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4. The influence of volcanism on the surface formation and current geological state of the Moon

Introduction

The Moon, Earth’s closest neighbor, has long been considered a geologically inactive world, its surface shaped solely by billions of years of meteorite bombardment. Historically, the first evidence for volcanism came from telescope observations that revealed dark patches of maria.

Today, ground-based radar is used to study surface texture and search for pyroclastic deposits [2]. However, since the Apollo era, it has become clear that volcanism [32, 33, 35, 36] has been one of the dominant processes that shaped the lunar landscape for much of its history. The dark patches visible to the naked eye from Earth, once called “maria”, are actually vast, frozen flows of basaltic lava [17]. Understanding these processes is key to reconstructing the thermal and geological evolution of the Moon.

About 4.5 billion years ago, a giant collision between the proto-Earth and a Mars-sized object known as Theia threw a huge amount of debris into orbit, from which the Moon formed. Initially, the Moon was a molten ball that gradually cooled. This initial “magma ocean” gradually differentiated; heavier minerals, such as olivine and pyroxene, sank to form the mantle, while lighter minerals, such as plagioclase anorthosite, rose to the surface, crystallized, and formed the primary, relatively light lunar crust.

Along with impact cratering, volcanism also played a key role in shaping the modern appearance of the lunar surface [31, 38].

The most significant contribution of volcanism was the formation of the lunar seas, which cover a significant part of the visible hemisphere. The filling of giant impact basins with basaltic lava flows [7] created the Moon's characteristic two-faced appearance – light, old continents and dark, younger seas (Fig. 4.1).

Fig. 4.1. Mare Imbrium is a flat surface covered with basaltic lava; it shows secondary craters, rays, and material ejected from the nearly 100 km diameter Copernicus impact crater located above; this crater formed after the lava in Mare Imbrium had already solidified; the large crater left of center is Pytheus (https://upload.wikimedia.org/wikipedia/commons/3/3a/Mare_Imbrium-AS17-M-2444.jpg).

Volcanic flows not only filled the basins, but also flooded and destroyed smaller craters on and around their bottoms. This led to a smoothing of the relief, the formation of "ghost craters" and a change in the albedo of the surface. Volcanic activity [42-44] led to the deposition of huge volumes of basalts on the surface, as well as localized pyroclastic materials (glass beads, ash) [24]. These materials have a different chemical composition and physical properties from the continental crust [47-49]. Impact cratering was the dominant process in the early stages of the Moon's history, creating the primary relief of the continents and giant basins (Fig. 4.2). It continues to this day, although with less intensity, creating new craters and shaping the regolith.

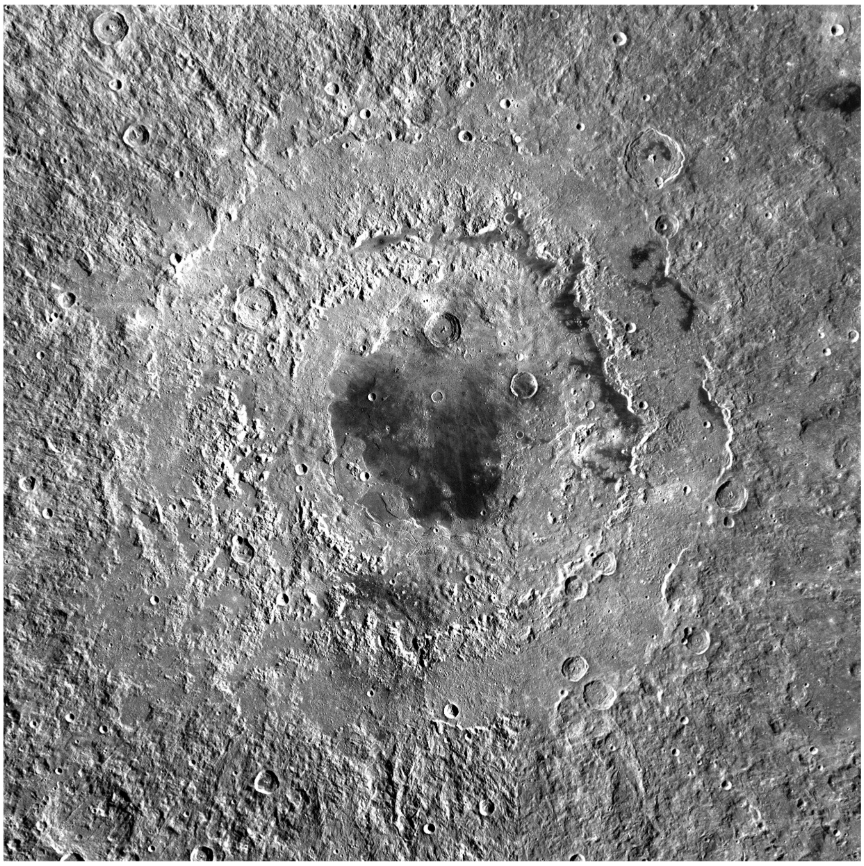

Fig. 4.2. Mare Orientale is the youngest of the large lunar basins, formed 3.8 billion years ago; its outer ring has a diameter of up to 1000 km; unlike most basins, it was not completely filled with lava (https://upload.wikimedia.org/wikipedia/commons/3/32/Mare_Orientale_%28LRO%29.png).

Volcanism on the Moon was most active during the first 1.5–2 billion years of the satellite's existence. It did not create new large landforms similar to impact craters; however, volcanic activity significantly modified existing features of the relief, filling lowlands with lava and creating characteristic volcanic structures (seas, domes, furrows, pyroclastic deposits).

In the early stages, these two processes acted synergistically: impacts created basins and faults, which facilitated the outflow of magma, and volcanism, in turn, covered the traces of impacts in the lowlands, forming seas. Without volcanism, the visible side of the Moon would resemble a completely cratered far side.

4.1. Historical surface landform changes and major manifestations of volcanism

The history of the Moon is divided into five generally recognized geological periods (Table 4.1), reflecting the evolution of its volcanic activity and landform formation.

Table 4.1.

Lunar geological time scale and associated volcanic activity.

Period/ Epoch Approxi-mate	**Age (billion years ago)**	**Key Events**	**Volcanic Characteristics and Effects on Landforms**
Pre-Nectarian	4.5 – 3.92	Formation of the lunar crust (~4.42 Ga), formation of 30 impact basins (e.g., South Pole-Aitken)	Early crustal differentiation; no significant marine basalts. Impact cratering dominates the landscape
Nectarian	3.92 – 3.85	Formation of 12 multi-ringed impact basins (e.g., Serenitatis, Crisium)	Early marine volcanism begins, but less extensive than in the Imbrian. The terrain is still heavily cratered, but the first signs of basin filling appear
Early Imbrian	3.85 – 3.80	Formation of the Imbrium and Orientale basins	Beginning of intense marine volcanism, filling of large basins. Formation of extensive dark plains, changing the global appearance of the Moon
Late Imbrian	3.80 – 3.2	Completion of large basin formation	Completion of large basin formation Peak of marine volcanism (3.8-3.2 Ga), formation of most visible seas. The relief is characterized by large, relatively smooth basaltic plains with ridges and wrinkled ridges
Eratosthe-nian	3.2 – 1.1	Craters almost completely destroyed by erosion (impact cratering)	Significantly fewer basaltic eruptions; activity possible until 1.2 Ga. Topography becomes more stable, but modification by impact cratering continues
Coperni-can	1.1 – Present	Presence of bright ray systems around craters	Very rare, small-scale volcanic events; activity possible up to 50-120 Ma. Topography predominantly formed by impact cratering, with very limited new volcanic formations (e.g., IMPs)

Early Moon (Pre-Nectarian–Imbrian periods). In its early stages, the Moon was a molten world that cooled over hundreds of millions of years, forming a crust and mantle. This period was characterized by intense bombardment, resulting in the formation of numerous large impact basins. These basins created significant topographic depressions that later became sites for extensive marine volcanism. The maximum volumetric output of marine volcanism occurred between 3.8 and 3.2 billion years ago, when low-viscosity basaltic lava filled these basins, forming the dark lunar seas that we see today. This led to a radical change in the relief, creating a contrast between light, heavily cratered highlands and dark, relatively smooth plains.

Late Moon (Eratosthenian–Copernican periods). After the peak of Imbrian volcanism, the volume of eruptions decreased significantly. The Moon's topography became more stable, and its subsequent modification was mainly due to impact cratering. However, more recent evidence suggests that volcanism did not cease abruptly, but gradually slowed down. The discovery of young basalts (2.03 billion years old) and potentially young glass beads (120 million years old) suggests that small-scale volcanic events continued to affect the topography even in relatively recent geological time, albeit on a limited scale, for example, forming irregular marine patches. These events, although not as large-scale as the formation of seas, nevertheless indicate the Moon's continued thermal activity and its capacity for local magma release.

Thus, the Moon's landscape was not always static. Its evolution, driven by volcanism, went through several key stages. The so-called *Marian volcanism* is the largest manifestation of lunar volcanism to date. After the formation of giant impact basins (e.g. Mare Imbrium, Mare Serenitatis, Mare Tranquillitatis), they were gradually filled over hundreds of millions of years by numerous flows of very liquid basaltic lava. These hot flows spread over vast areas, creating fairly smooth, dark plains. Their surface is not perfectly smooth; individual lava flows and lava channels can be distinguished on it.

Characteristic features of this type of volcanism are the so-called *Wrinkle Ridges*. These are long, winding folds on the surface of the seas, formed as a result of the compression of lava flows during their gradual cooling and subsidence. There are also *Rilles*. They are peculiar channels formed as a result of lava flows [5]. There are sinuous rilles, which are the remains of lava rivers (Fig. 2.3) or collapsed lava tubes (for example, the Hadley rille explored by "Apollo 15"), and *grabens*, which are straight grooves formed by crustal stretching (Fig. 2.1). After the outer part of the lava flow solidified, and the inner part continued to flow through peculiar underground tunnels, after the depletion of these flows, the so-called Lava Tubes remained. A striking example is *Vallis Schroteri* (Fig. 4.3). Today they are considered as potential sites for future lunar bases. In addition to seas, volcanism also manifested itself on a smaller scale in the form of ***Isolated volcanic structures***. These include the so-called *Lunar Domes* and *shield volcanoes*. Gentle shield volcanoes were formed as a result of the slow eruption of more viscous lava than that which formed the seas.

Рис. 4.3. Schröter's Valley (3.6BYr) is one of the most unusual geological structures on the Moon, marked by ancient volcanism and a much younger impact crater (Aristarchus, 500MYr). The area shown here is roughly 200 km across, and the smallest visible craters are ~1 km in diameter (https://dq0hsqwjhea1.cloudfront.net/aristarchuscolor2-1000x576.jpg).

Unlike Earth's conical stratovolcanoes, lunar volcanoes are low and broad structures formed by the eruption of very liquid lava. They are often hundreds of kilometers in diameter but only a few kilometers high. An example is the *Marius Hills*.

Evidence of past explosive eruptions is *pyroclastic deposits*. While most eruptions were quiet, some were more energetic, producing "fountains" of lava. At times when the magma contained a large number of volatile gases, it erupted to the surface in fountains, spraying small droplets of molten material. These droplets solidified as glassy globules, forming dark halos around some craters or covering large areas (e.g., Aristarchus Plateau, Fig. 4.4). These deposits are a valuable source of information about the composition of the lunar mantle.

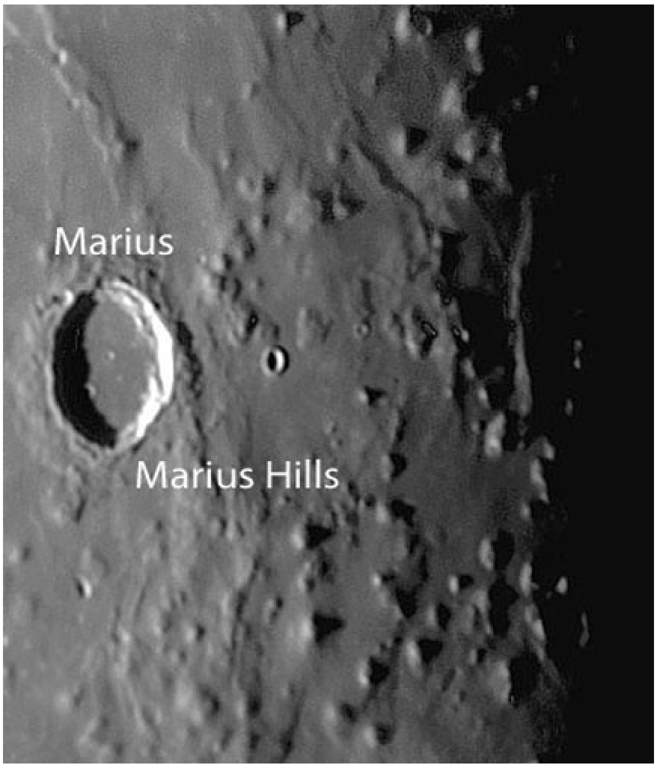

Fig. 4.4. Marius Hills is a wide field near Marius Crater with many domes between 200 and 500 m high. Marius Hills is a wide field near Marius Crater with many domes between 200 and 500 m high (https://skyandtelescope.org/wp-content/uploads/Domes-Marius-wide-Jim-Phillips_edited-1.jpg).

Volcanism not only created new landforms, but also changed the chemical composition of the surface. Lava flows brought rocks rich in iron, titanium, and magnesium to the surface, which gives the seas their dark color compared to the lighter, aluminum-rich lunar highlands.

4.2. Obtaining data on lunar volcanism and the chronology of volcanic activity

Understanding lunar volcanism is based on a combination of direct and remote sensing methods.

Sample return missions. The “*Apollo*” and “*Luna*” mission programs returned samples of lunar rocks and soil from known geological contexts to Earth. These samples, which include marine basalts and pyroclastic materials, provided direct information on the mineralogy [40, 41], chemical composition, and age of lunar volcanic rocks [10]. They have allowed the geological chronology of the Moon to be established and dating methods applied to other planetary surfaces to be calibrated.

The recent *Chinese mission “Chang'e-5”* returned samples of lunar volcanic rocks that were dated to 2.03 billion years ago, the youngest samples ever obtained from the Moon. This discovery significantly extends the known duration of lunar volcanism.

Remote Sensing from Orbiters. Modern orbiters [14, 20, 37, 52], such as NASA's Lunar Reconnaissance Orbiter (LRO), Clementine, and Kaguya/SELENE, have provided high-resolution images, topographic data, and spectral measurements of the lunar surface [13, 15, 16, 51].

Surface imaging and topography allow the identification and mapping of volcanic landforms, such as seas, ridges, domes, cones, and irregular sea patches.

Spectral analysis with instruments such as the *Moon Mineralogy Mapper* (M3) on board Chandrayaan-1 allows the determination of the mineralogical and chemical composition of surface materials, including pyroclastic deposits and basalts [3].

Early *telescopic observations*, such as those made by Galileo Galilei in 1610, allowed the first distinction between dark lunar plains (seas) and lighter highlands. As a result of this set of observational data, it was obtained that the bulk of the lunar seas formed during the so-called *Peak of Volcanic Activity* (3.8–3.0 billion years ago). Volcanism was then global and extremely intense. In the period 3.0–1.0 billion years ago, the Volcanic Extinction occurred. In those years, volcanic activity gradually decreased, and eruptions became more localized. The Moon was then cooling, and its lithosphere thickened, making it difficult for magma to rise. Our knowledge of lunar volcanism is based on a synthesis of data from various sources.

First of all, these are data obtained from the analysis of lunar samples obtained by the “Apollo” missions (USA, 1969-1972) and the “Luna” automatic stations (USSR, 1970-1976). These missions delivered to Earth more than 382 kg of lunar soil (regolith) and rocks from several different landing sites; mainly from lunar seas. Laboratory analysis of these samples made it possible to determine the exact chemical composition of the basalts, which confirmed their volcanic origin. And isotopic dating (for example, by the uranium-lead or potassium-argon methods) made it possible to establish the absolute age of the lava flows. Analysis of these samples has made it possible to accurately date periods of volcanic activity, determine the chemical and mineralogical composition of basalts, and confirm the theory of the existence of a magma ocean [12]. For example, for samples from the seas, their age is 3.3–3.8 billion years.

Modern orbital vehicles, in particular the “Lunar Reconnaissance Orbiter” (LRO), as well as the “Clementine”, “Lunar Prospector”, “Chandrayaan-1” (India), and “Kaguya” (Japan) missions, have conducted remote sensing of the surface from orbit. High-resolution imaging (LROC) has made it possible to map volcanic landforms in detail, distinguish individual lava flows, and find young formations such as Ina (Fig. 3.7). These missions have radically changed our understanding of the global distribution of volcanism.

Laser altimetry has made it possible to create accurate topographic maps that allow us to measure the volumes of lava flows and the height of volcanic domes. NASA's “*Lunar Reconnaissance Orbiter*”, launched in 2009, has produced the most detailed maps and images of the Moon's surface to date. Its instruments, such as the LOLA laser altimeter and the LROC camera, have identified thousands of previously unknown volcanic features, including small shield volcanoes and lava flows.

Spectrometry with the Diviner and M^3 instruments has been used to analyze the light reflected from the surface. This has allowed the mineral composition of the surface components to be determined. This has revealed differences in the composition of basalts and has found pyroclastic deposits rich in olivine and glass.

Gravimetry conducted in 2011-2012 by the “GRAIL” (*Gravity Recovery and Interior Laboratory*) mission equipment allowed us to create maps of the Moon's gravitational field, which revealed so-called mascons, i.e. mass concentrations associated with the uplift of dense mantle material and the thickness of basalts, as well as lava-filled cracks and "pockets" that fed ancient volcanoes, under the seas. The crater counting method is used to determine the relative age of surfaces. After all, the older the surface, the more meteorite craters it has accumulated. By calibrating the number of craters with the absolute age determined from the Apollo missions, it is possible to estimate the age of any area on the Moon. This is how the young age of the so-called irregular marine areas was determined.

For a long time, it was believed that volcanism ceased about 1 billion years ago. However, data from LRO have revealed the existence of ***irregular mare patches***, such as *Ina* (Fig. 3.7). These are small geological formations with very few meteorite craters. This indicates that they are extremely young; perhaps only a few tens of millions of years old. This suggests that the interior of the Moon may have remained warm for much longer than previously thought, and residual volcanic activity may have continued almost to the present day on a geological scale. That is, there was also so-called *recent volcanism (less than 50-100 million years ago*).

The main processes that change the relief today are meteorite bombardment; that is, the constant fall of micrometeorites and larger bodies creates new craters and mixes the upper layer of soil (regolith). Extreme temperature fluctuations between lunar day (+120°C) and night (-170°C) also cause thermal expansion and contraction of rocks, which leads to their slow destruction. Today, there is no active volcanism on the Moon. The surface is mainly modified by micrometeorite bombardments, solar wind, and sudden temperature changes. However, the discovery of young volcanism has forced scientists to reconsider models of the Moon's thermal evolution.

4.3. Current geological state of the Moon

Unlike the Earth, the Moon is today considered a geologically inactive body, especially in terms of volcanism and tectonics.

Geological inactivity. Large-scale volcanic activity on the Moon ceased billions or, at least, hundreds of millions of years ago. Its interior has cooled significantly, the lithosphere has become thick and rigid, which prevents the rise of magma and significant tectonic movements.

Residual processes. Despite the general lack of activity, some geological processes are still observed on the Moon:

Moonquakes. Seismometers installed by the Apollo missions recorded seismic activity. Deep moonquakes (~700-1000 km depth) are the most frequent and correlate with the Earth's tidal forces. Shallow moonquakes (<100 km depth) are less frequent but can be stronger; their origin is attributed to the accumulation of stress in the cold and brittle lithosphere, possibly due to the continued cooling and compression of the Moon or local tectonic processes. Thermal moonquakes, caused by sharp diurnal temperature changes on the surface, are also recorded.

Outgassing. *Transient Lunar Phenomena* (TLP) are short-term local changes in brightness or color on the lunar surface. Although their nature is not fully understood, some of them may be associated with the release of gases (such as radon, argon, and possibly volcanic gases) from the lunar interior through faults, cracks in crater floors, at the edges of lunar seas, or other locations that geologists associate with volcanic activity. These processes may be stimulated by tidal forces or meteoroid impacts. The hypothesis of gas release is supported by data obtained by the alpha particle spectrometer of the "Lunar Prospector" spacecraft, which recently managed to record the release of radon on the surface [11]. In particular, the results show that radon gas was released from the vicinity of the Aristarchus and Kepler craters during this two-year mission. These observations could be explained by slow and visually imperceptible diffusion of gas to the surface or by discrete explosive events. In support of explosive gas release, it has been proposed that a region of the lunar surface approximately 3 km in diameter was "recently" altered by a gas ejection event [19]. This object is thought to be about 1 million years old, suggesting that such large events are rare.

Possible ongoing compression. Analysis of young tectonic features, such as small *lobate scarps*, detected by LRO, suggests that the Moon may have been undergoing global compression relatively recently and that this process may still be ongoing at a very slow rate, as a result of the long-term cooling of its interior. Although the Moon does not have active volcanoes in the terrestrial sense, the presence of residual processes, such as moonquakes and gas emissions, suggests that it is not a completely "dead" body. These phenomena indicate ongoing slow cooling and some internal dynamics.

Volcanism is the second most dominant process that has modified the lunar crust, second only to impact cratering. Due to the absence of plate tectonics on the Moon, most of this modification has been preserved, allowing its geological history to be studied in high detail.2

4.4. Morphological features associated with volcanism

Formation of lunar mare and highlands. The most obvious and significant effect of volcanism on the lunar surface is the formation of lunar mare, which are large, dark, basaltic plains. These mares cover over 15% of the lunar surface, mostly on the near side, and appear as dark topographic features visible to the naked eye from Earth.

Lunar mare formed by eruptions of low-viscosity basaltic lava that filled large impact basins and craters. The lava flows are hundreds of meters thick and are similar to basaltic lava flows on Earth. The energy source for their formation is radiogenic heating in the primordial lunar interior [53].

Lunar basalts differ from terrestrial basalts in their higher iron content and lower silicon and aluminum content, which made the lava very fluid and allowed it to form thin, widely distributed flows. Analysis of samples returned by the “Apollo” and “Luna” missions has allowed the classification of marine basalts by TiO_2, Al_2O_3, and K content, which has provided information about the composition of the lunar mantle and the processes of differentiation.

The formation of the seas has created a sharp contrast with the *lunar uplands (terra)*, which are lighter, heavily cratered, and composed primarily of anorthosites, rocks formed by the flotation of plagioclase in the lunar magma ocean [4]. This dichotomy of the surface is a direct result of the early differentiation of the Moon and the subsequent extensive basaltic volcanism that filled the low-lying basins.

In addition to the vast lava plains, volcanism has created a *variety of smaller* *morphological feature*s that shape the Moon's modern topography:

Lava pipes are tunnels formed when the outer part of a lava flow cools, allowing the inner lava to continue flowing.1 Their presence indicates efficient lava transport beneath the surface.

Rilles are channel-like structures formed by lava flows.1 They can be straight, arcuate, or sinuous (sinusoidal), reflecting different lava flow mechanisms and subsurface processes.

Wrinkle ridges are tectonic features that form in areas of compression, often in the center of basins, where the surface bends around features beneath the lava, such as old impact craters.1 They are evidence of basin subsidence under the weight of accumulated lava flows.

Lunar domes and cones are small volcanic features, typically composed of basalt. Due to the Moon's low gravity (one-sixth that of Earth), eruptions can eject material much farther, forming broad, thin layers around the vent, rather than steep cones like on Earth.1 Examples include the Marius Hills and Mons Rümker, which are large volcanic complexes.1

Lunar pyroclastic deposits (DMDs) are low-albedo areas composed of fine-grained material formed by explosive volcanic eruptions. These deposits are often associated with sinusoidal ridges and irregular depressions. Pyroclastic glasses are the deepest and most primitive basalts on the Moon, originating directly from the lunar mantle. The discovery of water [22, 39] in this glass suggests that the lunar interior is much richer in volatiles than previously thought.

Irregular Mare Patches (IMPs) are mysterious volcanic features whose lack of craters and distinct appearance suggest that they formed less than 100 million years ago. The most famous example is Ina, a small structure photographed by Apollo 15 in 1971, whose origin is still debated. Their young morphology challenges long-held beliefs about the rapid cooling of the Moon.

The Moon has no active volcanoes today. However, evidence of past volcanic activity (such as caves [6], plains, and domes formed by cooled lava) is widespread. It was long thought that lunar volcanism ceased about 1 billion years ago. However, more recent evidence suggests that small-scale volcanism may have occurred over the past 50 million years.

Volcanic rocks returned by the Chinese “Chang'e-5” mission were dated to 2.03 billion years ago, making them the youngest basaltic samples ever recovered from the Moon. This discovery significantly extended the known duration of lunar volcanism by about 800–900 million years.

Among the thousands of glass beads in the Chang'e-5 soil samples, three were identified as volcanic and were only 120 million years old, although this discovery still needs to be verified.

This extension of the known duration of lunar volcanism has profound implications for understanding the *thermal evolution of the Moon*. It suggests that the Moon may not have cooled as rapidly as previously thought, and its interior may have remained warm enough to form magma even in relatively recent geological time. A possible explanation for the younger volcanism [21] could be the presence of radioactive elements underground that could generate enough heat to form magma.

4.5. Scientific evidence supporting the inferences about changes on the lunar surface

Inferences about the evolution and changes of volcanic features on the Moon [50] are based on several complementary scientific methods.

Radiometric dating. Radiometric dating is based on the principle of radioactive decay, where an unstable "parent" nuclide decays to a stable "daughter" nuclide at a known rate (half-life). The more daughter nuclide there is relative to the parent, the more time has passed since the decay clock was "started".

This method has been applied to a variety of volcanic materials. Samples returned by the “Apollo” and “Luna” missions, as well as lunar meteorites, have allowed the geological chronology of the Moon to be established. Radiometric dating of lunar sea samples has yielded an age range of 3.16 to 4.2 billion years [8]. The youngest crystallization age recorded for lunar basalts by radiometric dating is 2.03 billion years old, based on samples returned by the “Chang'e-5” mission. This discovery is critically important because it expands our understanding of the thermal evolution of the Moon.

Crater Counting. Crater counting is a method of estimating the age of a planet's surface based on the assumption that the new surface is free of impact craters and that craters then accumulate at a known rate. Counting the number of craters of different sizes in a given area allows us to determine how long they have been accumulating and, therefore, how long ago the surface formed. This method has been calibrated using radiometric dating of samples returned from the Moon by the Luna and Apollo missions. It allows us to determine relative ages (for example, heavily cratered lunar hills are older than dark lava plains). Crater counts on the Moon have shown a young age of about 1.2 billion years for some marine sediments.

Despite its value, crater counting has limitations and uncertainties, especially for very young surfaces and small craters. Factors that affect accuracy include incomplete knowledge of impact velocity, the influence of secondary craters (formed by ejecta from primary impacts), the properties of the target material, and the modification of craters after formation (erosion, deposition).

Geological mapping and stratigraphy. Geological mapping of the Moon, based on principles of stratigraphy (such as the law of superposition), allows for the ordering of geological events in time. The identification of impact basins [23, 43] such as Nectaris and Imbrium as stratigraphic markers has allowed for the creation of a relative chronology of lunar events. Modern geological maps of the Moon synthesize data from Apollo-era missions and more recent satellite missions.

Compositional analysis. Analysis of the chemical and mineralogical composition of lunar samples (marine basalts, pyroclastic glass) and remote sensing data (spectral measurements) [20, 28, 32] provides critical information about magma sources, mantle melting processes, the degree of lunar differentiation, and the presence of volatiles [1]. For example, the discovery of water in lunar pyroclastic glasses has changed the understanding of the volatile content of the lunar interior.

Conclusions

The Moon, Earth's closest neighbor, is a unique celestial body with a rich and complex geological history. Its general characteristics, such as its smaller size, mass, and density compared to Earth, as well as the lack of a dense atmosphere and a strong global magnetic field [29], have determined its specific evolutionary path. The differentiated internal structure, which includes an anorthosite crust, a silicate mantle, and a small iron core (with a solid interior and a liquid exterior), is evidence of early global melting and crystallization of a magma ocean.

Although major volcanic activity ceased billions of years ago due to the gradual cooling of the interior, recent studies indicate the possibility of much younger, albeit smaller, eruptions that lasted up to 2 billion years ago, and possibly much later. The Moon is currently considered geologically inactive in terms of volcanism, but residual processes such as moonquakes and outgassing indicate ongoing slow cooling and some internal dynamics.

That is, volcanism has played a central role in shaping the Moon's surface and its present [9] geological state. From vast basaltic seas [21] that formed billions of years ago to irregular seamounts and young volcanic samples, the Moon preserves a rich record of magmatic activity. These features not only created the distinctive landforms we see today but have also provided invaluable information about the Moon's internal structure [34, 46] and thermal evolution.

Data from sample-return missions (“Apollo”, “Luna”, “Chang'e-5”) and advanced remote sensing have not only identified and classified volcanic features, but also accurately dated them, revealing a dynamic history that extends far beyond what was previously thought. A combination of radiometric dating, crater counting, and geological mapping underpins these conclusions, providing both absolute and relative chronological frameworks.

For example, the outlines of Tycho are quite steep and sharp because this lunar crater, about 82 km in diameter, is only about 110 million years old (Fig. 4.5); it is one of the youngest of the very large lunar craters; its central peak rises 12 km above the crater floor. Over time, meteorite bombardment will grind and flatten these steep slopes, transforming them into smooth mountains.

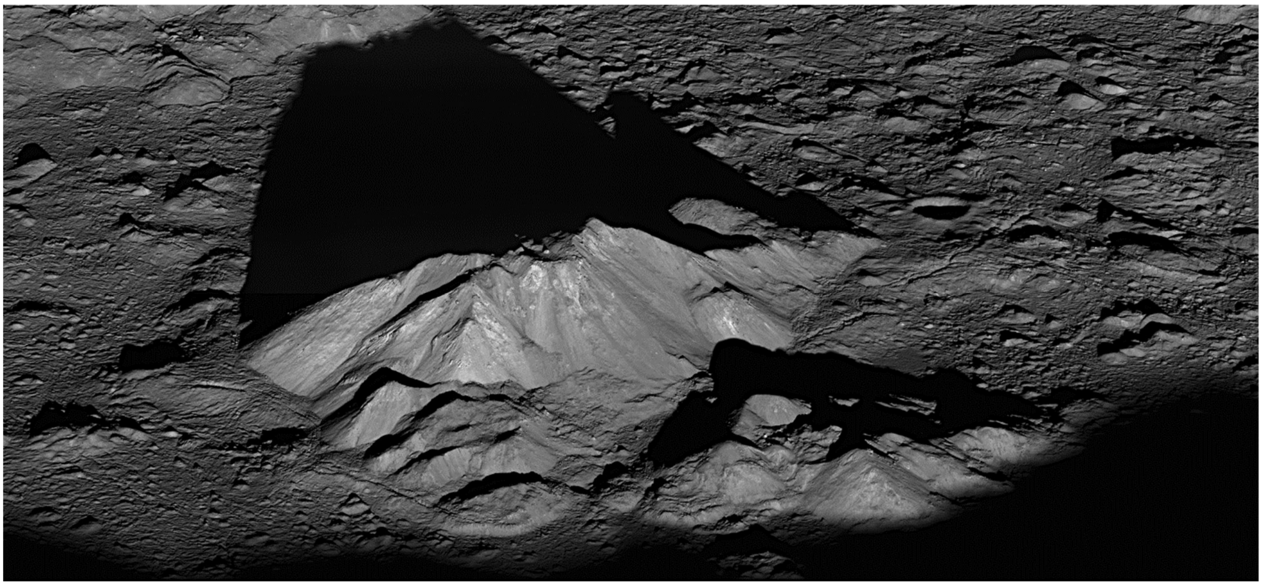

Fig. 4.5. The central peak of Tycho Crater in the image is about 15 km wide (left to right in this image) (https://lroc.im-ldi.com/news/uploads/M162350671LE.small2.png).

Compositional analysis of samples and spectral data further reveal the chemical evolution of the lunar interior. Despite significant progress, fundamental questions remain, including the mechanisms that supported late lunar volcanism and the asymmetry between the near and far sides of the Moon. Future missions and further data analysis promise to unravel these and other mysteries, deepening our understanding of volcanic processes throughout the Solar System.

That is, the study of the Moon remains extremely important for planetary science. Its well-preserved surface serves as a unique archive of the early history of the Solar System, and the study of its internal structure and volcanic evolution helps to better understand the processes of formation and development of the terrestrial planets, including our own planet.

Thus, volcanism was a fundamental process that not only created the lunar seas, but also significantly influenced the thermal and chemical evolution of the Moon. The data obtained through the combination of analysis of the delivered samples and remote sensing have allowed us to reconstruct the history of volcanic activity from its turbulent peak to almost complete extinction. The discovery of geologically young volcanic formations forces us to reconsider the idea of the Moon as a completely "dead" body and raises new questions about its internal structure and long-term evolution.

Future missions, such as the Artemis program, which plan to deliver samples from new, previously unexplored regions (for example, from pyroclastic deposits or from young lava flows), promise to reveal even more deeply the secrets of our satellite's fiery past.

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