanisms of mantle melting

Understanding the sources of magma and the cause of its melting is key to reconstructing the volcanic history of the Moon.

*Source of magma*. The source of the marine basalts was the partial melting of the upper mantle of the Moon at depths ranging from 100 to 400 km [4].

*Role of LMO and differentiation*. The composition of the molten mantle was heterogeneous and was determined by the processes that occurred during crystallization in the primary *lunar magma ocean* (LMO). As the LMO cooled, gravitational differentiation occurred: heavier minerals such as olivine and pyroxenes settled to the bottom, while lighter plagioclase rose to form the crust. The residual LMO fluid was enriched in incompatible elements, including radioactive K, REE, P (a component of KREEP), and titanium (in the form of the mineral ilmenite, forming ilmenite-bearing cumulates – IBCs) [9, 15, 37]. It is believed that these later, denser eruptive materials (IBC and KREEP) may have been gravitationally unstable and descended deeper into the mantle (a process of mantle overturning), mixing with material erupted earlier. Subsequent partial melting of these heterogeneous mantle sources, containing different proportions of early and later eruptive materials, resulted in the formation of magmas of different compositions; this may explain the diversity of lunar basalts (e.g., high- and low-titanium, KREEP basalts, etc.). The degree of partial melting was relatively small, typically less than 10%.

***Heat sources***. A source of heat was required for the melting of the mantle. The main sources are considered to be:

*Radiogenic decay*. The most important source of heat over long periods (billions of years) was the decay of the long-lived radioactive isotopes of uranium (U), thorium (Th), and potassium (K). These elements were particularly concentrated in the KREEP layer, mainly on the visible side of the Moon, which may have contributed to longer and more intense volcanism there.

*Other sources*. Residual heat from accretion and core/LMO formation, tidal heating (probably significant only in the early stages), and heat from large impacts may also have played a role in heating the interior.

*Core state*. Reanalysis of old Apollo seismic data in 2010 using modern processing techniques confirmed the existence of an iron core on the Moon. It found a solid inner core with a radius of 240 ± 10 km and a liquid outer core with a radius of 330 ± 20 km, surrounded by a partially molten lower mantle layer about 150 km thick (radius 480 ± 20 km). These results significantly revised previous, less precise estimates that suggested a core radius of about 500 km.

The evolution of seismic understanding of the Moon's interior is a striking example of scientific progress. The very first seismometer on the Apollo 11 mission, while groundbreaking, had serious limitations. Subsequent Apollo missions greatly improved data collection, extending the operating periods and measuring all three components of ground displacement. However, even these data were limited by the processing capabilities of the time.

A crucial "second wave" of understanding came from the reanalysis of these outdated Apollo data using modern seismological techniques, such as seismogram stacking. This approach overcame the problem of "noise" caused by the overlapping of signals in different fractions of the lunar crust, greatly improving the resolution of the data. This allowed the detection of layering also in the deep layers of the Moon, associated with the core, and its size and condition to be clarified.

This example demonstrates a significant trend in scientific discovery: initial data collection provides fundamental knowledge, but subsequent technological and methodological advances allow for deeper, more precise interpretations of the same data, leading to a more precise understanding of complex planetary interiors.

The discrepancy in estimates of the core radius (e.g., 500 km versus 330 km) directly illustrates this evolution of understanding. This highlights the long-term value of well-archived scientific data and the iterative nature of scientific progress, where new tools and theories can reveal hidden information from older data sets.

### 3.2. Gravitational and topographic data

Current understanding of the Moon's internal structure is largely based on high-precision gravitational and topographic data obtained by orbital missions. The "Gravity Recovery and Interior Laboratory" (GRAIL) mission used two identical spacecraft to map the Moon's gravity field in unprecedented detail, allowing it to determine its interior structure [33] with high precision. "GRAIL" significantly improved the resolution of the Moon's gravity field.

The "Lunar Prospector" mission (1998–1999) also contributed by mapping the Moon's gravity field with the Doppler Gravity Experiment (DGE), which used radio tracking to monitor changes in the spacecraft's orbit, providing information about the crust, lithosphere, and internal structure [1].

Gravity anomalies, particularly those known as mascons, play a key role in studying subsurface structures associated with volcanism. "GRAIL" data have allowed us to determine the density and porosity of the crust, and have also revealed long, narrow linear structures interpreted as ancient intrusions or fissures formed by magma. Strong positive gravity anomalies are associated with circular impact basins (Fig. 3.2), filled with dense dark material from the seas [30]. These anomalies require the crust-mantle boundary to be raised upward, which is a consequence of mass compensation. Gravity inversions allow for the modeling of small three-dimensional density variations in the lunar crust [6], varying in the range of 100–200 kg/m$^3$. Comparison of gravity data with topography allows for the identification of features that inform the structure and evolution of the Moon. For example, the Korolev Basin on the far side exhibits a central gravity maximum within a ring of peaks and a ring minimum at the crater floor, indicating a density deficit (possibly brecciated material) or a thickened crust.

**Fig. 3.2.** The photograph shows the contrast between the heavily cratered highlands and the smooth, dark basaltic sea plains. Mare Imbrium is prominent in the northwestern quadrant. The dark, basalt-flooded region to the west is Oceanus Procellarum. Mare Crisium is a dark, round basaltic patch on the eastern edge [30].

In the Oceanus Procellarum region, positive Bouguer anomalies can indicate denser or thicker sea material, which helps define the boundaries of the KREEP province. Gravity data, especially from high-resolution missions such as “GRAIL”, do not "see" magma or volcanic activity directly. Instead, they measure density variations in the interior of the Moon. These density variations are caused by geological processes such as magmatic intrusions, crustal thinning/thickening due to impacts and subsequent lava filling, and uplift of mantle material. Gravity data thus serve as a powerful indicator, allowing scientists to infer the subsurface distribution of materials and the processes that formed them.

The identification of mascons and their relationship to sea basalts and Moho uplift is a prime example of this possibility. The higher resolution of “GRAIL” data has greatly improved the ability to distinguish these subtle density variations.

Gravity mapping therefore provides a global, non-invasive method for understanding the internal architecture of the Moon, complementing localized seismic data and direct sample analysis. It reveals the large-scale effects of magmatic and impact processes [13, 29] on the structure of the Moon.

### 3.3. Heat flow and radioactive element distribution measurements

Measurements of heat flow from the Moon's interior provide important information about its thermal history and the distribution of radioactive elements. Direct measurements of heat flow on the Moon were successfully carried out during the Apollo program. The "Apollo" Heat Flow experiments (HFE) at the "Apollo 15" (Hadley Rille) (Fig. 3.3) and "Apollo 17" (Taurus-Littrow) mission sites provided the only in situ temperature measurements to date. The measured heat flux values were 21 ± 3 $mW/m^2$ and 15 ± 2 $mW/m^2$, respectively [32]. For comparison, the average heat flux on Earth is 87 $mW/m^2$.

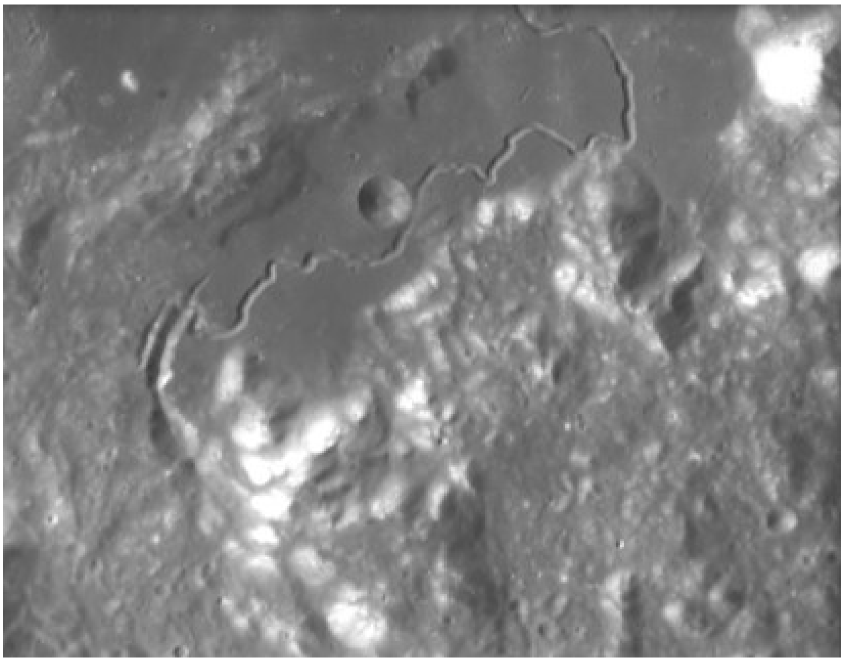

**Fig. 3.3.** The image shows the winding Hadley Rille, reminiscent of river valleys on Earth; it runs through the upper half of this image; below it are the Apennine mountains (1-2 km high); the large crater in the center of the image is Hadley C crater with a diameter of 5.5 km (https://cdn.sci.esa.int/documents/34677/35605/1567219136347-hadley1.jpg).

The low values for the Moon are consistent with its smaller size, which contributes to the rapid early cooling of its interior layers. The HFE probes measured temperatures at depths of 1.7 m (“Apollo 15”) and 2.5 m (“Apollo 17”), which allowed the thermal properties of the regolith, and the heat flux values to be calculated. Long-term drift of the subsurface temperature and a decrease in the thermal gradient with time were observed.

The Moon's heat flux is largely determined by the abundance of radioactive elements, especially uranium and thorium, in its interior. It is believed that the Moon's present-day heat flux is largely the result of heat generated by radioisotopes down to a depth of about 300 km. However, estimates of the total uranium abundance on the Moon (from 20-21 ppb to 46 ppb) still have significant uncertainties, making them difficult to use for testing the giant impact model.

To obtain a global picture of the distribution of radioactive elements, the Gamma Ray Spectrometer (GRS) on board the Lunar Prospector mission was used. This instrument produced global maps of the distribution of elements such as potassium (K), uranium (U), and thorium (Th), which are the main sources of the Moon's endogenous heat. These data showed that the Moon's surface heat flux varies regionally from 10.6 to 66.1 mW/m$^2$. The Procellarum KREEP Terrane (PKT) region is particularly enriched in thorium and uranium, which likely contributes to the significant increase in heat flux in this area (5 to 20 mW/m$^2$). This explains the longevity and intensity of volcanism observed in the PKT.

Direct measurements of heat flux from “Apollo”, although rare (only two locations), have provided critical in situ data. Low values compared to Earth immediately indicated a rapidly cooling body. However, variations in heat flux, especially in combination with orbital gamma-ray spectrometry (“Lunar Prospector”), which shows a heterogeneous distribution of radioactive elements (KREEP), reveal a more nuanced picture. For example, the high heat flux in the PKT directly links radiogenic heating to concentrated, prolonged volcanism in this region.

The discrepancy between the observed heat flux and the expected rapid cooling, especially in light of recent discoveries of young volcanism, implies that localized radioactive enrichments (like KREEP) could have sustained pockets of magma for much longer than global thermal models have predicted. This challenges the simplistic narrative of "small body cools rapidly," introducing heterogeneity as a critical factor in thermal evolution and volcanic longevity.

This suggests that the Moon's internal heat engine, although generally quenched, had "hot spots" fueled by concentrated radioactive elements that allowed volcanism to occur at late stages. This has profound implications for understanding the thermal evolution of other differentiated but seemingly "dead" planetary bodies.

The heat flux of each body provides unique information about its internal composition [22]. The geothermal heat flux from the Moon is thought to vary mainly through the distribution of radiogenic materials both spatially and vertically through the lunar crust. Although the results of the Apollo missions provide an important starting point, questions remain about the average lunar heat flux and its variations across geological regions.

For example, measurements from "Apollo 15" were made at the periphery of a geochemically unique region, Oceanus Procellarum (Fig. 3.4), which is highly enriched in thorium and probably uranium according to orbital geochemical observations. Thermal modeling suggests that the high radioactivity in this region could add 5 $mW/m^2$ to the average heat flux at the "Apollo 15" landing site and up to 20 $mW/m^2$ in the center of this region.

Oceanus Procellarum is a vast, flat basaltic basin covering about 17% of the Moon's near side, surrounded by numerous linear gravity anomalies (shown in red) found in data from the GRAIL spacecraft. These anomalies indicate that this large basin was formed by volcanic processes, not by an asteroid impact, according to a new study.

The presence of radioactive elements in large quantities could generate enough heat to keep the Moon's upper mantle hotter, slowing the cooling process over time. This explains why younger lava flows, like those collected by "Chang'e-5", could have originated from much shallower depths than previously thought. There could still be hot pockets in the mantle even during the late stages of the Moon's cooling.

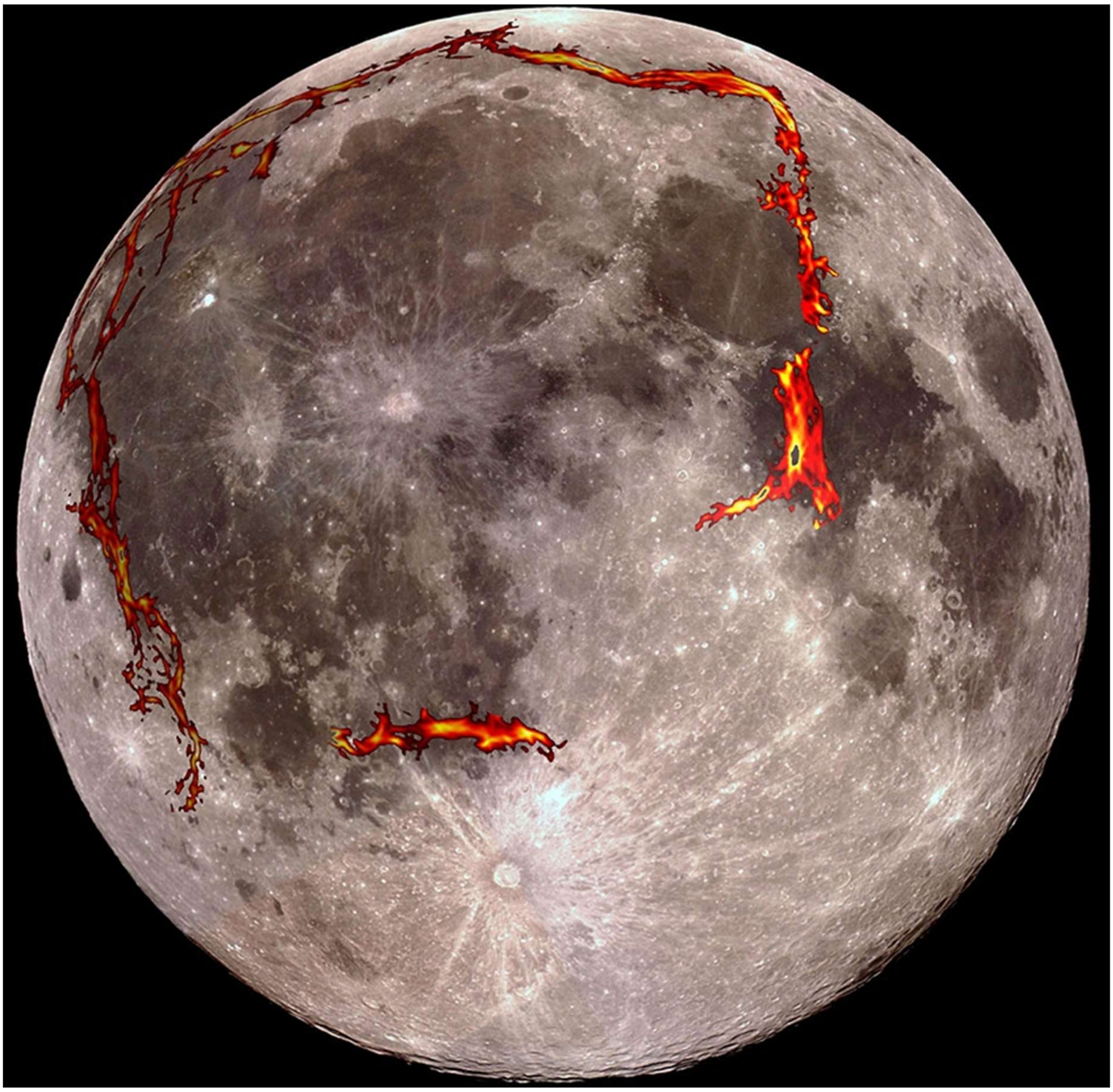

**Fig. 3.4.** Image of the *Oceanus Procellarum* region surrounded by many linear gravitational anomalies (highlighted in red), detected by NASA's GRAIL spacecraft (http://www.americaspace.com/wp-content/uploads/2014/10/Figure2_fullmoon.jpg)

### 3.4. Analysis of lunar soil and rock samples

Analysis of lunar soil and rock samples returned by the “Apollo” and “Chang'e” missions is a key finding in understanding lunar volcanism (Table 3.1). The Apollo program returned a significant number of samples that, along with other data, transformed our understanding of the Moon. These samples include basalts derived from lunar seas, impact breccias, and unique glass beads.

**Table 3.1.**

**Major missions and methods for studying the interior of the Moon.**

| Main Instruments/ Methods | Data Obtained | Contribution to the Understanding of Volcanism |
|---|---|---|
| Passive Seismometers (PSE), Heat Flow Experiment (HFE) | Moonquakes (deep, shallow, shock), Heat flux (21 ± 3 mW/m$^2$, 15 ± 2 mW/m$^2$), Temperature gradients | Determination of internal structure (crust, mantle, core), heat sources, duration and intensity of volcanism, mechanisms of eruptions. First direct measurements of heat flow and seismic activity. |
| Gamma-ray Spectrometer (GRS), Doppler Gravity Experiment (DGE), Magnetometer/Electron Reflectometer (MAG/ER) | K, U, Th distribution; Global gravity field | Mapping of the distribution of radioactive elements (KREEP), which is a source of heat for volcanism. Information on the thickness of the crust and internal structure. |
| Gravity Mapping (two spacecraft) | High-precision global gravity field, Crustal thickness (35-40 km), Crustal density, Mascons | Detailed mapping of the gravity field to study internal structure, detection of ancient magmatic intrusions (dykes) and the connection of mascons with basalts of the seas. |
| Analysis of Returned Samples (Basalts, Glass Beads) | Composition and age of volcanic rocks/glass beads (3.16-4.2 Ga, 2.03 Ga, 123 ± 15 Ma) | Direct dating of volcanic events, determination of magma composition and eruption conditions (volatiles, pressure). Evidence of unexpectedly late volcanism. |
| Orbital Spectroscopy | Composition of pyroclastic deposits (DMDs) | Remote analysis of the composition of volcanic formations, which complements sample data and allows mapping of the distribution of volcanic materials. |

***Basalts.*** These rocks that make up the lunar seas are dark, fine-grained, and rich in iron, magnesium, and plagioclase. Radiometric dating of these basalts indicates an age of 3.16 to 4.2 billion years, with most eruptions occurring between 3 and 3.5 billion years ago.

***Glass beads***. Microscopic in size (less than a millimeter), these orange and black glass beads have been found in lunar regolith and rocks. They formed when lava droplets in explosive volcanic plumes cooled rapidly in the vacuum of the lunar surface about 3.3 to 3.6 billion years ago.

Detailed analysis has shown that the black beads contain zinc sulfide nanocrystals, which indicate the presence of hydrogen and sulfur as the main volatile elements in the plumes. In contrast, the orange globules do not contain significant amounts of zinc sulfide, suggesting that the conditions of the eruptions have changed over time. The existence of the glass globules, especially their distinct composition (black vs. orange, presence/absence of zinc sulfide) and nanoscale features (microbubbles with iron gradients), provides an incredibly detailed, "fossilized" record of the specific conditions of explosive lunar eruptions. It is not just evidence that volcanism occurred, but *how* it occurred: changes in pressure, volatile content (hydrogen, sulfur), and how these conditions evolved over time.

This level of detail, obtained using advanced analytical techniques on tiny samples, offers a unique window into the mechanics of ancient lunar volcanism that cannot be obtained through remote sensing alone. These microscopic features are valuable "time capsules" that allow scientists to reconstruct the physicochemical environment of ancient lunar volcanic plumes, providing information on the volatile content of magma and the dynamics of eruptions, which is critical for understanding early lunar degassing and atmospheric evolution.

***“Chang'e-5” samples***. The “Chang'e-5” mission returned lunar soil samples to Earth in 2020, including basalts that are 2.03 billion years old [2, 5]. This already indicated much younger volcanic activity than previously thought. However, the most unexpected data came from three volcanic glass beads from these samples. Radioisotope dating of these beads showed an age of 123 ± 15 million years ago, providing definitive evidence for much younger lunar volcanism than expected. This discovery contradicts thermal models of the Moon, which predicted that its interior would have cooled long before this period.

In addition to sample analysis, orbital spectral data are used. For example, data from the “Moon Mineralogy Mapper” ($M^3$) are used to remotely analyze the composition of volcanic formations such as pyroclastic deposits (*Dark Mantle Deposits, DMDs*) [7]. These DMDs are low-albedo, fine-grained regions that vary in composition: large ones contain iron- and titanium-rich glass, while smaller ones are iron-bearing mafic minerals.

Spectral identification of volcanic glasses is a strong indicator of their pyroclastic origin [36]. Comparison of orbital spectra with laboratory measurements of similar materials allows inference of probable formation processes without the need for sample-return missions. The synergy between direct sample analysis and remote sensing is extremely effective. While direct analysis of samples provides unparalleled detail and absolute dating, orbital remote sensing offers global coverage and context.

The combination of these two approaches is powerful; samples provide detailed temporal data on their compositional changes, which then allow for the calibration and interpretation of broader orbital data sets. For example, the discovery of specific mineralogy in samples (e.g., anorthosite, KREEP, basalt, glass beads) informs the interpretation of spectral signatures observed from orbit, allowing scientists to map the distribution of these materials globally. Conversely, orbital data help select optimal landing sites for future sample-return missions to address specific questions. This integrated approach maximizes scientific return by providing both microscopic understanding and macroscopic mapping of lunar volcanic processes across its surface and history.

### 3.5. Manifestations of volcanic activity in the historical past of the Moon

The volcanic history of the Moon is a fundamental aspect of its geological evolution, starting with its formation and initial differentiation.

**3.5.1. Formation of the lunar magma ocean and initial differentiation**. The generally accepted hypothesis for the formation of the Moon assumes a giant collision between the proto-Earth and another planetary body. Due to the rapid accretion of the Moon, which occurred over a period of months to years, gravitational potential energy was converted into thermal energy. This led to the formation of a global Lunar Magma Ocean, which probably existed from 4.5 or 4.4 billion years ago to tens or hundreds of millions of years after the formation of the Moon. The LMO is key to explaining such features of the Moon as its anorthosite crust, the Europa anomaly, and the presence of

KREEP material [35].

During the crystallization of the LMO (Fig. 3.5), denser minerals such as olivine and orthopyroxene sank to the base, forming the mantle. In contrast, lighter minerals, such as plagioclase, rose to the surface, forming the Moon's original anorthosite crust. This differentiation process occurred primarily between 4.5 and 3.9 billion years ago. Zircon dating from Apollo 14 samples indicates that the lunar crust differentiated approximately 4.51 ± 0.01 billion years ago. The lunar magma ocean is not just a theoretical construct for the Moon's early state; it is a fundamental event that predicted the entire subsequent volcanic history of the Moon.

Differentiation within the LMO created distinct crustal and mantle compositions and structures (e.g., thin near-side crust, KREEP enrichment) that then controlled where and when further partial melting (sea basalts) could occur. Without this initial global melting and differentiation, the lunar volcanic manifestations would be very different or would not exist in the forms we observe.

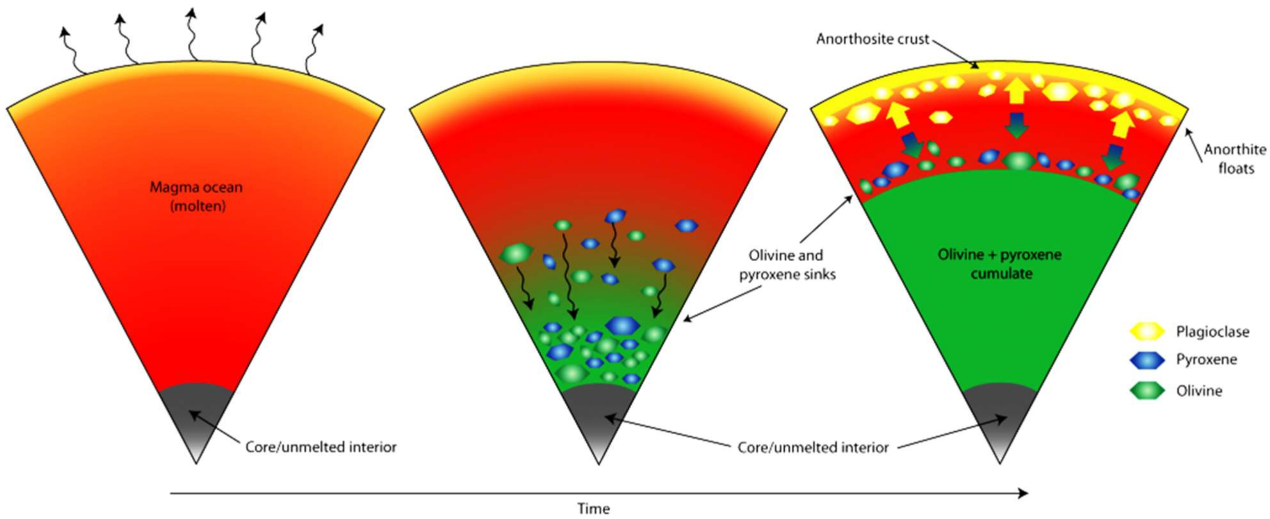


**Fig. 3.5.** Cross-section of the lunar interior during and after the formation of a hypothetical lunar magma ocean. Heavy minerals (olivine and pyroxene) sink to the surface of the core and form a thick mantle rich in mafic rocks. Lighter minerals (plagioclase feldspar) float to the surface, forming an anorthosite crust (https://clrn.uwo.ca/wp-content/uploads/2022/06/Lunar-Magma-Ocean-Illustration-1024x452.png).

The longevity of the LMO and the potential for additional heat sources (such as tidal heating in the very early Moon, as suggested by the 270 million year age difference in the FAN samples) are critical to understanding the initial heat budget available for volcanism. The LMO hypothesis thus provides the necessary geological context for all subsequent lunar volcanism, linking the formation of the Moon directly to its long-term thermal and magmatic evolution.

**3.5.2. Formation of lunar maria.** The most obvious manifestation of lunar volcanism is the formation of large dark plains called maria. Lunar maria are large, dark, basaltic plains that are the most visible manifestations of lunar volcanism. They were formed by the outpouring of lava into ancient impact basins. Due to their iron-rich composition, they are less reflective than the surrounding "mountainous areas" and therefore appear dark to the naked eye.

The main period of the most intense eruptions that formed most of the seas occurred during the so-called Late Heavy Bombardment, with a peak of activity between 3.8 and 3.2 billion years ago. The vast majority of the seas are located within huge impact basins that were formed by the impact of giant asteroids or comets. However, radiometric dating of sea samples shows a wider age range – from 3.16 to 4.2 billion years. These impacts not only created deep depressions, but also probably pierced the thin lunar crust at that time or created deep fault systems, which facilitated the ascent of magma from the interior.

That is, the formation of the seas is attributed to a combination of impact cratering, which created large basins, and subsequent volcanic activity, which filled these basins with lava. The magmas of the basalts of the seas are denser than the anorthosite materials of the upper crust. Eruptions may have been more favorable in locations with low elevations and thin crust.

The formation of seas is a classic example of how external (impact events) and internal (magmatism, crustal structure) processes interact. Although impacts created basins, subsequent lava filling was not necessarily a direct, immediate consequence of the impact itself. The concentration of seas on the near side of the Moon, despite the lowest elevations on the far side (the South Pole-Aitken Basin), defies simple explanations based solely on crustal thickness or the Earth's gravitational influence (which in the lunar frame is balanced by centrifugal force).

The key insight is that the distribution is likely a complex interplay of crustal thickness (thinner crust on the near side facilitates magma ascent), distribution of heat-generating elements (enrichment of KREEP in the Oceanus Procellarum, a large region of seas), and possibly deep mantle heterogeneities (thermal anomalies influencing the distribution of deep moonquakes, as suggested by “GRAIL” data). This moves beyond a single causal factor to a more integrated understanding.

Thus, after basin formation, massive outpourings of basaltic magma from the Moon's interior occurred over the next hundreds of millions of years. This magma, formed by partial melting of the mantle, rose to the surface through faults and flooded the basin lowlands. Lunar basaltic lavas had very low viscosity, allowing them to spread over vast areas (hundreds of thousands of square kilometers) and form very flat, level surfaces [8] of the seas. The thickness of the lava flows varied from a few meters to tens of meters, but the total thickness of the basaltic fill in the centers of large basins can reach several kilometers.

Thus, the asymmetric distribution of the seas is a fundamental feature of the Moon, reflecting deep-seated, long-term thermal and structural asymmetries that are still not fully understood. This suggests that although the impacts provided "containers", the internal thermal state of the Moon and structural weaknesses dictated where and when these containers were filled.

**3.5.3. Other specific volcanic landforms.** In addition to the vast seas, the lunar surface contains a variety of other volcanic features, smaller but characteristic landforms that indicate a complex magmatic history.

***Volcanic domes*** are low (a few hundred meters), flat-topped shield-shaped hills, often with a small crater (caldera) at the top. Most of these domes are basaltic in composition and were formed by eruptions of relatively small volumes of lava from a central vent. Examples include the Hortensia domes and the Marius Hills complex. There are also rarer domes (e.g., Gruythuizen) that, according to remote sensing data, have a silicate (richer in $SiO_2$, similar to granite) composition. Their existence indicates more complex processes of magmatic differentiation that may have occurred in the lunar interior, although on a much smaller scale than on Earth.

***Winding sinusoidal rilles*** are probably the most recognizable small volcanic features on the Moon, often resembling river valleys on Earth. They are interpreted as lava channels or collapsed lava tubes formed during marine volcanism. Analysis of lunar samples confirms their volcanic origin, indicating that the Moon has always been dry, in contrast to the water-based erosion processes on Earth. Hadley Rille, near the Apollo 15 landing site, is one of the best-known examples of sinusoidal rilles.

***Volcanic domes and cones*** are small volcano-like formations, typically a few hundred meters high and 10–15 km in diameter, characterized by irregular outlines and small central pits. Unlike their terrestrial counterparts, lunar explosive eruptions likely spread material much farther due to lower gravity and the absence of an atmosphere, forming broad, thin layers (dark mantle deposits) instead of the typical cones. Most lunar domes and cones are composed of basalt, suggesting that they were formed from barely molten lava, unlike the viscous, non-basaltic lavas that form domes on Earth. The Marius Hills are the largest group of such features, and also contain sinusoidal rilles. Some domes, such as the Gruithuisen Domes (Fig. 3.6), may be rare examples of non-basalt lunar volcanism. The Gruithuisen Domes are formed by silica-rich magma similar in composition to granite. Observations from the Lunar Reconnaissance Orbiter confirmed that the Gruithuisen Domes are distinct from the surrounding terrain, which is covered by ancient, hardened basaltic lava flows. Basalt lavas are thin and fluid, unlike silicic lavas, which are thick. The Gruithuisen Domes were formed by eruptions of silicic lavas that did not flow easily to the surface.

***Dark Mantle Deposits (DMDs) and Glass Beads***. Over 100 dark mantle deposits have been identified on the Moon, ranging in size from 10 to 50000 $km^2$. They are thought to be the products of explosive volcanic eruptions known as "fire fountains". During such eruptions, magma, saturated with volatile gases (probably CO, S), rising to the surface, foams and sprays into small droplets, which quickly cool in a vacuum, forming glass balls.

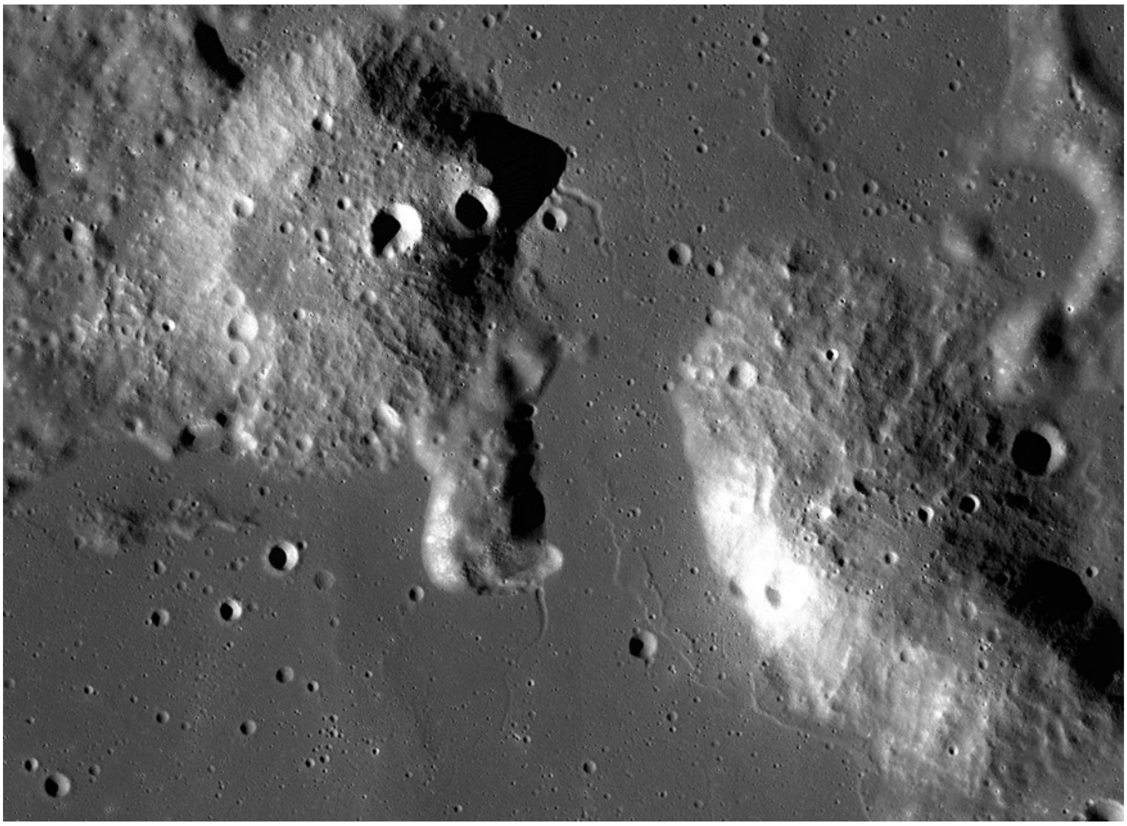

**Fig. 3.6.** The Gruythuizen domes were formed by eruptions of silicic lavas (https://assets.science.nasa.gov/dynamicimage/assets/science/psd/lunar-science/2023/08/Gruithuisen_Domes-1.png?w=1100&h=1100&fit=clip&crop=faces%2Cfocalpoint).

These globules, mostly in the tens of microns, are basaltic in composition and are often coated with a thin layer of condensed volatile elements (Zn, Pb, S, Cl). The most famous example is the "orange soil" found by the “Apollo 17” mission near *Shorty Crater in the Taurus-Littrow Valley*.

These regions are therefore composed of low-albedo, fine-grained material that varies in composition: large DMDs, such as those in *Taurus-Littrow* and *Mare Vaporum*, contain iron- and titanium-rich glass, while smaller DMDs are typically composed of iron-bearing mafic minerals such as pyroxene and olivine. Spectral identification of volcanic glass is a strong indicator of their pyroclastic origin. Glass globules found in the Apollo samples are direct evidence of explosive eruptions that occurred 3.3–3.6 billion years ago. Their chemical composition and microstructure reflect the conditions of the eruptions, including pressure and volatile content. The existence of DMDs is compelling evidence that lunar magmas contained sufficient volatiles for explosive eruptions.

The diversity of lunar volcanic forms is not limited to vast seas. The presence of rilles, domes, cones, and pyroclastic deposits indicates a wide range of eruption styles, from effusive lava flows (seas, rilles) to more viscous or explosive events (domes, pyroclastic deposits). Differences in morphology and composition compared to terrestrial volcanoes (e.g., lunar explosive eruptions producing extensive mantle deposits rather than cones) directly reflect the unique lunar environment (lower gravity, vacuum, different magma composition).

Detailed analysis of the glass beads provides microscale evidence for volatile-driven explosive volcanism, a process that was not immediately apparent from macroscopic observations. This diversity of volcanic landforms and materials provides a comprehensive record of the Moon's magmatic processes, showing that lunar volcanism, while dominated by effusive marine basalt eruptions, also included more complex and dynamic eruption styles driven by internal processes and the influence of the lunar environment.

### 3.6. Nature of Lunar Eruptions and the Evolution of Lunar Volcanic Activity: Past to Present

Lunar eruptions have had their own characteristics, driven by the composition of the magma, low gravity, and lack of an atmosphere.

***Effluent vs Explosive***: Effluent eruptions dominated, leading to the formation of vast marine plains. This is due to the predominantly basaltic composition of the magma and its low viscosity. However, explosive eruptions have also occurred, producing pyroclastic deposits (DMDs). These eruptions were caused by the release of gases from the magma as pressure drops during ascent to the surface. The low gravity and lack of an atmosphere facilitated the dispersion of pyroclastic material (glass beads) over long distances [34].

**Lava composition**: Lunar lava was predominantly basaltic, similar to terrestrial basalts of oceanic crust or trap formations. It was characterized by low viscosity, which favored the formation of long flows and flat seas. There was a significant diversity of basalts (e.g., titanium content, KREEP), reflecting the heterogeneity of the mantle sources.

The evolution of lunar volcanic activity is a complex history, reflecting its thermal and geological dynamics over billions of years.

***Early Intense Volcanism***. The period during which most of the lunar mare formation occurred, between 3.9 and 3.2 billion years ago, was a time of the most intense lunar volcanism. This period coincides with the hypothetical *Late Heavy Bombardment* (LHB) event, when the inner Solar System experienced intense collisions [29] with asteroids and comets approximately 4.1 to 3.8 billion years ago. Although the direct causal relationship between impacts and eruptions remains a matter of debate, the intense bombardment may have created numerous cracks and fractures in the lunar crust, which facilitated the emergence of magma to the surface. High internal heat flux, driven by the radioactive decay of elements such as uranium, thorium, and potassium, supported active magma formation in the lunar mantle. The temporal overlap between the *Late Heavy Bombardment* and the peak of marine volcanism is a significant observation. Although the direct impact triggering of the eruptions is debated, the LHB undoubtedly strongly fractionated the lunar crust. These fractures could have provided channels for magma to rise, regardless of whether the impact itself initiated melting. This suggests a synergistic relationship: external impacts created structural weaknesses, while internal heat (from radioactive decay) provided magma. This highlights how the early geological history of the Moon was shaped by a complex interplay of accretionary, impact, and internal thermal processes.

Thus, the LHB, while destructive, may have inadvertently facilitated large-scale marine volcanism by creating pathways for magma, thereby shaping the Moon's visible surface features.

***Decay and Late Volcanism***. After a period of intense volcanism, the Moon's volcanism gradually declined. It was long believed that lunar volcanism ceased completely around 3.1 billion years ago, and that all surface rocks were older than this age. However, new data have challenged this notion. Samples returned by the Chinese

“Chang'e-5” mission include basalts that are 2.03 billion years old, which already indicated much younger activity.

The most surprising data came from three volcanic glass beads also collected by the “Chang'e-5” mission. Radioisotope dating of these beads showed an age of 123 ± 15 million years ago. This is conclusive evidence of much younger volcanism than expected, suggesting active eruptions on the Moon at a time when dinosaurs still roamed the Earth (the Cretaceous Period). In addition, about 70 small volcanic formations known as *irregular mare patches* (IMPs) have been discovered, the age of which is estimated to be less than 100 million years, and some even less than 50 million years (e.g. Ina (Fig. 3.7) ~33 million years, Sosigenes ~18 million years).

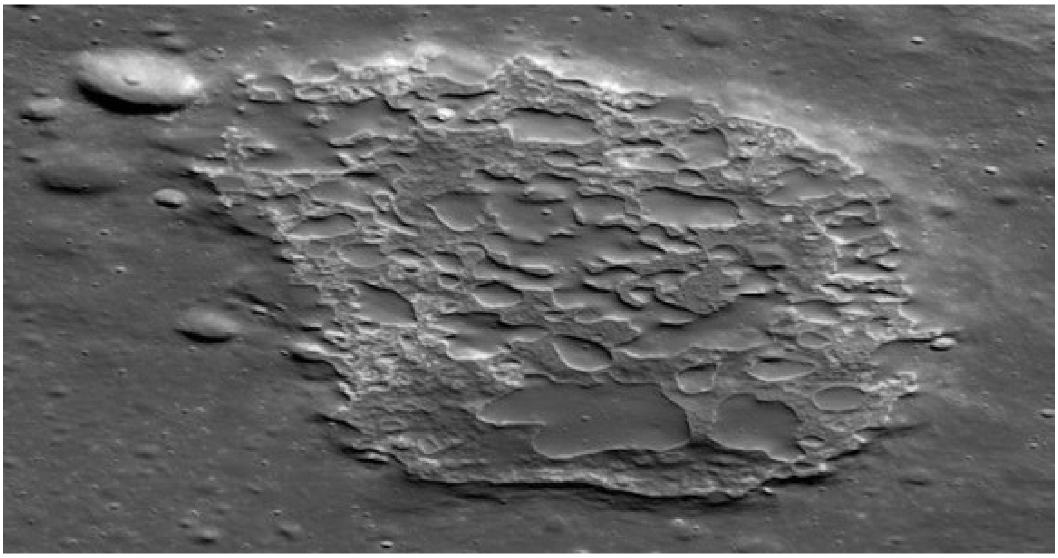

**Fig. 3.7.** The volcano called Ina is about 3 km long, 2 km wide, and 50 meters deep. Its floor is covered with many small, low lava mounds. The number of craters observed on the mounds indicates that the eruptions occurred about 33 million years ago (https://earthsky.org/upl/2014/10/mon-volcano-2-e1413139625498.jpg).

The reasons for the extinction of volcanism on the Moon are related to its rapid cooling. Being much smaller than the Earth, the Moon lost its internal heat much faster, which led to the extinction of volcanism, since magma could not form at a certain temperature. The decrease in the number of radioactive elements (U, Th, K), which are the main source of internal heat, also contributed to the decrease in heat flow. Over time, the Moon's lithosphere thickened, making it difficult for magma to rise to the surface. The traditional narrative of lunar thermal evolution assumed rapid cooling due to its small size, which led to the cessation of volcanism relatively early (about 1-2 billion years ago). The discovery of volcanism occurring as early as 120-50 million years ago directly contradicts these established thermal models. This contradiction forces us to reconsider our understanding of the thermal evolution of planets.

This suggests that the Moon's interior either retained heat for much longer than expected, or that localized heat sources (such as the KREEP province, which is enriched in radioactive elements and associated with prolonged volcanism) played a more significant role in supporting late-stage magmatism than previously considered in global models. It is currently unknown how such a small celestial object could have supported active volcanism without having cooled completely by today.

The existence of such late volcanism implies that the Moon's internal thermal structure was more complex and heterogeneous than simple cooling models suggested. This opens new avenues for studying the mechanisms of localized heat retention, the role of specific compositional anomalies (such as KREEP), and the rheology of the deep lunar interior at later stages of evolution. It also has broader implications for understanding the thermal evolution of other small planetary bodies.

### 3.7. Current state of volcanism

There is currently no active volcanism on the Moon, as evidenced by the lack of observed eruptions. However, moonquakes continue to occur, although they are much weaker than earthquakes and rarely exceed magnitude 2 on the Richter scale. This suggests that the Moon is not completely geologically "dead" but retains some internal activity. Deep moonquakes, which make up the majority of recorded events, are associated with tidal forces acting on the Moon from the Earth. The presence of shallow moonquakes, although rare, may also indicate continued brittle failure in the shallow crust, indicating the accumulation and release of stresses [3].

The lack of active volcanism may lead to the conclusion that the Moon is geologically inert. However, the continuous occurrence of moonquakes, even if they are weak, indicates ongoing internal processes. Deep moonquakes are directly related to the Earth's tidal forces, demonstrating a constant external influence on the Moon's interior. Shallow moonquakes, although less frequent, indicate brittle fracture in the crust, indicating the accumulation and release of stresses.

This continuous seismic activity, even in the absence of volcanism, indicates that the Moon is not a static body, but one undergoing slow, long-term geological change. Thus, the Moon, although volcanically quiescent, remains a dynamic body, providing a natural laboratory for studying long-term planetary evolution in the absence of plate tectonics and significant internal heat (Table 3.2).

**Table 3.2.**

**Chronology of Volcanic Activity on the Moon.**

| **Period (billion years ago)** | **Major Manifestations of Volcanism** | **Characteristics** | **Key Data Sources** |
|---|---|---|---|
| ~4.5 - 4.4 | Formation of the Lunar Magma Ocean (LMO) | Global melting, differentiation | Theoretical models, Apollo 11 samples |
| 4.5 - 3.9 | Initial differentiation of the crust and mantle | Formation of anorthosite crust, ferruginous mantle | Apollo samples |
| 3.9 - 3.2 (peak) | Formation of most lunar seas | Filling of impact basins with basaltic lava, formation of rilles, domes | Apollo samples, Luna, orbital data (Clementine, Lunar Prospector, GRAIL) |
| 3.3 - 3.6 | Explosive eruptions (glass balls) | Emissions of volatiles, formation of microscopic glass beads | Apollo samples (especially orange soil) |
| ~2.0 | Late basaltic eruptions | Low-Ti/Al/K basalts | Chang'e-5 samples |
| ~0.123 | Volcanic glass balls | Unexpectedly young age, evidence of prolonged thermal activity | Chang'e-5 samples |
| <0.1 - <0.05 | Irregular marine patches (IMPs) | Small, low-lying volcanic formations that contradict cooling models | LRO (crater count) |
| Today | Lack of active volcanism, but ongoing moonquakes | Tidal moonquakes, shallow moonquakes | Apollo seismometric data |

***Implications of young eruptions***. Evidence for relatively recent volcanic activity (2 billion years ago and younger) challenges traditional models of the Moon's thermal evolution. They indicate that the Moon may have cooled more slowly than previously thought, or that there were local mechanisms to maintain melting in the mantle for a longer time. Possible factors could be the concentration of radioactive KREEP elements or the presence of low-melting compounds in the mantle.

**Conclusions and future research on volcanism**

The Moon has had a complex and dynamic volcanic history, beginning with the formation of a global magma ocean and subsequent early differentiation around 4.5 billion years ago. The bulk of the volcanic activity occurred during the formation of extensive basaltic seas between 3.9 and 3.2 billion years ago. However, new data, particularly samples returned by the Chang'e-5 mission, indicate a much longer history of volcanic activity than previously thought, with eruptions occurring as early as 120 to 50 million years ago. Our understanding of this history is based on a synergy of diverse data from seismic surveys ("Apollo"), gravity and topographic measurements ("GRAIL" and "Lunar Prospector" missions), heat flow measurements, and detailed analysis of returned lunar rock samples.

Despite significant progress, important open questions remain that shape future research directions:

***The paradox of late volcanism***. One of the most important questions is how the Moon, a relatively small body, could have maintained volcanic activity for so long (until 50-120 million years ago), despite the expected rapid cooling of its interior. This requires a revision of existing models of the Moon's thermal evolution and the investigation of alternative mechanisms of heat retention or localized melting.

***KREEP distribution***. The mechanism of concentration of KREEP material, which is the source of increased heat flux and prolonged volcanism, especially in the Oceanus Procellarum region, is still not fully understood. Further study of this phenomenon is critical for understanding regional anomalies in lunar volcanism.

***Global heat flux***. Additional, geographically distributed heat flux measurements are needed to better determine the average value of the Moon's heat flux and its variations. This will help to refine models of the Moon's internal composition and thermal structure.

***Detailing crustal and mantle thickness***. The three-layered model of the lunar crust and the lateral variations of mantle seismic velocities related to its thermal state require further refinement.

***Future missions***. New lunar missions [10, 12, 14, 16], especially those that return samples from young volcanic regions such as irregular marine patches (IMPs) or other areas discovered by Chang'e-5, could provide crucial data to address these questions. These missions would provide "ground truth" and further direct evidence that could completely change our understanding of the late volcanic history of the Moon.

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