International Science Group
ISG-KONF.COM

FEATURES OF VOLCANIC ACTIVITY ON THE MOON

VIDMACHENKO A. P., KUZNYETSOVA J. G., OVSAK O. S.

ISBN 979-8-90214-588-2
DOI 10.46299/979-8-90214-588-2

Vidmachenko A. P., Kuznyetsova J. G., Ovsak O. S.

FEATURES OF VOLCANIC ACTIVITY ON THE MOON

Monograph

2026

UDC 523.3

Authors:

Vidmachenko A. P., Kuznyetsova J. G., Ovsak O. S.

Editor:

Vidmachenko Anatoliy Petrovych, Doctor Phys.-Math. Sci., Professor, Professor of Department of Physics. National University of Life and Environmental Sciences of Ukraine, Kyiv, Ukraine. ORCID 0000-0002-0523-5234

Reviewers:

Grudynin B.O. - Doctor of Pedagogical Sciences, Associate Professor of the National University of Life Resources and Environmental Management of Ukraine. ORCID 0000-0001-8084-653X

Mozghovyi O.V. - Candidate of Technical Sciences, Associate Professor of the Vinnytsia State Pedagogical University named after M. Kotsiubynskyi. ORCID 0000-0002-0797-8779

Vidmachenko A. P., Kuznyetsova J. G., Ovsak O. S. Features of volcanic activity on the Moon. Monograph. – Primedia eLaunch, Boston, USA, 2026 – 153 p.

Library of Congress Cataloging-in-Publication Data

ISBN – 979-8-90214-588-2
DOI – 10.46299/979-8-90214-588-2

UDC 523.3

ISBN – 979-8-90214-588-2

ABSTRACT

The Moon is the closest large celestial body to us and one of the most studied objects in the Solar System. Due to the absence of plate tectonics, atmosphere and biosphere, the Moon's surface has preserved traces of intense meteorite bombardment and large-scale volcanism. The study of the Moon, starting from its general physical parameters and ending with the details of its internal structure and volcanic evolution, allows us to reconstruct its own history and shed light on the early stages of the development of the Earth and other planets. The average radius of the Moon is 1737.1 km. The Moon has a very low reflectivity with an albedo of about 0.11. The Moon's surface experiences temperature fluctuations from +130 °C during the day to -170 °C at night. It revolves around the Earth in an elliptical orbit for 27.32 Earth days at an average distance of 384,400 km. Due to tidal capture, the Moon always faces the Earth with the same hemisphere. Current models of the Moon's interior are based on data from "Apollo" seismic experiments, measurements of the Moon's gravity field and laser ranging, and analyses of lunar samples returned by the "Apollo" missions and lunar stations. The Moon's differentiated structure, with its distinct crust, mantle, and core, is the result of the fractional crystallization of a global magma ocean that existed shortly after its formation. This process caused heavier minerals (olivine and pyroxene) to sink to the center, forming the mantle, and lighter minerals (plagioclase and silica-rich crystals) to rise to the surface, forming the crust. This in turn led to the formation of a dense metallic core that is rich in iron, some nickel, and traces of sulfur. The inner core, with a diameter of ~480 km, is solid, while the outer core is liquid, increasing the total diameter of the core to ~660 km. Above the core is the mantle, with a thickness of approximately 1338 km, and the lunar crust. They formed when the magma ocean began to cool, and crystals sank and rose to the surface. The lunar crust is predominantly anorthosite in composition. Dark areas, known as lunar seas, are filled with solidified basalt, which is the result of past volcanic activity. According to geophysical data, the lunar crust has an average thickness of ~60 km on the near side and ~100 km on the far side. The upper part of the lunar crust is 35–40 km thick and is

less dense. The presence of a partially molten layer in the lower mantle serves as a physical mechanism for the generation of magma at depth. Its uplift caused the eruption of marine basalts onto the lunar surface, especially where the crust is thinner. Studies show that enrichment with radioactive elements can keep the upper mantle hotter, even billions of years after the Moon's formation. The surface of the Moon is characterized by two main types of terrain, which contrast sharply in color, height, and age: light, high-altitude, composed mainly of anorthosite rocks rich in aluminum and calcium, the continents (Terrae), and dark lowlands - Maria. The lunar continents are old, heavily cratered highlands; they occupy up to 83% of the entire surface of the Moon and are mostly located on the far side. The lunar Maria are large, dark, relatively flat lowlands; they occupy about 17% of the surface, mostly on the visible side. The evolution of the lunar relief is related to its geological history, which is divided into several geological epochs: the Pre-Nectarian period (up to 3.92 billion years ago), when a magma ocean existed and intensive accretion of material and formation of the primary crust occurred; the Nectarian period (3.92–3.85 billion years ago) was a period of intensive bombardment, during which most of the large impact basins were formed; the Imbrian period (3.85–3.2 billion years ago) is a period when, after the late intensive bombardment, a period of massive eruptions of basaltic lavas began, which filled the low-lying impact basins, forming dark seas; during the Eratosthenian period (3.2–1.1 billion years ago), volcanic activity decreased significantly, and during the Copernican period (1.1 billion years ago–today) the intensity of meteorite impacts also decreased. Therefore, during rare impact events, craters formed during this period are relatively “fresh”, with bright ray systems.

The Moon was dominated by low-viscosity effusive eruptions, which led to the formation of vast marine plains. However, explosive eruptions also occurred, which produced pyroclastic deposits. The low gravity and lack of an atmosphere contributed to the dispersion of pyroclastic material over long distances. In addition to the seas, volcanism also created a variety of smaller morphological features that shape the Moon's modern terrain. These include lava tubes, which are tunnels formed by the cooling of the outer part of a lava flow; furrows (rilles) are channel-like structures formed by lava flows; wrinkle ridges are tectonic features that form in areas of compression, often in the center of basins, where the surface bends around features under the lava, such as old impact craters; lunar domes and cones are small volcanic formations, usually composed of basalt; lunar pyroclastic deposits are low-albedo areas composed of fine-grained material formed by explosive volcanic eruptions; irregular mare patches are volcanic features whose absence of craters and clear appearance indicate that they formed less than 100 million years ago. That is, volcanism played a central role in shaping the Moon's surface and its current geological state.

Volcanism in the Solar System is divided into two main types: silicate and cryovolcanism. Silicate volcanism involves the eruption of molten silicate rock, which is the predominant type of volcanism on rocky bodies such as Earth, the Moon, Mars, and Venus. Mafic (magnesium- and iron-rich) lavas, typically basaltic, are common and tend to create broad, gently sloping shield volcanoes and large lava plains. In contrast, cryovolcanism involves the extrusion of liquids and vapors composed of volatile compounds such as water, ammonia, and methane. These substances are frozen on the surfaces of icy bodies in the outer Solar System but may exist there in liquid or slushy form beneath the surface. The Moon therefore plays a unique and invaluable role in understanding the early history of the Solar System.

TABLE OF CONTENTS

DOI: 10.46299/979-8-90214-588-2.1

1. General characteristics of the Moon and features of its internal structure

Introduction

The Moon, Earth's only natural satellite. It is the closest large celestial body to us and one of the most studied objects in the Solar System. Its proximity and lack of a dense atmosphere make it a unique natural laboratory for studying the processes that shaped the terrestrial planets [17] billion years ago. Unlike the geologically active Earth, where plate tectonics [25], erosion, and the biosphere [4, 8] are constantly changing the landscape, the Moon's surface has preserved evidence of its turbulent youth, including traces of intense meteorite bombardment [22] and large-scale volcanism. Studying the Moon, from its general physical parameters to the details of its internal structure and volcanic evolution, allows us not only to reconstruct its own history, but also to shed light on the early stages of the development of the Earth and other planets. Let us dwell on a detailed overview of current knowledge about the Moon, covering its astronomical and physical characteristics, a model of its internal structure, major landforms, evidence, and features of past volcanic activity, its influence on the formation of the lunar surface, and the current geological state of the satellite.

1.1. General characteristics of the Moon

The Moon differs significantly from the Earth in its physical and orbital parameters, which determines its unique properties and appearance.

Astronomical and physical parameters. The Moon has an average radius of 1737.1 km, which is about 27% of the Earth's radius. Its diameter (about 3475 km) is about four times smaller than that of the Earth. [17] The Moon's total surface area is about 38 million square kilometers. Although the Moon is much smaller than the Earth, it is an unusually large satellite relative to the size of its parent planet. This ratio (about 1/4 the diameter) is much larger than that of most other satellite systems in the Solar System, resulting in strong gravitational interactions between the Earth and the Moon. The Moon's mass is estimated to be 7.3477×10^{22} kg, which is only about 1.2% (or 1/81) of the Earth's mass.

The Moon's average density is 3.346 g/cm³, which is much less than the average density of the Earth (about 5.51 g/cm³). This relatively low density indicates a lower iron content and a smaller metallic core compared to Earth. This fact is one of the key arguments in favor of the giant impact theory, according to which the Moon formed mainly from lighter, mantle materials of the proto-Earth and the impactor, while the heavy iron core of the impactor was mostly incorporated into the Earth's core [18].

The acceleration of gravity on the Moon's surface is about 1.62 m/s², which is about six times less than on Earth. This means that objects on the Moon weigh six times less. The second cosmic velocity (the speed required to overcome gravitational attraction) is 2.38 km/s. Low gravity significantly affects geological processes on the satellite: emissions from meteorite impacts are scattered over much greater distances, and volcanic structures have a different morphology. Also, weak gravity is unable to maintain a dense atmosphere.

The Moon has a very low reflectivity. Its Bond albedo is about 0.11, and its geometric albedo is about 0.12. This means that the lunar surface reflects only 11–12% of the sunlight that falls on it [3, 5, 6]. Despite this, the Moon is the brightest object in the night sky (after the Sun) due to its proximity to the Earth. The dark color of the regolith surface [11, 12] is the result of processes of space weathering - the long-term impact of the solar wind and micrometeorite bombardment on lunar rocks.

Due to the lack of an atmosphere to regulate temperature, the Moon experiences extreme temperature fluctuations. During the day at the equator, temperatures can reach +120°C to +130°C, while during the long lunar night it drops to -160°C or even -170°C. The average surface temperature is estimated to be approximately -20°C. Such extremes are a direct result of the Moon's lack of atmosphere [14] and its slow rotation on its axis.

Orbit and Rotation. The Moon orbits the Earth in an elliptical orbit. The average distance between the centers of the Earth and the Moon is 384,400 km. Due to the ellipticity of the orbit, this distance varies: at perigee (the point closest to Earth), it averages 363,300 km, and at apogee (the point furthest away), it averages 405,500 km.

The average eccentricity of the orbit is 0.0549. This change in distance causes variations in the apparent size of the Moon in the sky and is the main factor determining the tides on Earth.

The time it takes the Moon to complete a complete revolution around the Earth relative to distant stars is approximately 27.32 Earth days (27 days 7 hours 43 minutes).

The time between two identical phases of the Moon (for example, from full moon to full moon) is approximately 29.53 Earth days. This period is longer than the sidereal period, because during the Moon's rotation, the Earth also moves in its orbit around the Sun. A unique feature of the Moon is its synchronous rotation. The Moon's period of rotation around its axis is exactly equal to its sidereal period of rotation around the Earth (~27.32 days). As a result, the Moon always faces the Earth with the same hemisphere. This condition, known as tidal capture, is the result of tidal forces between the Earth and the Moon over billions of years, which have gradually slowed the Moon's axial rotation until it is fully synchronized with its orbital motion.

The Moon's orbit is inclined to the plane of the ecliptic (the plane of the Earth's orbit around the Sun) at an angle of approximately 5.145°. The inclination of the orbit to the plane of the Earth's equator varies from 18.28° to 28.58°. The Moon's axis of rotation is inclined to the plane of its orbit at an angle of 6.68°. The inclination of the orbit to the ecliptic is the reason why solar and lunar eclipses do not occur every month, but only when the Moon, in the new or full phase, crosses the plane of the ecliptic.

1.2. Comparing the characteristics of the Moon and Earth

A comparison of the basic characteristics of the Moon and Earth reveals both significant differences and certain similarities that reflect their common, yet unique, history. As can be seen from Table 1.1, the Moon is significantly smaller than the Earth in size, mass, and density. Its gravity is much weaker, which does not allow it to maintain a dense atmosphere. The absence of an atmosphere and a global magnetic field leads to extreme temperature changes on the surface and unprotected from cosmic radiation and meteorite impacts. Synchronous rotation is also a significant difference from the rapid rotation of the Earth. Despite the differences, both bodies have an almost spherical shape and a differentiated internal structure (crust, mantle, core).

Table 1.1.

Comparative characteristics of the Moon and Earth.

Characteristics	Moon	Earth	Ratio (Moon/Earth)
Average radius (km)	1 737.4	6 371.0	0.2727
Mass (10^{22} kg)	7.3477	597.24	0.0123
Average density (g/cm³)	3.346	5.514	0.607
Surface gravity (m/s²)	1.62	9.80	0.165
Second cosmic velocity (km/s)	2.38	11.2	0.213
Surface temperature (°C)	from -170 to +130	from -89 to +57 (average +15)	-
Albedo (Bond)	0.11	0.294	0.37
Atmosphere	Very thin exosphere (almost vacuum)	Dense (N_2, O_2, Ar...)	~10^{-14} Earth's pressure
Global magnetic field	None (weak local fields)	Present (dipole)	~0
Rotation	Synchronous (27.3 days)	23.9 hours	-

The isotopic composition of some elements (for example, oxygen) in lunar rocks is very similar to that of Earth, which supports the theory of their common origin as a result of a giant collision.

1.3. The internal structure of the Moon

The Moon, our closest cosmic neighbor and Earth's only natural satellite. Current models of the Moon's internal structure are based on data from the Apollo seismic experiments, measurements of the Moon's gravitational field and laser ranging, and analysis of lunar samples. These data suggest that the Moon, like the Earth, is a differentiated celestial body consisting of geochemically distinct layers [17]: a crust, a mantle, and a core (Fig. 1.1). This structure likely formed as a result of the crystallization of a global magma ocean that existed early in the Moon's history. Its average density of 3346.4 kg/m³ is significantly lower than that of Earth (5510 kg/m³). This relatively low modern density is a key indicator of its unique composition and formation history, indicating a much lower iron content than Earth. This layered structure is thought to have resulted from fractional crystallization of a global magma ocean shortly after its formation approximately 4.5 billion years ago.

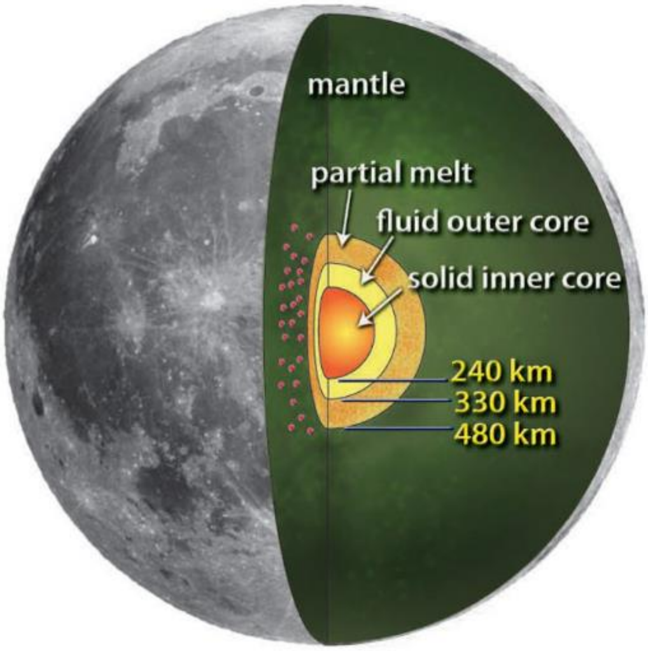

Fig. 1.1. The interior of the Moon, as observed by lunar earthquakes (red dots); a liquid iron core (yellow) and a solid iron inner core (orange) have been discovered there (https://www.science.org/do/10.1126/article.29453/full/sn-lunarcore-1644929015487.jpg).

Understanding of the Moon's interior has evolved significantly over many decades of research. The first direct data were obtained during the Apollo program with the deployment of seismometers on the lunar surface.These initial measurements laid the foundation for further, more detailed studies, which included gravity mapping from orbit by the Lunar Prospector and GRAIL missions, and analysis of lunar samples. Current models are the result of the integration and reanalysis of these diverse data sets [1]. The following is a detailed description of the physical characteristics of the Moon's interior, explains some of the methods by which these characteristics were obtained, and outlines the main current models of the interior.

1.4. Methods for studying the interior of the Moon

Our knowledge of what is inside the Moon is based not on direct observations, but on the interpretation of data obtained by several key methods.

a) ***Seismic studies***. The most direct data on the interior of the Moon have been obtained by seismic experiments during the “Apollo” program and by passive seismic experiments. For example, the Apollo program deployed four passive seismic experiments (PSEs) on the lunar surface at the landing sites of “Apollo 11, 12, 14, 15, and 16”. The purpose of these experiments was to measure vibrations of the lunar surface, caused by both natural and artificial sources of seismic energy, in order to determine the internal structure and composition of the Moon.

The PSE instruments consisted of three long-period seismometers, aligned orthogonally to measure the vertical and two horizontal components of surface motion, and one short-period vertical seismometer. The “Apollo 11” seismometers operated only during lunar days due to their dependence on solar panels, while later, more advanced seismometers deployed by “Apollo 12 through 16” transmitted data until September 1977 and measured all three components of ground displacement. Radioisotope heaters were used to protect the instruments from the extreme temperatures of the lunar night. Thus, lunar seismology is the most powerful tool for studying the interior. The “Apollo” seismometer network operated from 1969 to 1977. The seismometers recorded several types of seismic events. Natural “moonquakes” were detected deep in the mantle, at depths of approximately 700-1100 km, and occurred with a monthly periodicity associated with tidal stresses from the Earth. A few weak moonquakes were also recorded at a depth of about 100 km. In addition, the instruments recorded impacts of meteoroids when they fell on the surface of the satellite (Fig. 1.2); these impacts could create quite powerful seismic vibrations. Artificial impacts, such as the fall of spent S-IVB rocket stages and lunar landing modules after missions, were used as calibration sources. The impact of the “Apollo 12” lunar module caused the Moon to vibrate for more than 55 minutes, and seismometers recorded signals that resonated for a long time. Spent “Saturn V” rocket stages and “Apollo” modules were also deliberately directed at the Moon to create seismic events with known coordinates and energies. Data collected by Apollo seismometers were used to study the propagation of seismic waves through the entire body of the Moon.

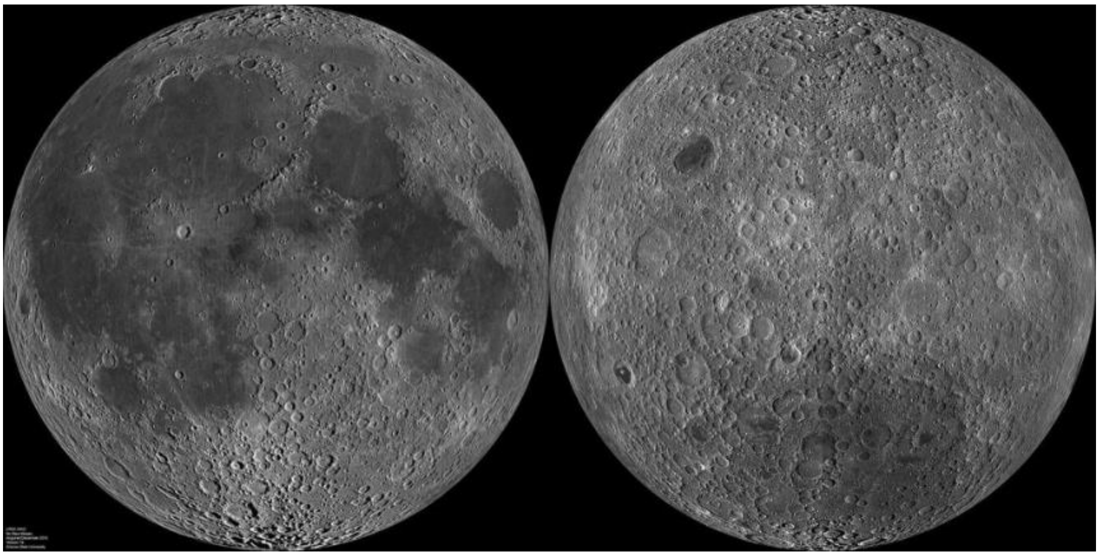

Fig. 1.2. Near and far hemispheres of the Moon (https://universemagazine.com/wp-content/uploads/2025/05/there-might-be-a-hot-s-1024x512.jpg).

By analyzing the arrival time and characteristics of P-waves (longitudinal) and S-waves (transverse), as well as their reflection and refraction, it was possible to determine the boundaries between the main layers of the Moon and the internal structure, density and physical state of individual layers of the Moon. The key is the fact that S-waves cannot propagate in liquids. Their attenuation at a certain depth became direct evidence of the existence of a liquid outer core. And it was the reanalysis of old seismic data from the Apollo spacecraft using modern processing methods that confirmed the presence of an iron-containing core and a partially molten layer in the lower mantle. To overcome the problems of “noise” caused by multiple reflections of signals in the fractionated crust of the Moon, approaches such as digital separation of seismic data signals were used. These methods allowed us to identify how and where seismic waves passed through or reflected from elements of the lunar interior, indicating the composition and state of layer boundaries at different depths. Seismic profiles obtained from these data provided constraints on the thickness of the crust and mantle, as well as on the values of seismic wave velocities in these layers.

b) ***Gravimetry and laser altimetry***. Gravity mapping from orbit is another powerful tool for studying the internal structure of the Moon, since variations in the gravitational field reflect the distribution of mass and density inside the celestial body under study. After all, orbiters orbiting the Moon since even slight changes in its gravitational field, caused by the uneven distribution of mass inside. The "Gravity Recovery and Interior Laboratory" (GRAIL) mission, consisting of two identical spacecraft ("Ebb" and "Flow") orbiting the Moon, measured the changes in the distance between the two spacecraft, and was able to detect these changes with an accuracy of one micrometer, and provided a very detailed map of the Moon's gravitational field. The twin satellites flew in an extremely low orbit, constantly measuring the distance between them (Fig. 1.3). The data obtained allowed for the creation of the most detailed map of the Moon's gravitational field, which was able to reveal the structure of the crust, mantle and core density. Laser altimetry (e.g., on the "LRO" spacecraft) was able to make precise measurements of surface elevation and allowed the topography of the lunar surface to be correlated with the obtained gravity data.

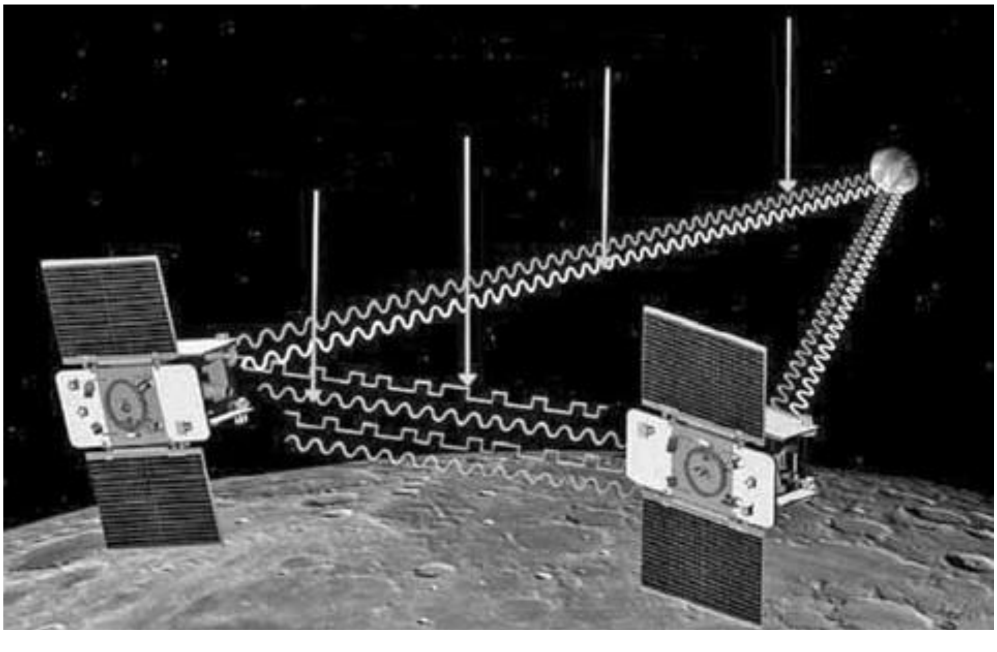

Fig. 1.3. "GRAIL" data transmission scheme [2]

The "Lunar Prospector" mission (1998-1999) also included a Doppler Gravity Experiment, which used S-band radio signals to monitor changes in the spacecraft's orbit; this allowed the lunar gravity field to be measured and mapped with high precision. Analysis of the data obtained by the "GRAIL" mission allowed for a significant improvement in the resolution of the lunar gravity field. Combined with topographic data, these data were used to determine variations in crustal thickness and mantle density. By subtracting the gravitational effect caused by topography from the observed field, it was possible to confirm that the lunar crust is asymmetric, with a thicker crust in mountainous areas and a thinner one under sea basins.

Gravity data also allowed the identification of increased mass concentrations or "mascons"; these are strong positive gravitational anomalies; they are most often associated with large impact basins. Such mascons are explained by the lifting of a central block of dense mantle material during the impact, as well as the subsequent filling of the formed basins with dense basalts of the seas.

c) ***Lunar Laser Ranging***. Since the Apollo missions, so-called corner reflectors have remained on the Moon. Powerful laser pulses were directed at them from Earth, and their return time was measured with an accuracy of a few millimeters. These long-term measurements allowed us to track the smallest fluctuations in the Moon's rotation, the so-called librations. The nature of these fluctuations depends on how the inner layers "slip" relative to each other. Analysis of librations confirmed that the Moon's outer core is liquid and is not rigidly connected to the mantle.

d) ***Analysis of lunar samples***. The samples delivered by the Apollo missions (a total of over 382 kg of rock) and the automatic Luna stations from their landing sites (Fig. 1.4) made it possible to determine the chemical and mineral composition of the lunar crust and, indirectly, the mantle. For example, the prevalence of anorthosite in the crust supports the theory that the Moon was covered by a global magma ocean at an early stage.

1.5. Physical characteristics of the layers in the middle of the Moon

Overall average density and differentiation. The average density of the Moon is

3346.4 kg/m³, making it the second densest satellite in the Solar System after Io. This relatively low density compared to Earth (5510 kg/m³) indicates a significantly lower iron content in its composition. The Moon's differentiated structure – with its distinct crust, mantle, and core – is a direct result of the fractional crystallization process of a global magma ocean that existed shortly after its formation.

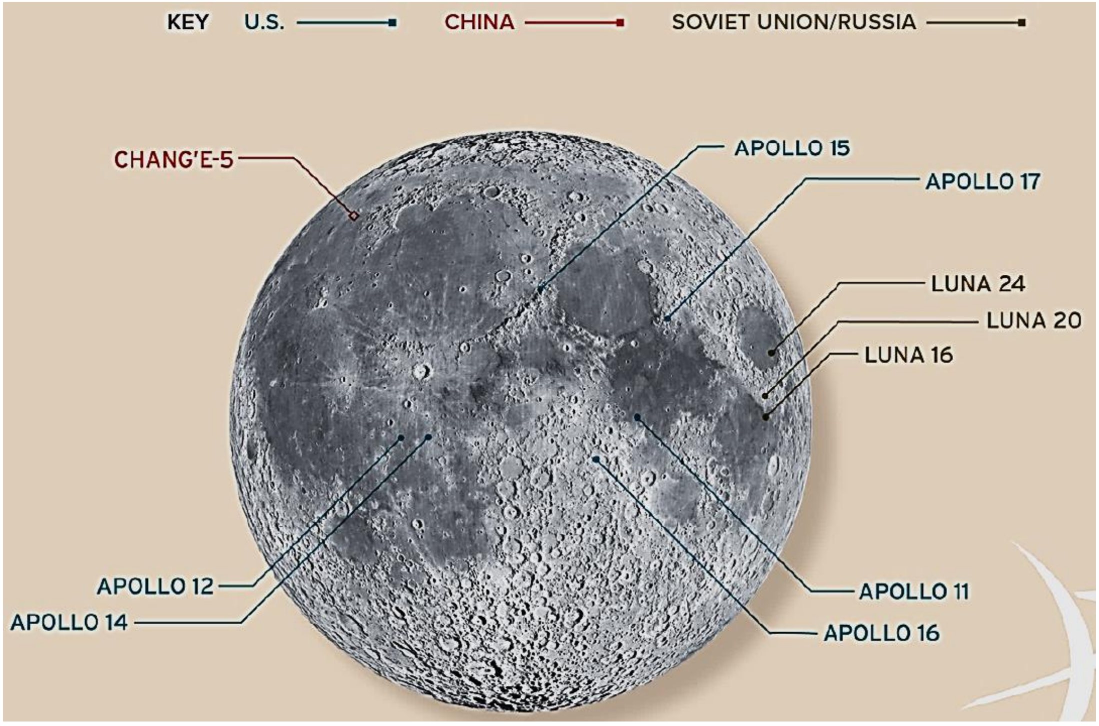

Fig. 1.4. The map shows the locations of lunar sample collection sites delivered from the near side of the Moon by missions from the United States, the Soviet Union, and China from 1969 to 2020. In 2024, the Chinese mission "Chang'e-6" delivered the first lunar samples from the far side (not visible) (https://knowablemagazine.org/docserver/fulltext/g-map-lunar-sample-sites.png)

This process caused heavier minerals, such as olivine and pyroxene, to sink to the center, forming the mantle, and lighter minerals, such as plagioclase and silica-rich crystals, to rise to the surface, forming the crust.

This resulted in a dense metallic core containing a lot of iron, some nickel, and traces of lighter elements such as sulfur. The core has two components: an inner core and an outer core. The inner core is a solid, iron-rich mass ~480 km in diameter, while the outer core is a liquid that increases the diameter of the core to ~660 km. It is the outer core that generates the magnetic field as the material rotates around the inner core. The Earth's outer core is still active and hot, creating a strong magnetic field that protects life from intense solar radiation and storms. However, on the Moon, the outer core is no longer active, and its magnetic field has greatly diminished. Compared to the entire diameter of the Earth, the Moon's core is small (only 20% of the Moon's total diameter). Above the core are the Moon's mantle and crust. These components are of particular interest because the differences in their composition tell the story of when the Moon was completely, or almost completely, covered by a magma ocean. The mantle and crust formed when this magma ocean began to cool and crystals sank and rose to the surface. Heavier minerals, such as olivine and pyroxene, sank to the bottom of the magma ocean, while lighter minerals, such as plagioclase feldspar, rose to the surface, forming the lunar anorthosite crust. The mantle is approximately 1338 km thick (for comparison, the Earth's is ~2900 km).

Lunar crust: composition, thickness and variations. Geochemical mapping from orbit indicates that the lunar crust has a predominantly anorthosite composition; this is consistent with the hypothesis of the existence of an ancient magma ocean. It is composed mainly of oxygen, silicon, magnesium, iron, calcium and aluminium. Some minor and trace elements, such as titanium, uranium, thorium, potassium, sulfur, manganese, chromium and hydrogen, are also present in the crust. Water has been found in the peripolar regions [9, 19]. Detailed studies have shown that the upper crust consists of 88±4% plagioclase by volume, while the lower, more mafic part of the crust contains 65±8% plagioclase and includes norite or gabbronorite [27].

The uppermost part of the crust is composed mainly of anorthosite, a light-colored rock rich in aluminum and calcium. This is essentially the "continental" crust of the Moon. Dark areas, known as lunar seas, are filled with solidified basalt, the result of volcanic activity [20, 21] in the past. The upper part of the crust is hard, brittle, with a density of ~2900 kg/m³. According to geophysical data, the lunar crust is thinner on the near side and thicker on the far side; the crust has an average thickness of ~60 km on the near side and ~100 km on the far side (Fig. 1.4).

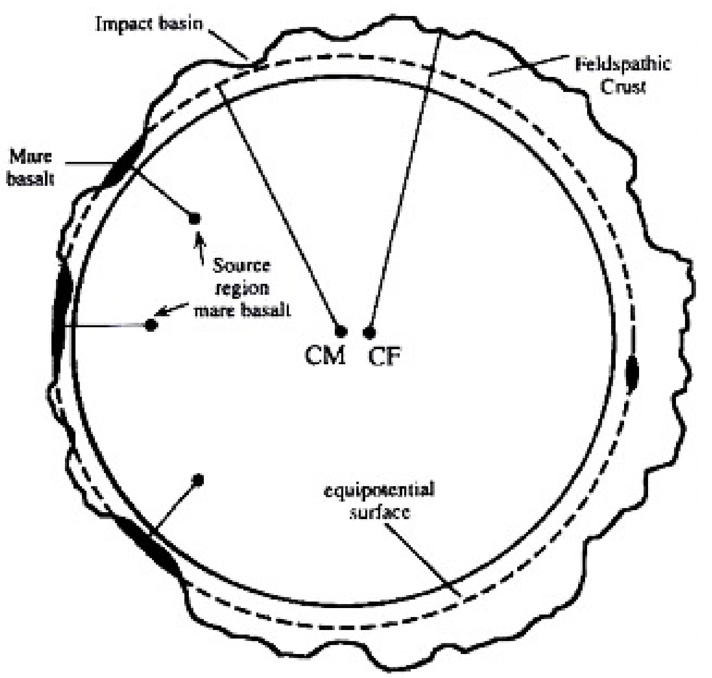

Fig. 1.4. Schematic cross-section of the Moon in the equatorial plane, showing the displacement of the Moon's center of mass towards the Earth (left in the figure) due to the presence of a thicker crust on the far side (right). The thickness of the crust is exaggerated for clarity. The equipotential surface is indicated by a dashed line [23].

The origin of the heterogeneous thickness of the crust is still a matter of debate, but the most accepted hypothesis is that the near side was struck by several large meteoritic bodies, which struck, lifted and absorbed a significant part of the crust, while the far side was affected very little. This asymmetry is a significant factor in the synchronous rotation of the Moon around the Earth. GRAIL data have shown that the upper crust of the Moon is 35–40 km thick and is less dense, and therefore more porous, than previously thought [26]. Large ancient impacts have significantly fragmented and homogenized the density structure of the upper crust. At the same time, lunar basalts, which are products of lunar volcanism, are predominantly found on the near side. This crustal asymmetry is also a major factor contributing to the Moon's synchronous orbit around the Earth. The thinner crust on the near side facilitates the release of magma to the surface. Thus, the observed asymmetric crustal thickness is not simply a geometric feature but a critical causal factor in the distribution of lunar volcanism. Magmas generated in the mantle, even if they originate from similar depths, would encounter significantly greater resistance as they rise through the much thicker crust on the far side. This directly explains the prevalence of marine basalts on the near side, providing a compelling link between early lunar differentiation (which established this crustal asymmetry during the crystallization of a magma ocean) and its subsequent magmatic history. Understanding this correlation is fundamental to reconstructing the magmatic and thermal evolution of the Moon.

Lunar mantle: composition, layering, and seismic properties. The lunar mantle, which formed from the crystallization of a magma ocean, is mafic. Analyses of basalts indicate that it is composed primarily of the minerals olivine, orthopyroxene, and clinopyroxene. The lunar mantle is richer in iron than the terrestrial mantle. Some lunar basalts contain high levels of titanium (in the mineral ilmenite), indicating significant heterogeneity in the composition of the mantle. Moonquakes have been detected deep in the Moon's mantle, approximately 1000 km below the surface.

These deep moonquakes occur with a monthly periodicity and are associated with tidal stresses caused by the Moon's eccentric orbit around the Earth. Modern reanalysis of Apollo seismic data has revealed that the core is partially (10-30%) surrounded by a molten layer of lower mantle with a radius of 480 ± 20 km (about 150 km thick). Mantle models assume a pyroxenitic composition for the upper mantle and a magnesium-rich composition for the lower mantle, with increasing Mg content with depth. The composition of the Moon's mantle, characterized mainly by olivine and pyroxene, is also noticeably rich in iron. However, the discovery of lunar basalts with significant titanium content indicates that the mantle is not chemically homogeneous.

This compositional heterogeneity of the lunar mantle, especially the variable titanium content of marine basalts, provides important evidence for its complex history of partial melting. This implies that the mantle contains distinct geochemical reservoirs that melted at different times or under different pressure and temperature conditions, rather than being a uniformly mixed source.

The presence of a partially molten layer in the lower mantle serves as a direct physical mechanism for the generation of magma at depth. The ascent of these magmas, influenced by the heterogeneous composition of the mantle, then leads to the eruption of marine basalts onto the lunar surface, especially where the crust is thinner. Understanding this mantle heterogeneity is fundamental to reconstructing the magmatic and thermal evolution of the Moon [24]. This suggests that the dynamics of the lunar interior involve more complex processes than simple, uniform cooling and convection, with distinct compositional regions that influence the timing, volume, and chemistry of volcanism.

The mantle thus extends from the base of the crust to the core. It is heterogeneous and is divided into the upper mantle, which is a solid, rigid layer that extends to a depth of about 700 km and, together with the crust, forms the lunar lithosphere; and the lower mantle (asthenosphere), which extends to the boundary with the core; seismological data indicate that this layer is partially molten (1-5% melt); and this zone is the region where deep moonquakes originate.

The mantle is mainly composed of minerals such as olivine and pyroxene, which are rich in iron and magnesium. The density of the mantle increases with depth from ~3000 to almost 4200 kg/m³.

The lunar core: size, condition, and chemical composition. Recent reanalysis of seismic data from the Apollo missions, using modern processing techniques, has confirmed that the lunar core is quite small, with a radius of about 330 ± 20 km; this is only about 20% of the diameter of the Moon itself. The solid inner core consists of almost pure iron, and has a radius of 240 ± 10 km. A liquid outer core, about 90 km thick, surrounds the solid inner core, and has a radius of 330 ± 20 km. These results indicate that 40% of the volume of the core is now solidified. The density of the liquid outer core is about 5000 kg/m³. The composition of the lunar core is not well established, but it is believed (Table 2.1) to consist of a metallic iron-nickel alloy with a small amount of sulfur. The liquid outer core may contain up to 6% sulfur by weight. Studies also indicate the presence of light elements in the core, which has parallels with recent seismological studies of Earth, which also suggest the presence of light elements, such as sulfur and oxygen, in a layer around the Earth's core. Analysis of changes in the Moon's rotation period also indicates that the core is at least partially molten. Its temperature is estimated at 1570–1720 K.

Table 1.2.

Internal structure of the Moon

Layer	Approximate thickness/radius (km)	Main composition	Physical state
Crust	50 - 100 (average ~50-70)	Anorthosite (rich in plagioclase, Al, Ca, Si)	Solid
Mantle	~1350 (thickness)	Silicates (olivine, pyroxenes), richer in Fe	Mostly solid, possible partial melt near the core
Outer core	Radius ~330-480	Iron (Fe), Nickel (Ni), Sulfur (S)	Liquid (molten)
Inner core	Radius ~240-258	Mostly Iron (Fe)	Solid

1.6. Modern models of the Moon's internal structure

The current understanding of the Moon's interior is based on the integration of all available geophysical data, lunar samples, and theoretical models developed to date.

The layered model of the Moon's interior suggests that the satellite is a differentiated body consisting of three main layers: the crust, mantle, and core.

The lunar crust is predominantly anorthosite and is globally asymmetric: it is thinner on the near side of the Moon (on average ~60 km) and thicker on the far side (on average ~100 km). This model assumes a two-layer crust, in which the upper layer is anorthosite and the lower, more mafic layer, containing norite or gabbro-norite. The Moon's mantle is mafic and is believed to consist mainly of minerals such as olivine, orthopyroxene, and clinopyroxene. It is richer in iron than the Earth's mantle. Seismic data indicate the presence of a partially molten layer in the lower mantle surrounding the core. Deep moonquakes occur in the mantle at a depth of about 1000 km.

The lunar core is relatively small, with a radius of about 330 km. It is differentiated into a solid inner core of pure iron (radius 240 ± 10 km) and a liquid outer core (radius 330 ± 20 km), consisting of a metallic iron-nickel alloy with a small amount of sulfur (up to 6% by weight). This means that about 40% of the core volume is solidified. The lunar magma ocean hypothesis is a cornerstone of modern models of the formation and differentiation of the Moon. According to this hypothesis, shortly after its formation, approximately 4.5 billion years ago, the Moon was largely or completely molten. The energy required to melt the Moon's outer surface is usually attributed to the giant impact event that is postulated to have formed the Earth-Moon system, and the subsequent re-accretion of material in Earth's orbit.

This magma ocean underwent fractional crystallization: denser minerals such as olivine and pyroxene sank to the ocean floor, forming the mantle, while lighter minerals such as plagioclase rose to the surface, forming the anorthosite crust. This process explains the observed anorthosite composition of the lunar crust and the overall differentiated structure of the Moon. The details of the Moon's post-magmatic ocean structure are sensitive to assumptions about the composition, depth of the magmatic ocean (shallow or full), and the crystallization process (fractional or equilibrium), each of which is imperfectly known. Thermal evolution models – seek to explain its thermal history and its effects on internal structure and surface features.

Cooling and heat sources. Due to its small size, the Moon is thought to have undergone rapid early cooling. However, the present-day heat flux from the Moon [15] is mainly the result of heat generated by radioactive isotopes such as uranium, thorium, and potassium, which are found in the interior at depths of up to 300 km. These radionuclides play a key role in maintaining the Moon's internal heat and influencing its long-term cooling.

Impact on magmatism. The thermal evolution of the Moon is directly related to partial melting processes in the mantle, which lead to the eruption of marine basalts to the surface. Studies show that enrichment with radioactive elements can keep the upper mantle hotter, even billions of years after the Moon's formation [14]. This explains why younger magmas may have originated from shallower depths than previously thought, since these "pockets" of mantle remained hot enough to partially melt even during the late stages of the Moon's cooling.

Conclusions

Thus, the Moon's internal structure is the result of a complex history of differentiation that may have begun with a hypothetical global magma ocean. Today, the Moon is a well-differentiated body consisting of an anorthosite crust, a mafic mantle, and a small, partially molten iron-nickel-sulfur core.

The Moon's crust exhibits a significant thickness asymmetry, being thinner on the near side and thicker on the far side, which has profound implications for the distribution of lunar volcanism and its synchronous rotation around the Earth. The mantle, although composed primarily of olivine and pyroxene, exhibits compositional heterogeneity. This suggests a complex history of partial melting.

The presence of a partially molten layer in the lower mantle and a liquid outer core confirms that the Moon is still not a completely solid body.

Understanding these physical characteristics has been made possible by interpreting disparate data obtained by different methods. The “Apollo” seismic experiments, which recorded moonquakes and artificial impacts, have provided fundamental data on the layering of the internal structure and on the different values of the propagation velocities of seismic disturbances in different layers of the Moon.

Gravity mapping, in particular by the “Lunar Prospector” and “GRAIL” missions, has made it possible to determine in detail the variations in crustal thickness and identify mascons. Heat flux measurements by the “Apollo” missions and mapping of radioactive elements from orbit have provided critical constraints on the thermal evolution of the Moon and on the distribution of internal heat over its surface. Finally, laser ranging of the Moon has provided information on the state of the core and its oblateness. Current models of the Moon's internal structure continue to be refined [1] by re-analyzing the “Apollo” archive data using new computational methods and by receiving new data from current and future missions [7, 10, 16]. These studies are key to a better understanding of the formation and evolution of the Moon, as well as to expanding our knowledge of the differentiation and dynamics of other celestial bodies in the Solar System.

References:

1. Garcia, R.F., Khan, A., Drilleau, M. et al. (2019) Lunar Seismology: An Update on Interior Structure Models. Space Sci Rev. 215, P. 50.

2. Gravity Recovery and Interior Laboratory (GRAIL) Launch / NASA Press Kit/august 2011. http://www.nasa.gov/pdf/582116main_GRAIL_launch_press_kit.pdf.

3. Morozhenko A.V., Vid'machenko A.P. (2006) Mapping of physical characteristics of a superficial layer of the Moon and ultra-violet polarimetry from orbital lunar station. 36th COSPAR Scientific assembly. The second world space congress. Huston, Texas, USA, 12-21 October 2006, p. 54-55.

4. Morozhenko A.V., Vidmachenko A.P. (2004) Moon Base and Problems of Global Changes on the Earth. Journal of Automation and Information Sciences. 36(11), p. 27-31.

5. Morozhenko A.V., Vidmachenko A.P., Kostogryz N.M. (2015) Spectrophotometric properties of Moon's and Mars's surfaces exploration by shadow mechanism. Highlights of Astronomy. 16, p. 182-182.

6. Morozhenko O.V., Vidmachenko A.P. (2017) Features of the method for mapping of physical characteristics of lunar surface according to the data of ultraviolet polarimetry. 17th Ukrainian Conference on Space Research, Odessa, Aug. 21- 25 2017: abstracts, p. 43.

7. Shkuratov Yu.G., Lytvynenko L.M., Shulga V.M., et al. (2003) Objectives of a prospective Ukrainian orbiter mission to the Moon. Advances in Space Research. 31(11), p. 2341-2345.

8. Steklov A.F., Vidmachenko A.P. (2020) Ways to colonize the Moon. 22 International scientific conference Astronomical School of Young Scientists. December 11–12 2020. Kyiv, Ukraine, p. 84-85.

9. Steklov E.A., Vidmachenko A.P., Steklov A.F. (2019) The water resource of the Moon is sufficient for its colonization. 6-th Gamow International Conference in Odessa "New Trends in Astrophysics, Cosmology and HEP after Gamow" and 19-th Gamow Summer School "Astronomy and beyond: Astrophysics, Cosmology, Radioastronomy and Astrobiology", Ukraine, Odessa, August 11-18, 2019, p.

10. Steklov O.F., Vidmachenko A.P., Kolotilov M.M., et al. (2020) Moon should become a testing ground for special adaptation systems at terraforming of planets.

Collection of abstracts. II International scientific-practical conference, II Shklov readings "Problems of modern natural sciences and mathematics and methods of their teaching", October 28-29, 2020, Glukhiv. P. 33-34.

11. Vid'Machenko A.P., Morozhenko A.V. (2004) Mapping of physical characteristics of the Moon's superficial layer and ultra-violet polarimetry from a lunar orbital station. Kosmichna Nauka i Tekhnologiya. 10(5/6), p. 21-27.

12. Vid'Machenko A.P., Morozhenko A.V. (2006) The application of the brewster angle data for the lunar surface mapping by the real part of the refractive index. Solar System Research. 40(6), p. 462-467.

13. Vidmachenko A.P. (2014) Study of Earth-like planets. 16 International scientific conference Astronomical School of Young Scientists. Kirovohrad, Ukraine. May 29–31, 2014. P. 12-13.

14. Vidmachenko A.P. (2018) Features of volcanoes on different Solar system bodies. Astronomical School's Report. 14(1), p. 1-14.

15. Vidmachenko A.P. (2018) Modern volcanic activity on the Moon. 20 International scientific conference Astronomical School of Young Scientists. May 23-24, 2018. Uman, Ukraine. P. 5-7.

16. Vidmachenko A.P., Morozhenko A.V. (2013) Will there be Ukraine on the moon? 13 Ukrainian Conference on Space Research with International Participation. September 2-6, 2013, Yevpatoria, Ukraine, p. 219.

17. Vidmachenko A.P., Morozhenko O.V. (2014) The physical characteristics of surface Earth-like planets, dwarf and small (asteroids) planets, and their companions, according to distance studies. MAO NAS of Ukraine, NULES of Ukraine. Kyiv, Publishing House "Profi". -388 p.

18. Vidmachenko A.P., Morozhenko O.V. (2019) Physical parameters of terrestrial planets and their satellites. Kyiv, Editorial and Publishing Department of NULES of Ukraine. -468 p.

19. Vidmachenko A.P., Mozgovyi A.V., Steklov O.F. (2021) The Moon and its water resources. Astronomy and the present: materials of the 10th All-Ukrainian

scientific conference, April 12, 2021, Vinnytsia / ed.: V.F. Zabolotny, O.V. Mozgovyi. - Vinnytsia: LLC "TVORY", p. 58-59.

20. Vidmachenko A. P., Steklov O. F. (2023) Features of volcanic activity on the surface of Venus. Basics of learning the latest theories and methods. Proceedings of the IX International Scientific and Practical Conference. (March 07 – 10, 2023). Chapter 7. Boston, USA. International Science Group, p. 39-46.

21. Vidmachenko A.P., Steklov O.F. (2025) Evidence and forms of volcanic activity on Venus. In book: Vidmachenko A. P., Ovsak O. S., Kuznetsova J. G., Steklov O. F. The influence of volcanic activity on the formation of the Venus surface. Chapter: 4. Publisher: Primedia eLaunch, Boston, USA. DOI: 10.46299/979-8-89814-227-8.

22. Vidmachenko A.P., Vidmachenko H.A. (2007) Is it dangerous asteroids? Astronomical almanac. 53, p. 195-207.

23. Weber R.C. (2014) Interior of the Moon. Chapter 24. Encyclopedia of Solar System, ed. by T. Spohn, T. Johnson, D. Breuer, 3rd edn. (Elsevier, Amsterdam, 2014), p. 539–554.

24. Weber R.C., Garcia R., Johnson C.L., et al. (2010) The use of deep moonquakes for constraining the internal structure of the Moon. American Geophysical Union, Fall Meeting 2010, abstract id. U51B-0037.

25. Weber R.C., Lin P.-Y., Garnero E.J., Williams Q., Lognonné P. (2011) Seismic Detection of the Lunar Core. Science. 331(6015), p. 309.

26. Wieczorek M. A., Neumann G. A., Nimmo F., Zuber M. T. (2012) The crust of the moon as seen by GRAIL. Science, 339(6120), p. 671-675.

27. Wieczorek M.A., Zuber M. T. (2001) The composition and origin of the lunar crust: Constraints from central peaks and crustal thickness modeling. Geoph. Research Letters, 28(21), p. 4023-4026.

DOI: 10.46299/979-8-90214-588-2.2

2. Physical characteristics and relief of the surface of the Moon

Introduction

The Moon, our only natural satellite; it is the closest and most studied celestial body after Earth. Its surface preserves a unique geological history of the Solar System, offering a wide range of data on the processes of planetary evolution [25, 26]. A detailed study of the physical characteristics of the surface layer (regolith) and the relief of the Moon's surface is key to understanding its formation history, tectonic activity (or lack thereof), the impact of space weathering, and the potential for future exploration [32] and colonization [6, 9, 11, 14, 17, 19]. The surface relief is characterized by two main types of terrain, which contrast sharply in color, elevation, and age.

2.1. Methods for obtaining data on the physical characteristics and relief of the lunar surface

Knowledge of the lunar surface has been accumulated over centuries of research, starting with telescopic [8, 12, 13] visual observations and reaching its peak with space missions [22].

Telescopic observations. The first systematic visual observations by Galileo Galilei in 1609 revealed the presence of mountains, craters and so-called "Mare" (dark plains) on the lunar surface. Over time, telescopes became more powerful, allowing an increasing number of surface details to be mapped.

Analysis of the *spectra* [10, 21, 22] of reflected sunlight allows the identification of the mineral composition of surface rocks, since different minerals absorb and reflect light at different wavelengths. This gave the first ideas about the presence of basalts in seas [3] and anorthosites in mountainous areas.

The emission of radio waves to the Moon and the analysis of the reflected signal during ground-based radar surveys made it possible to obtain information about the topography, surface roughness and even about some subsurface structures at a depth of several meters.

Space missions. The ***missions of the "Luna" series (USSR)*** and ***"Ranger", "Surveyor" (USA)*** in the 1960s provided the first close-up images of the Moon, confirming the cratered nature of the surface and its unevenness. The Surveyor missions made a soft landing and sent the first images of the lunar soil.

The "***Lunar Orbiter" series*** of missions (USA) provided almost complete photographic coverage of the Moon's surface with high resolution. It became the basis for detailed mapping; with their help, detailed maps of the surface were created with a resolution of up to 0.5 meters per pixel

The astronauts of the "***Apollo" manned missions (USA)*** made six successful landings on the Moon between 1969 and 1972. They conducted visual observations, took photographs, installed scientific instruments such as seismometers and laser light reflectors on the surface, and most importantly, collected and delivered 382 kg of lunar soil and rock samples to Earth.

Laboratory analysis of these samples in Earth laboratories provided the most reliable data on the mineralogical, chemical, isotopic composition, age of rocks, and physical properties of the lunar regolith [4]. This allowed for the development of a detailed geological chronology of the Moon [18].

The "***Clementine" mission (USA, 1994)*** was the first orbital mission to provide global topographic mapping of the Moon using a laser altimeter and a multispectral camera. It also provided the first evidence of water ice in permanently shadowed craters near the poles.

The neutron spectrometer on the "***Lunar Prospector" (USA, 1998-1999***) confirmed the presence of hydrogen (presumably in the form of water ice) in the polar regions, and also detected gravitational field anomalies: the so-called mascons.

The "***Kaguya" mission (Japan, 2007-2009***) provided high-quality images, topographic data, and data on the Moon's gravitational field.

The "***Lunar Reconnaissance Orbiter" (LRO) mission (USA, 2009-present***) is currently the most advanced orbital mission. LRO is equipped with a set of instruments that allow you to obtain a wide range of observational data. The LROC (Lunar

Reconnaissance Orbiter Camera) cameras create high-resolution images with a resolution of up to 0.5 m/pixel, which allows you to study craters, individual boulders, lunar vehicles and even astronaut tracks in detail.

The LOLA (Lunar Orbiter Laser Altimeter) laser altimeter using laser altimetry created the most accurate topographic map of the Moon, revealing the smallest irregularities and allowing you to measure the depth of craters and the height of mountains. The Diviner (Lunar Radiometer Experiment) instrument measures surface temperature, which allows you to create temperature maps; they provide information about the thermal properties of the regolith and the presence of frozen volatiles.

Using ***neutron spectroscopy***, LEND on LRO continues to detect hydrogen (and therefore potential water) by measuring the flux of neutrons from the surface. This is how maps of water ice distribution in the polar regions have been constructed [33-35].

The Cosmic Ray Telescope for the Effects of Radiation (CRaTER) instrument measures radiation levels on the lunar surface. This radiation data is important for future manned missions.

The **“Chang'e”** series of missions (China's space program) includes orbiters, landers, and lunar rovers. In particular, “Chang'e-3” and “Chang'e-4” (the first landing on the far side of the Moon) provided new data on the composition of the regolith and subsurface structures using ground-penetrating radar. And the “Chang'e-5” mission successfully returned lunar soil samples in 2020, collecting samples of relatively young rocks [1].

2.2. Physical characteristics of the lunar surface layer (Regolith)

Unlike the Earth, the Moon does not have a dense atmosphere and hydrosphere, so its surface is not protected from cosmic radiation and constant bombardment by micrometeorites. These processes over billions of years have transformed the upper layer of bedrock into a unique formation - regolith. Regolith is a layer of loose, crushed material that covers the entire surface of the Moon. It was formed as a result of centuries of bombardment of the Moon by meteorites, micrometeorites, and particles of the solar wind.

The regolith consists of a mixture of dust, sand, gravel, and larger rock fragments (breccias). The particle size varies from micrometers to tens of centimeters. Small fractions (< 1 mm) constitute about 50% of the mass. That is, the lunar regolith consists of rock fragments, minerals, glass spherules, and sintered particles (agglutinates). Its thickness varies from 2–8 meters in young seas to 10–20 meters or more on ancient continents and in very old craters. Although the regolith appears homogeneous at the macroscopic level, studies of many cores have revealed its complex layered structure, reflecting a history of meteorite impacts and mixing. In the deeper layers of the regolith, breccias are often found - rocks consisting of fragments of various lunar rocks cemented by fine-grained material; they indicate intense impact processes [20, 44].

The average bulk density of the regolith is approximately 1.3–1.7 g/cm^3, which is significantly lower than the density of solid rocks (about 3 g/cm^3). This low density is explained by its high porosity. That is, the regolith is a very porous material (40-50%), which explains its low thermal conductivity and high insulating properties. The color of the regolith varies from light gray to dark gray or brown, depending on the mineral composition and the presence of glassy particles formed as a result of micrometeorite impacts.

The particles of the regolith have low cohesion under vacuum conditions, which makes it very loose. However, electrostatic forces (due to the influence of the solar wind) can cause it to “stick together” and form dust pillars.

Regolith is an excellent insulator. The lack of an atmosphere to retain heat and the low thermal conductivity of the regolith means that the temperature at the Moon's equator fluctuates in extremes, leading to extreme temperature drops on the Moon's surface: from +127°C during the day to -173°C at night. In permanently shaded regions near the poles, the temperature can drop to -240°C, creating “cold traps” for volatile substances. This property is important for the design of lunar bases.

Regolith is a good dielectric. Under the influence of solar ultraviolet and X-ray radiation, dust particles on the dayside of the Moon acquire a positive electrical charge. This leads to their electrostatic repulsion and levitation, forming a kind of “dust atmosphere” at a height of several centimeters to tens of meters.

The regolith has a low bearing capacity, which requires special designs for lunar landers and vehicles. Traces of astronauts and lunar rovers on the Moon indicate its friability and ability to compact.

The lunar regolith, like other lunar rocks, is predominantly diamagnetic or paramagnetic material. However, some samples also show weak residual magnetism [24]. This indicates the presence of an ancient magnetic field of the Moon in the early stages of its history, which later disappeared.

2.3. Relief of the Moon's surface

The surface of the Moon is a kind of chronicle of the history of the Solar System, which has preserved traces of events that occurred billions of years ago. The relief of the Moon's surface is characterized by two main types of terrain, which contrast sharply in color, height and age: light, high-altitude continents (terrae) and dark, low-altitude seas (maria).

Data on which conclusions about changes in the physical state of the Moon's surface are based. Conclusions about changes in the physical state of the Moon are based on data obtained from the study of lunar soil samples. Laboratory analysis of these samples, collected by the “Apollo” and “Luna” missions, provided information about the age of the rocks, chemical and mineralogical composition, the presence of glassy particles and their transformation under the influence of space weathering. The presence of nanophase iron (nFe0) is direct evidence of space weathering. Impact crater density (i.e., the number of craters per unit area) is used to date lunar surfaces [5]. The more craters there are in an area, the older it is. This method is calibrated by radioisotope dating of lunar rock samples from known geological regions.

Modern orbiters, such as LRO, continuously acquire high-resolution images of the surface. Comparing images taken years apart allows the detection of new craters and rifts, which indicates ongoing activity [30]. And a network of seismometers installed by Apollo astronauts has been operating for many years, recording lunar earthquakes. Analysis of these data has provided insight into the internal structure of the Moon and its ongoing tectonic activity [7, 15, 45].

High-precision topographic maps obtained using laser altimeters (LOLA on LRO) have allowed us to study the morphology of the relief, identify landslide cliffs and other small tectonic features. Maps of the lunar gravity field (obtained, for example, by the GRAIL mission) allow us to detect mascons (concentrations of mass in certain regions), which are the result of filling basins with dense basaltic lavas. These data provide an idea of the history of volcanic activity [27, 28, 31, 38, 40]. And observations of the lunar exosphere and dust cloud phenomena provide information about volatiles and dust movement.

Data on changes in the physical state of the lunar surface throughout the historical past and to the present. Changes in the physical state of the lunar surface occur on different time scales. With long-term changes over billions of years, the regolith becomes darker over time. This phenomenon, known as “space weathering,” occurs as a result of micrometeorite impacts. This forms nanophase iron (nFeO) in glassy particles, which changes the optical properties of the regolith.

Ion bombardment, or solar wind, changes the chemical composition of the surface of the particles. Meteorite impacts also eject lighter, fresh material from deep within, temporarily illuminating areas; but then they darken again. Craters are eroded over time, leading to the smoothing of their rims and the filling of the bottom. This process occurs much more slowly than on Earth, due to the absence of an atmosphere and water.

The thickness and structure of the regolith are constantly changing as a result of bombardment. Tectonic processes, although very slow, affect the formation of rifts and lead to minor displacements of crustal blocks [47, 49]. In the case of short-term changes (years, decades, centuries), new impact craters continue to form on the Moon as a result of meteorite impacts. After all, modern spacecraft [50] (for example, LRO) regularly record the formation of new, small craters. This is direct evidence of ongoing changes in the relief. Seismometers installed on the surface of the Moon as part of the Apollo program recorded lunar earthquakes. They are divided into deep lunar earthquakes associated with the Earth's tidal forces acting on the Moon. They occur regularly - about 3000 per year - but are weak.

Surface lunar earthquakes are rarer and more powerful; they are probably associated with tectonic movements along cliffs and cracks. Seismometers have also recorded meteorite impacts.

Electrostatic forces induced by the solar wind and ultraviolet radiation can cause lunar dust to move across the surface, especially at the terminator (the day-night line). This dust can leave fine trails or settle on spacecraft. Also, the constant heating and cooling cycles of the surface cause expansion and contraction of surface rocks; this leads to their gradual destruction and a kind of "loosening" of the regolith.

How has the relief of the Moon's surface changed historically? The evolution of the lunar relief is closely related to its geological history, which is divided into several geological eras.

Pre-Nectarian period (up to 3.92 billion years ago). The Moon was formed approximately 4.51 billion years ago, probably as a result of a giant collision. At this stage, there was a magma ocean, intensive accretion of material and the formation of a primary crust. Lighter minerals (plagioclase) floated, forming a primary anorthosite crust - the future continents.

The surface of the Moon at that time was subjected to intense bombardment by asteroids and cometary nuclei, which led to the formation of many large impact basins and craters. Today, they form continental areas. Some of these basins were so large that they caused repeated regional melting. During this same period, differentiation of lunar material occurred, and lighter, less dense rocks (anorthosites) surfaced, forming the primary lunar crust.

The Nectarian period (3.92–3.85 billion years ago) was a period of particularly intense bombardment, during which most of the large impact basins were formed. They were later filled with lava, forming seas such as Mare Nectaris and Mare Imbrium.

The Imbrian period (3.85–3.2 billion years ago) is a period when, after the late intensive bombardment, a period of massive eruptions of basaltic lavas began, which filled the low-lying impact basins, forming dark seas. This lava flowed through faults in the crust formed as a result of numerous impacts. It was during this period that the basic appearance of the lunar surface, which we see today, was formed. At the same time, the compression of solidified lavas formed wrinkled ridges.

During the *Eratosthenian period (3.2–1.1 billion years ago*), there was a period when volcanic activity [39] decreased significantly; although occasional eruptions still occurred, producing some of the youngest marine basalts. Surface bombardment also continued, although at a lower intensity. Therefore, craters were formed that could not be filled with lava. However, the regolith continued to build up.

During the *Copernican period (1.1 billion years ago – present*), the intensity of meteorite impacts decreased significantly. Therefore, during rare impact events, craters formed during this period are relatively "fresh", with bright ray systems. Examples of these are the craters Copernicus and Tycho. Their ejecta has not yet darkened by space weathering.

At this time, the Moon's surface continues to be subjected to continuous micrometeorite bombardment, which leads to slow but constant mixing of the regolith, its darkening and the formation of glassy particles. Extreme temperature fluctuations on the surface (from -173°C to +127°C) lead to significant "fatigue" of rocks, which causes their destruction and the formation of new regolith particles.

The Moon, in comparison with the Earth, is geologically inactive. However, there are still minor tectonic processes that lead to the formation of "lobate scarps". These are small faults that arose as a result of the Moon's compression as it cooled, and the core contracted [45]. These structures indicate that the Moon is still slowly contracting.

Major landforms. *The lunar continents (Terrae)* are the dominant type of terrain on the Moon. These are bright, high-altitude areas that cover about 83% of the entire surface of the Moon and are mostly located on the far side. They are characterized by a highly rugged relief and a high density of craters. That is, they are old, heavily cratered, bright areas composed mainly of anorthosite rocks, rich in aluminum and calcium. These rocks are the remains of the primary lunar crust, which was formed during the crystallization of the magma ocean. The average height of the continents is much higher than the seas. They are the oldest parts of the lunar crust, whose age reaches 4.4–4.5 billion years. The high density of craters on their surface indicates that these areas were subjected to intense bombardment in the early history of the Solar System.

The lunar Marias, despite their name, are large dark, relatively flat lowlands. They occupy about 17% of the surface, mostly on the visible side (about 31-40% of its area). These are ancient impact basins that were filled with liquid basaltic lavas during a period of intense volcanic activity (3.9–3.2 billion years ago, although some volcanic processes could have lasted up to 1 billion years ago). They are composed mainly of dark basalts, rich in iron, which determines their dark color and low albedo. Some seas are also rich in titanium. They contain fewer craters than continents; this indicates their younger age. The largest sea is the Oceanus Procellarum.

Impact craters – are the most prominent and widespread features of the lunar landscape. They are formed by impacts from meteorites, asteroids, and cometary nuclei. Craters vary greatly in size and morphology, depending on the size and energy of the impactor. Craters cover almost the entire surface of the Moon, from microscopic pits to giant basins. There are about 300,000 craters over 1 km in diameter on the visible side, and over a million on the entire surface. In ancient continental areas, the density of craters is so high that the surface has reached a saturation point, where new impacts destroy as many old craters as they create new ones.

A typical fresh crater has the following main elements*:* a well-defined shaft (raised rim), a floor (inner depression), inner slopes (often with terraces in complex craters), and a central hill (in complex craters). Around the crater is an ejecta blanket – a layer of debris thrown out during the impact. Light rays – bands of lighter material thrown out over long distances – radiate from young craters. Secondary craters can also form around large craters from the fall of large debris. The study of craters (their morphology, distribution, density) is a key method for determining the relative and absolute age of different areas of the lunar surface and reconstructing the history of meteorite bombardment in the Solar System.

Simple craters are small, cup-shaped depressions up to 15–20 km in diameter, with a smooth bottom and steep slopes.

Complex craters are somewhat larger (~15–20 km to ~150–200 km), with flat floors, central hills formed by crustal uplift after impact, and terraced inner slopes of the shaft formed by collapses; the flat floor is often filled with solidified melt.

Examples include the craters Copernicus, Aristarchus, and Tycho.

Impact basins are very large impact structures with diameters of over 300 km and up to over 1000 km; they often have several concentric ring shafts (mountain ranges); examples include the Eastern Sea and the Sea of Rains (Imbrium). Most sea basins are also impact basins filled with basaltic lavas. The impacts that formed the basins were so powerful that they could have pierced the lunar crust and caused the uplift of mantle material or subsequent lava flows that formed the seas. The largest known impact basin in the Solar System is the South Pole-Aitken Basin on the far side of the Moon.

Mountain ranges are often remnants of ridges around craters and large impact basins. Unlike Earth, where mountains are mainly formed by tectonic activity (plate collisions) or volcanism, most lunar mountains are of impact origin. They are mainly the uplifted edges (ridges) of large impact basins and craters. The giant collisions that created the basins lifted and deformed the surrounding crust, forming mountain ranges surrounding these structures. The central peaks of complex craters are also mountains of impact origin. The most famous lunar mountain ranges have terrestrial names: Apennines (ridge of the Mare Rainii basin, peaks up to 5 km high), Alps (with the Alpine Valley), Caucasus. Some lunar peaks reach considerable heights, up to 9 km above the surrounding terrain, exceeding the height of Mount Everest relative to the base level. The so-called *Rilles* are long, narrow, sinuous or straight depressions on the lunar surface, resembling channels or cracks [2]. They are classified by morphology, which reflects different mechanisms of formation.

Sinuous rilles are the most common type. They have a characteristic meandering, river-like shape. They can be hundreds of kilometers long and a few kilometers wide. They often start from small crater-like depressions, which are considered volcanic vents. Their formation is associated with lava flows: they can be either open lava channels or collapsed lava tubes through which molten basaltic lava once flowed during the formation of the seas. That is, they were formed by lava flows in lava tubes that later collapsed. An example is Hadley Rille, explored during the "Apollo 15" mission. *Straight rilles* are often associated with tectonic faults. They are linear, straight, or slightly curved depressions that resemble grabens - lowered blocks of crust between two parallel faults. Their origin is associated with tectonic processes - stretching of the lunar crust. Examples are the Ariadaeus Rille (Fig. 2.1), Vallis Alpes (Fig. 2.2), Cauchy Rille (Fig. 2.3).

Fig. 2.1. Image of the Ariadaeus Rille, which is hundreds of kilometers long. Photo of the "Apollo 10" crew in 1969 as they approached an altitude of 14 km above the lunar surface (https://apod.nasa.gov/apod/image/0210/rille_apollo10_big.jpg).

Fig. 2.2. Vallis Alpes, as seen by the "Lunar Reconnaissance Orbiter" (https://c02.purpledshub.com/uploads/sites/48/2019/08/Vallis_Alpes_4115_h3-147c260-e1566997446657.jpg?webp=1&w=1200).

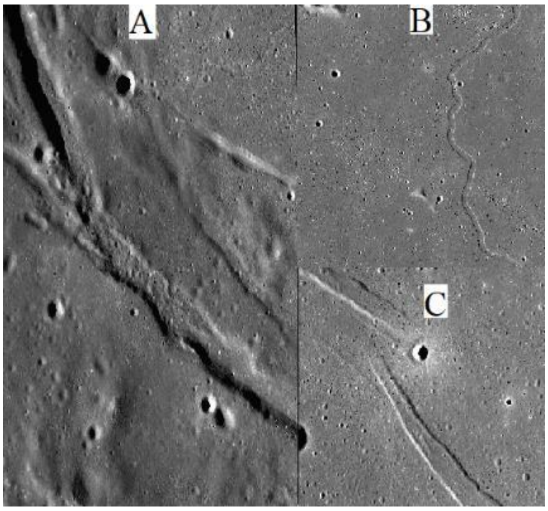

Рис. 2.3. Sinuous, Straight and Arcuate Rilles: A – Rille Sulpicious Gallus (20°N Lat, 10°E Lon), B – Rille Sharp (46°N Lat, 309°E Lon), C – Rille Cauchy (10°N Lat, 38°E Lon) (https://lroc.im-ldi.com/ckeditor_assets/pictures/893/content_Rilles_rilles_rilles_anote.png).

Arcuate rilles have a smooth arcuate shape and are usually located at the edges of lunar seas, sea basins and are associated with the lowering of the basin floor; therefore, they are located parallel to the sea-continent boundary. They are believed to have formed as a result of the subsidence and compression of heavy basaltic layers in the center of the basin after their cooling and solidification, which caused stretching and faults at the periphery. Example: *Rille Hippalus* on the edge of *Mare Humorum*.

The variety of groove types (Table 3.1) indicates the complex nature of geological processes on the Moon, which included both large-scale volcanism (Sinuous rilles) and tectonic stresses in the lithosphere (*Straight* and *Arcuate rilles*).

Formations such as *Domes* are quite low and have rounded shapes; they are considered volcanic formations of the shield volcano type [29, 41-43, 49].

Table 2.1.

Types of Rilles on the Moon.

Type of rilles	**Appearance**	**Likely Formation Mechanism**	**Examples**
Sinuous	Meandering, river-like, often begins in a crater-like depression	Lava channel or collapsed lava tube	Hadley Rille, Schroeter Valley
Arcuate	Smooth bend, parallel to the sea edge	Subsidence/compression of lava in the basin	Hyppal Rille
Straight	Linear, straight or slightly curved depression	Tectonic fault (graben)	Ariadea Rille, Alpine valley

Wrinkle Ridges are long, winding ridges that cross the surface of seas. They are the result of tectonic compression of basaltic lavas after they have cooled and solidified.

Global topography of the Moon. The visible side of the Moon is dominated by seas; this gives it a darker appearance; the Sea of Rains, the Sea of Tranquility, and the Sea of Clarity stand out in particular. Continental regions are less common, but still present.

The *far side* of the Moon is mainly composed of heavily cratered continents. Seas are much rarer and smaller here; examples include the Mare Moscoviense and the Mare Desiderii. This asymmetry is explained by the thickness of the lunar crust, which is much thicker on the far side; this is what prevented magma from reaching the surface and filling impact basins.

The *lowest point* on the Moon is located in the South Pole-Aitken Basin on the far side of the satellite. It is one of the largest impact basins in the Solar System: about 2500 km in diameter and up to 13 km deep. It is the lowest and one of the oldest and largest impact structures on the Moon. The *highest point* is located at the edge of the South Pole-Aitken basin, at an altitude of up to 8-10 km above the mean level of the Moon.

2.4. Mineralogical composition of the surface layers of the Moon

The mineralogical composition of the surface layers of the Moon reflects its geological history [36, 37] and differentiation processes.

The ***main minerals*** on the surface of the Moon are the following ***feldspars***:

a) Plagioclase dominates in continental rocks (anorthosites), giving them a light color. Anorthite ($CaAl_2Si_2O_8$) is the main mineral of the primary lunar crust, formed by upwelling during the crystallization of the magma ocean.

b) Pyroxenes: $(Ca,Mg,Fe)_2(Si,Al)_2O_6$.

c) Clinopyroxenes (e.g., augite) are common in marine basalts.

d) Orthopyroxenes (e.g. enstatite, hypersthene) are found in both marine and continental rocks.

e) Olivine $(Mg,Fe)_2SiO_4$ is common in marine basalts, also found in some continental breccias.

Ilmenite (***$FeTiO_3$***) is an important mineral in some marine basalts, especially in basalts with a high titanium content. Its presence gives some seas a darker hue. Ilmenite is also considered a potential resource for obtaining oxygen and titanium on the Moon.

Chromite, Ulvospinel and other oxides are found in basalts.

Iron-nickel metals are found in small quantities in the form of particles originating from meteorites or formed as a result of the reduction of iron from minerals under the influence of the solar wind. ***Glass*** is formed as a result of meteorite impacts that melt local rocks. Lunar glass can be of different colors (brown, green, yellow) depending on its chemical composition. It is a common component of the regolith.

Typical rocks in the surface layer of the Moon are ***Basalts***. These are dark, fine-grained igneous rocks that make up the seas. They are rich in pyroxenes, olivine and plagioclase (with a relatively high content of iron and magnesium). ***Anorthosites*** are light, coarse-grained igneous rocks that make up the continents. They consist almost entirely of plagioclase (anorthite).

Breccias are rocks composed of fragments of various lunar rocks (basalts, anorthosites, impact glass) cemented by a fine-grained matrix. They are very common in the regolith, especially in continental areas, and are evidence of intense impact bombardment. ***Regolith breccia*** is a type of breccia composed of regolith fragments cemented by pulsed melting.

KREEP lands are unique areas (the largest of which is the Burr Ocean) enriched in incompatible elements such as **K** (potassium), **REE** (rare earth elements) and **P** (phosphorus). They are believed to be the remnants of the last fractions to crystallize from a former magma ocean.

Observational data from "LRO", "Chandrayaan-1" and "LCROSS" have confirmed the presence of ***water ice*** in permanently shadowed regions near the poles (Fig. 2.4). Ice is mixed with the regolith in concentrations ranging from a few to tens of percent by mass [16]. Its sources are thought to be comets, asteroids, and chemical reactions involving hydrogen from the solar wind.

Space weathering, such as bombardment by micrometeorites and the solar wind, also significantly alters the mineralogical composition of particles on the surface. One of the most important consequences of such weathering is the formation of nanophase iron (nFeO).

Iron atoms from minerals are reduced to form nanometer-sized particles of metallic iron, which settle on the surface of dust particles. This leads to a darkening of the regolith and a decrease in its reflectivity. As a result of meteorite bombardment, the crystal structure of minerals can be disrupted, transforming them into amorphous glass.

And solar wind particles (mainly hydrogen, helium, carbon, nitrogen) can be implanted into the surface layers of minerals; this is of great importance for the potential extraction of resources, such as helium 3.

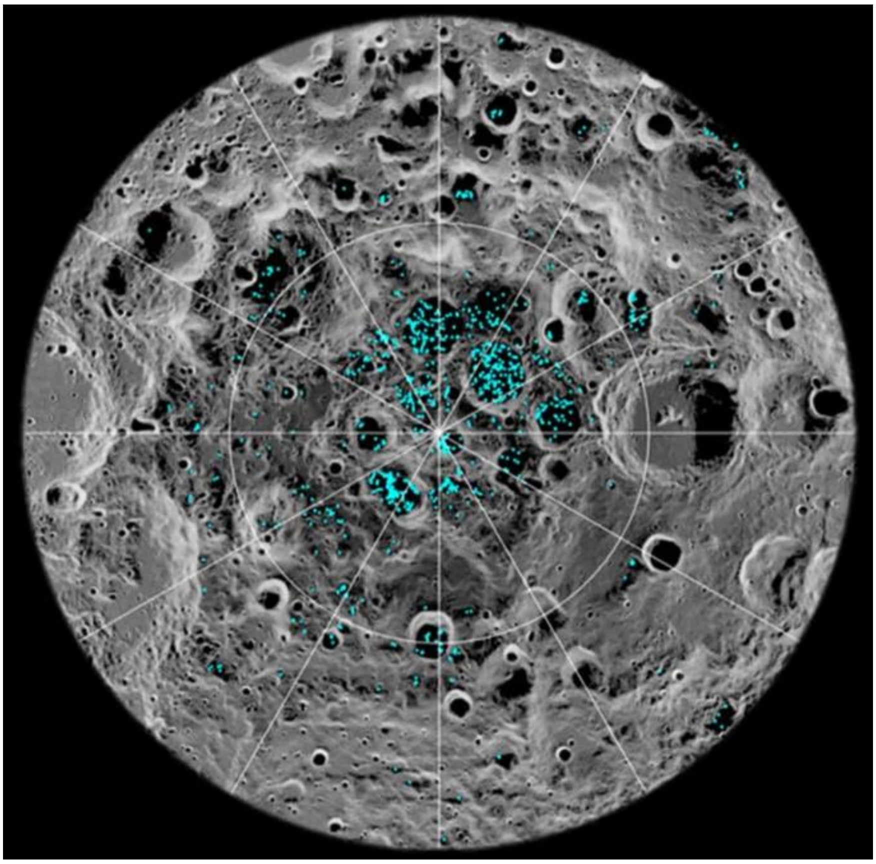

Fig. 2.4. Extensive hydrogen deposits in the Moon's shadowed regions have been revealed. It is unveiled extensive hydrogen deposits in the Moon's shadowed regions (https://www.thebrighterside.news/uploads/2024/12/ice-1-scaled.webp?format=auto&optimize=high&width=1200).

Conclusions

The Moon is a unique natural object, whose surface carefully preserves the history of intensive bombardment and volcanic activity in the early stages of the development of the Solar System. A detailed study of its regolith, relief and mineralogical composition has allowed us to build a comprehensive model of lunar evolution. The continued acquisition of data from new missions such as "LRO" and the "Chang'e" mission, along with re-evaluations of existing samples and data, continues to deepen our understanding of this amazing celestial body and its role in Earth's history. Future lunar missions, including the Artemis program, promise new discoveries and an even more detailed look at the physical characteristics and evolution of our closest neighbor.

References:

1. Braden S.E., Stopar J.D., Robinson M.S., et al. (2014) Evidence for basaltic volcanism on the Moon within the past 100 million years. Nat. Geosci. 7(11), p. 787-791.
2. Farrand W.H., Trang D., Li Sh. (2023) Dark mantles over domes and rilles on the Moon: Evidence for pyroclastic materials. Icarus. 406, December, Article 115759.
3. Head III J.W., Wilson L., Hiesinger H., et al. (2023) Lunar mare basaltic volcanism: Volcanic features and emplacement processes. Reviews in Mineralogy and Geochemistry, 89(1), p. 453-507.
4. Heiken G.H., Vaniman D.T., French B.M. (1991) Lunar Sourcebook, A User's Guide to the Moon, ISBN 0521334446, Cambridge University Press.
5. Hiesinger H.V., Van Der Bogert C.H., Pasckert J.H., et al. (2012). How old are young lunar craters? Journal of Geophysical Research: Planets. 117(E00H10), p. 1-15.
6. Kuznyetsova Y.G., Vidmachenko A.P., Steklov A.F. (2020) Astrobiology aspect of Moon' study in the process of colonization. 20-th Gamow International Astronomical Conference-School "Astronomy and beyond: astrophysics, cosmology and gravitation, high energy physics, astroparticle physics, radioastronomy and astrobiology", Ukraine, Odessa, August 9-16, p. 21-22.
7. Lognonne P., Kobayashi N., Garcia R., et al. (2012) Lunar interior as seen by seismology: from Apollo to future missions. 39th COSPAR Scientific Assembly. Held 14-22 July 2012, in Mysore, India. Abstract D2.6-11-12, p.1102.
8. Morozhenko A.V., Vid'machenko A.P. (2006) Mapping of physical characteristics of a superficial layer of the Moon and ultra-violet polarimetry from orbital lunar station. 36th COSPAR Scientific assembly. The second world space congress. Huston, Texas, USA, 12-21 October 2006, p. 54-55.
9. Morozhenko A.V., Vidmachenko A.P. (2004) Moon Base and Problems of Global Changes on the Earth. J. of Automation and Inform. Sciences. 36(11), p. 27-31.

10. Morozhenko A.V., Vidmachenko A.P., Kostogryz N.M. (2015) Spectrophotometric properties of Moon's and Mars's surfaces exploration by shadow mechanism. Highlights of Astronomy. 16, p. 182-182.

11. Morozhenko O.V., Vid'Machenko A.P. (2004) An observing base on the Moon and the global ecological problem of the Earth. 4th Ukrainian Conference on Space Research with International Participation. August 31-September 5, 2004, Kyiv, Ukraine, p. 29.

12. Morozhenko O.V., Vidmachenko A.P. (2017) Features of the method for mapping of physical characteristics of lunar surface according to the data of ultraviolet polarimetry. 17th Ukrainian Conference on Space Research, Odessa, Aug. 21- 25 2017: abstracts, p. 43.

13. Morozhenko O.V., Vidmachenko A.P. (2017) Possible space experiment "Mineralogical mapping of the Moon's surface". 17th Ukrainian Conference on Space Research, Odessa, Aug. 21- 25 2017: abstracts, p. 44.

14. Morozhenko O.V., Vidmachenko A.P., Nevodovskyi P.V., Choliy V.Ya. (2017) Monitoring of Global Climate Change in the Earth from the Moon. 17th Ukrainian Conference on Space Research, Odessa, Aug. 21- 25 2017: abstracts. P. 47.

15. Neal C.R. (2006) Why the next generation of Moon exploration needs a global seismic network. European Planetary Science Congress 2006. Berlin, Germany, 18 - 22 September 2006, p. 291.

16. Pieters C.M., Goswam J., Clarket R.N., et al. (2009). Character and Spatial Distribution of OH/H2O on the Surface of the Moon Seen by M3 on Chandrayaan-1. Science, 326(5952), p. 568-572.

17. Shkuratov Yu.G., Lytvynenko L.M., Shulga V.M., et al. (2003) Objectives of a prospective Ukrainian orbiter mission to the Moon. Advances in Space Research. 31(11), p. 2341-2345.

18. Snape J.F., Nemchin A.A., Bellucci J.J., et al. (2016). Lunar basalt chronology, mantle differentiation and implications for determining the age of the Moon. Earth and Planetary Science Letters. 451, p. 149-158.

19. Steklov A.F., Vidmachenko A.P., Miniaylo D.N. (2019) Ways of human survival on the Moon. 6-th Gamow International Conference in Odessa “New Trends in Astrophysics, Cosmology and HEP after Gamow” and 19-th Gamow Summer School “Astronomy and beyond: Astrophysics, Cosmology, Radioastronomy and Astrobiology”, Ukraine, Odessa, August 11-18, 2019, p. 57.

20. Vid’Machenko A.P. (1995) Settling of dust in Jupiter’s atmosphere after the impact of fragments of comet Shoemaker-Levy 9. Kinematics and Physics of Celestial Bodies. 11(4), p. 14-16.

21. Vid’Machenko A.P., Morozhenko A.V. (2004) Mapping of physical characteristics of the Moon's superficial layer and ultra-violet polarimetry from a lunar orbital station. Kosmichna Nauka i Tekhnologiya. 10(5/6), p. 21-27.

22. Vid’machenko A.P., Morozhenko A.V. (2005) Mapping of the physical characteristics and mineral composition of a superficial layer of the Moon or Mars and ultra-violet polarimetry from the orbital station. 36th Lunar and Planetary Science Conference, March 14-18, 2005, League City, Texas, abstract #1015.

23. Vid’Machenko A.P., Morozhenko A.V. (2006) The application of the brewster angle data for the lunar surface mapping by the real part of the refractive index. Solar System Research. 40(6), p. 462-467.

24. Vidmachenko A.P. (2012) The magnetic field of planets, satellites and asteroids. Astronomical School's Report. 8(2), p. 136-148.

25. Vidmachenko A.P. (2014) Study of Earth-like planets. 16 International scientific conference Astronomical School of Young Scientists. Kirovohrad, Ukraine. May 29–31, 2014. P. 12-13.

26. Vidmachenko A.P. (2016) Activity of processes on the visible surfaces of Solar System bodies. Astr. School’s Report. 12(1), p. 14-26.

27. Vidmachenko A.P. (2018) Comparative features of volcanoes on Solar system bodies. 20 International scientific conference Astronomical School of Young Scientists. May 23–24, 2018. Uman, Ukraine, p. 9-12.

28. Vidmachenko A.P. (2018) Features of volcanic activity on various bodies of the Solar system. Materials of the International Scientific and Practical Conference

"The Objectives of the Sustainable Development of the Third Millennium: Challenges for Universities of Life Sciences", vol. 5, May 23-25, 2018, Kyiv, p. 41-42.

29. Vidmachenko A.P. (2018) Features of volcanoes on different Solar system bodies. Astronomical School's Report. 14(1), p. 1-14.

30. Vidmachenko A.P. (2018) Modern volcanic activity on the Moon. 20 International scientific conference Astronomical School of Young Scientists. May 23-24, 2018. Uman, Ukraine. P. 5-7.

31. Vidmachenko A.P. (2023) Volcanoes of Mars. Conference Proceedings of the VIII International Scientific and Practical Conference «Theories of world science and technology implementation» (May 08-10). Chapter 2. Osaka, Japan, p. 13-19.

32. Vidmachenko A.P., Morozhenko A.V. (2013) Will there be Ukraine on the moon? 13 Ukrainian Conference on Space Research with International Participation. September 2-6, 2013, Yevpatoria, Ukraine, p. 219.

33. Vidmachenko A.P., Morozhenko O.V. (2017) The physical characteristics of the surface of the satellites and rings of giant planets. Kyiv: Editorial and publishing department of NUBiP of Ukraine. -412 p.

34. Vidmachenko A.P., Morozhenko O.V. (2019) Physical parameters of terrestrial planets and their satellites. Kyiv, Editorial and Publishing Department of NULES of Ukraine. -468 p.

35. Vidmachenko A.P., Mozgovyi A.V., Steklov O.F. (2021) The Moon and its water resources. Astronomy and the present: materials of the 10th All-Ukrainian scientific conference, April 12, 2021, Vinnytsia / ed.: V.F. Zabolotny, O.V. Mozgovyi. - Vinnytsia: LLC "TVORY", p. 58-59.

36. Vidmachenko A.P., Steklov A.F. (2020) Mineral resources can be mined on different bodies of the Solar System. 22 International scientific conference Astron. School of Young Scientists. December 11–12 2020. Kyiv, Ukraine, p. 89-92.

37. Vidmachenko A.P., Steklov A.F. (2020) Minerals will be mined on the Moon. 22 International scientific conference Astron. School of Young Scientists. December 11–12 2020. Kyiv, Ukraine, p. 94-95.

38. Vidmachenko A.P., Steklov O. F. (2023) Features of volcanic activity on the surface of Venus. Basics of learning the latest theories and methods. Proceedings of the IX International Scientific and Practical Conference. (March 07 – 10, 2023). Chapter 7. Boston, USA. International Science Group, p. 39-46.

39. Vidmachenko A.P., Steklov A.F. (2022) Activity of volcanic processes on Jupiter's Moon Io. Proceedings of IX International Scientific and Practical Conference. International scientific innovations in human life. (March 16-18, 2022). Chapter 12. Cognum Publishing House, Manchester, United Kingdom. P. 80-89.

40. Vidmachenko A.P., Steklov A.F. (2022) Features of lunar volcanism. International scientific innovations in human life. Proceedings of the 8th International scientific and practical conference. Cognum Publishing House. Manchester, United Kingdom. 16-18.02.2022. P. 180-188.

41. Vidmachenko A.P., Steklov A.F. (2022) Features of volcanic structures on Venus. Proceedings of the 9th International scientific and practical conference. Modern directions of scientific research development. BoScience Publisher. Chicago, USA. 23-25.02.2022. P. 195-204.

42. Vidmachenko A.P., Steklov A.F. (2022) Modern volcanism on Venus. Proceedings of the 7th International scientific and practical conference. Innovations and prospects of world science. (March 2-4, 2022). Chapter 19. Perfect Publishing. Vancouver, Canada. P. 119-129.

43. Vidmachenko A.P., Steklov O.F. (2025) Evidence and forms of volcanic activity on Venus. In book: Vidmachenko A. P., Ovsak O. S., Kuznetsova J. G., Steklov O. F. The influence of volcanic activity on the formation of the Venus surface. Chapter: 4. Publisher: Primedia eLaunch, Boston, USA. -101 p.

44. Vidmachenko A.P., Vidmachenko H.A. (2007) Is it dangerous asteroids? Astronomical almanac. 53, p. 195-207.

45. Weber R.C., Garcia R., Johnson C.L., et al. (2010) The use of deep moonquakes for constraining the internal structure of the Moon. American Geophysical Union, Fall Meeting 2010, abstract id. U51B-0037.

46. Weber R.C., Lin P.-Y., Garnero E.J., et al. (2011) Seismic Detection of the Lunar Core. Science. 331(6015), p. 309.

47. Wieczorek M. A., Neumann G. A., Nimmo F., Zuber M. T. (2012) The crust of the moon as seen by GRAIL. Science, 339(6120), p. 671-675.

48. Wieczorek M. A., Zuber M. T. (2001) The composition and origin of the lunar crust: Constraints from central peaks and crustal thickness modeling. Geoph. Research Letters, 28(21), p. 4023-4026.

49. Wieczorek, M. A., Phillips, R. J. (2000). The “Procellarum KREEP Terrane”: Implications for mare volcanism and lunar evolution. Journal of Geophysical Research: Planets, 105(E8), 20417-20430.

50. Yatskiv Ya.S., Vidmachenko A.P., Sosonkin M.G., Lapchuk V.P. (2009) Development of the onboard devices for Moon research. 9 Ukrainian Conference on Space Research with International Participation. August 31-September 5, 2009. The program and abstracts. Yevpatoria, Ukraine. P. 37.

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.

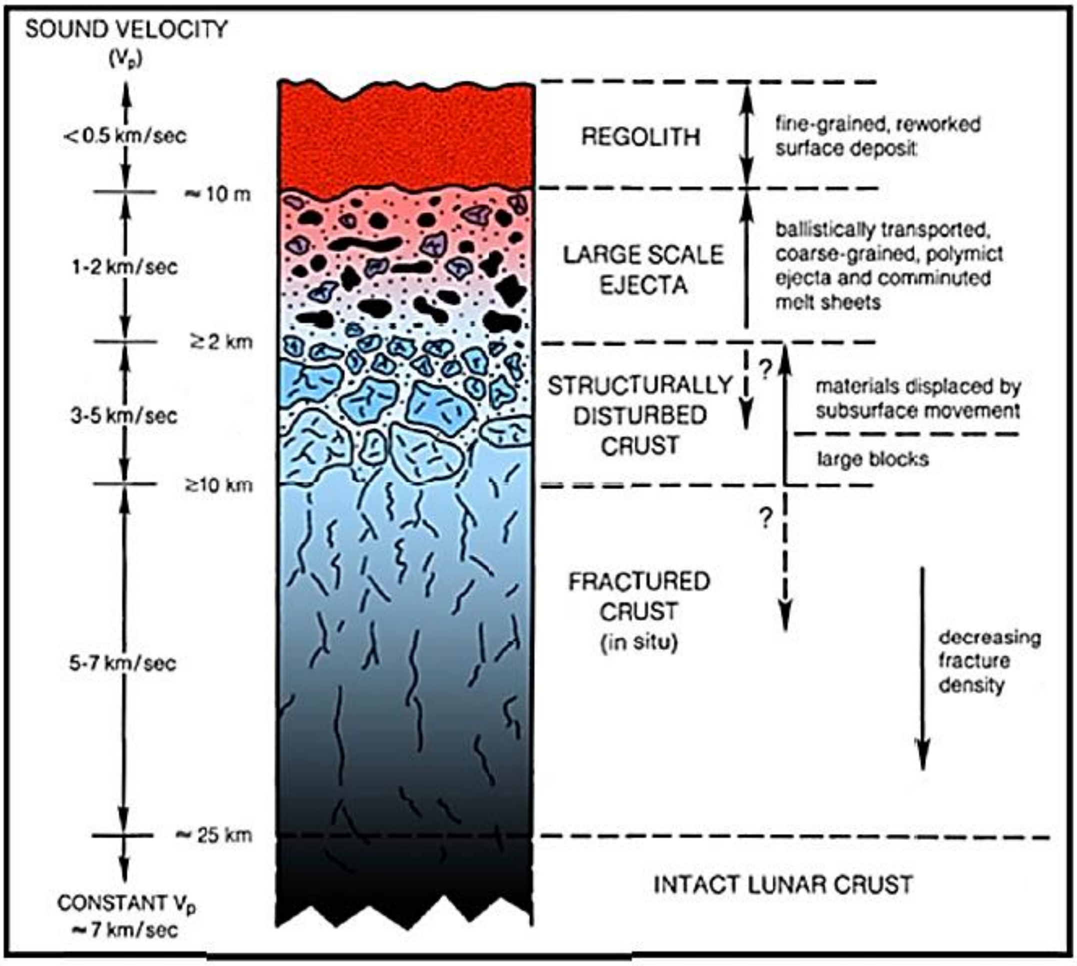

Fig. 3.1. Schematic cross-section of the upper 25 km of the lunar surface, illustrating the effect of large-scale cratering on the structure of the lunar crust [30]

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.

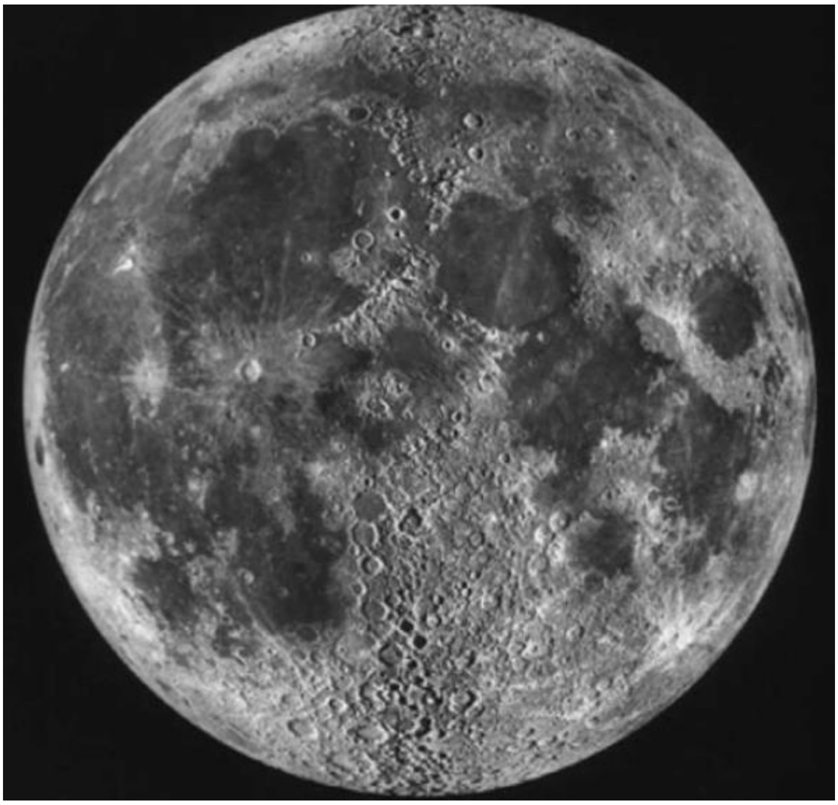

Fig. 3.2. The photograph shows the contrast between the heavily cratered highlands and the smooth, dark basaltic sea plains. Mare Imbrium is prominent in the northwestern quadrant. The dark, basalt-flooded region to the west is Oceanus Procellarum. Mare Crisium is a dark, round basaltic patch on the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

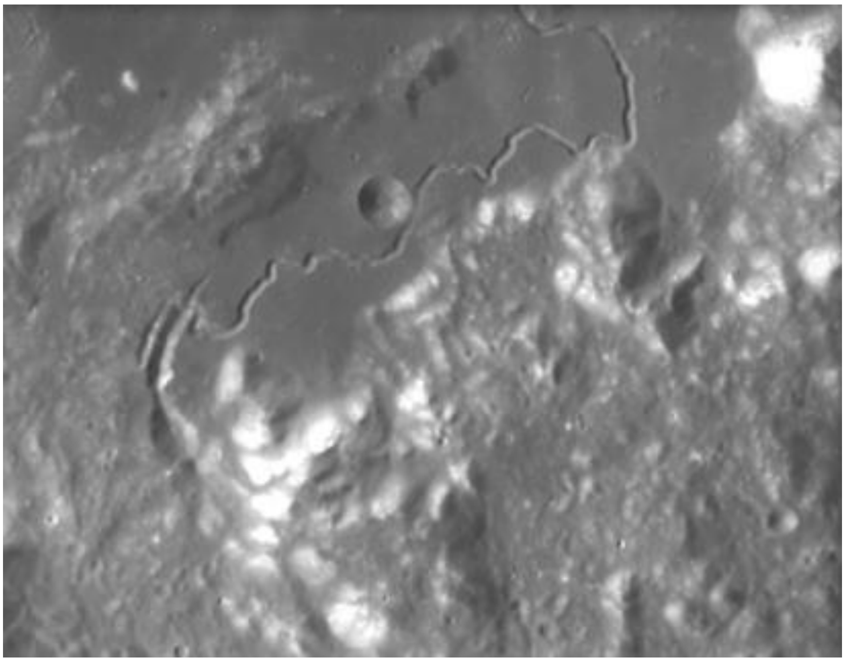

Fig. 3.3. The image shows the winding Hadley Rille, reminiscent of river valleys on Earth; it runs through the upper half of this image; below it are the Apennine mountains (1-2 km high); the large crater in the center of the image is Hadley C crater with a diameter of 5.5 km (https://cdn.sci.esa.int/documents/34677/35605/1567219136347-hadley1.jpg).

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.

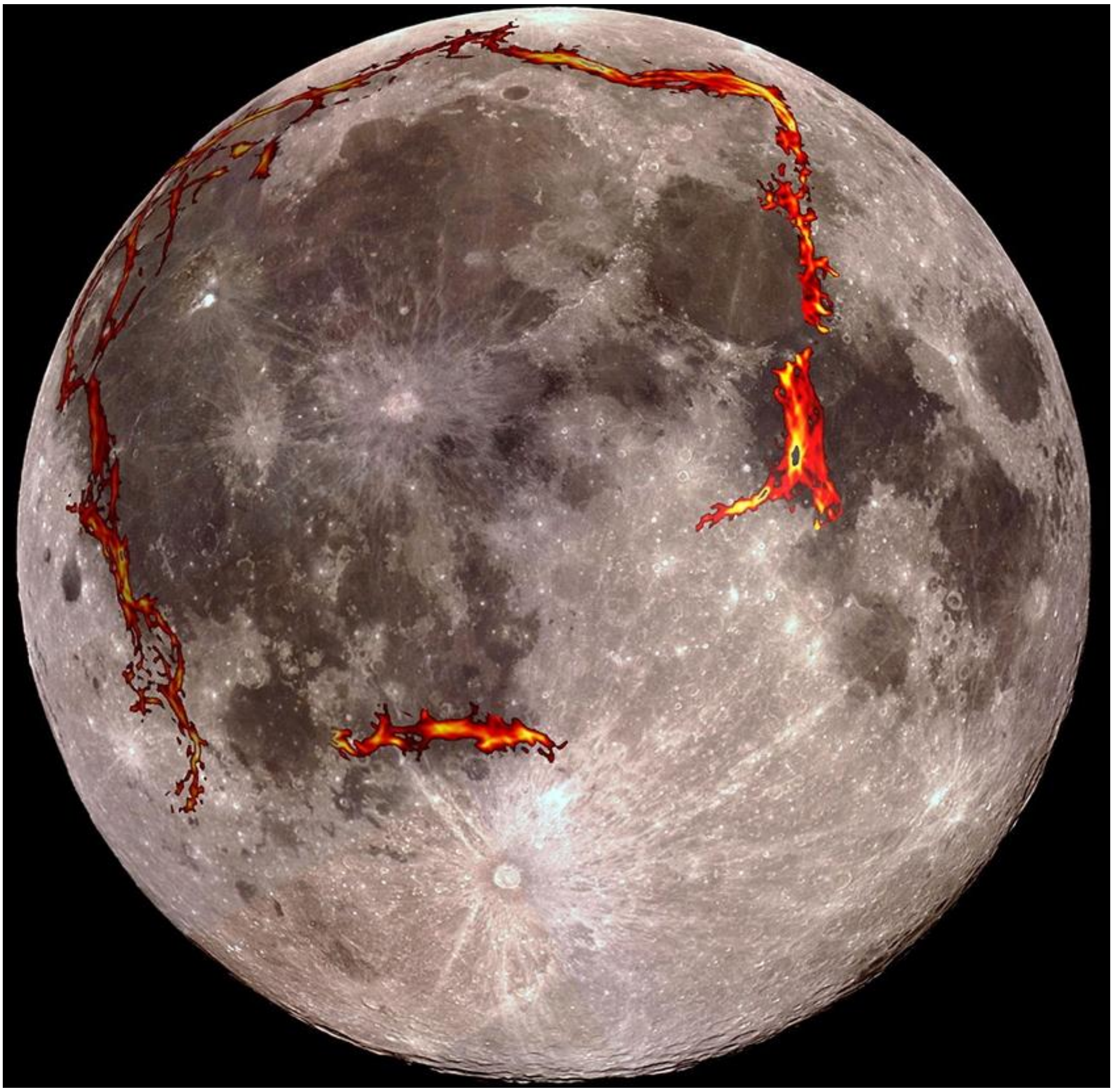

Fig. 3.4. Image of the *Oceanus Procellarum* region surrounded by many linear gravitational anomalies (highlighted in red), detected by NASA's GRAIL spacecraft (http://www.americaspace.com/wp-content/uploads/2014/10/Figure2_fullmoon.jpg)

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.

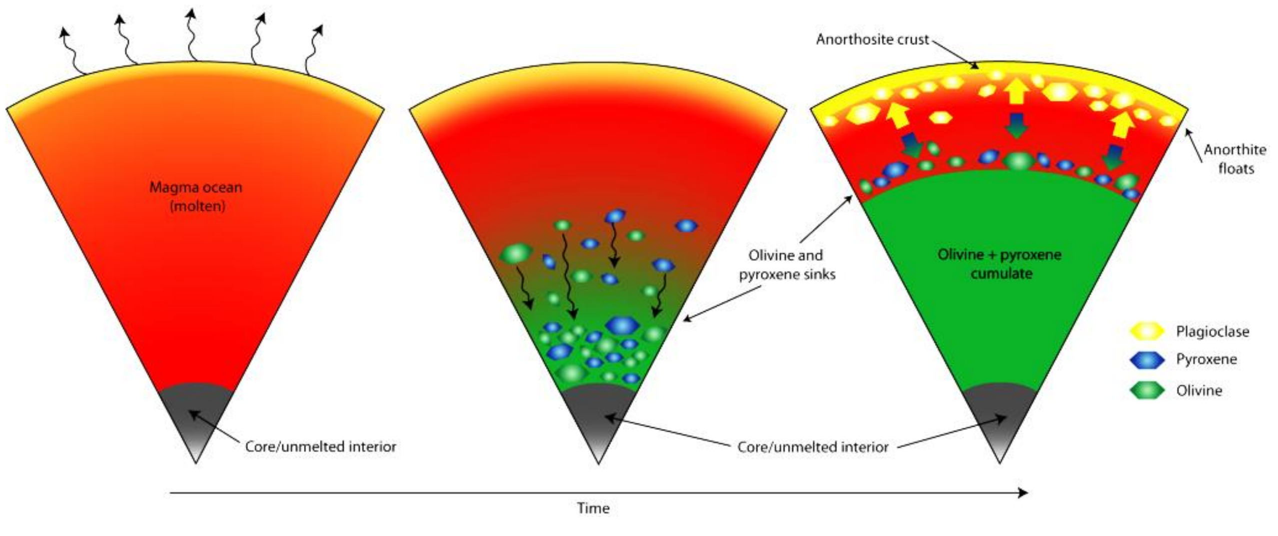

Fig. 3.5. Cross-section of the lunar interior during and after the formation of a hypothetical lunar magma ocean. Heavy minerals (olivine and pyroxene) sink to the surface of the core and form a thick mantle rich in mafic rocks. Lighter minerals (plagioclase feldspar) float to the surface, forming an 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.

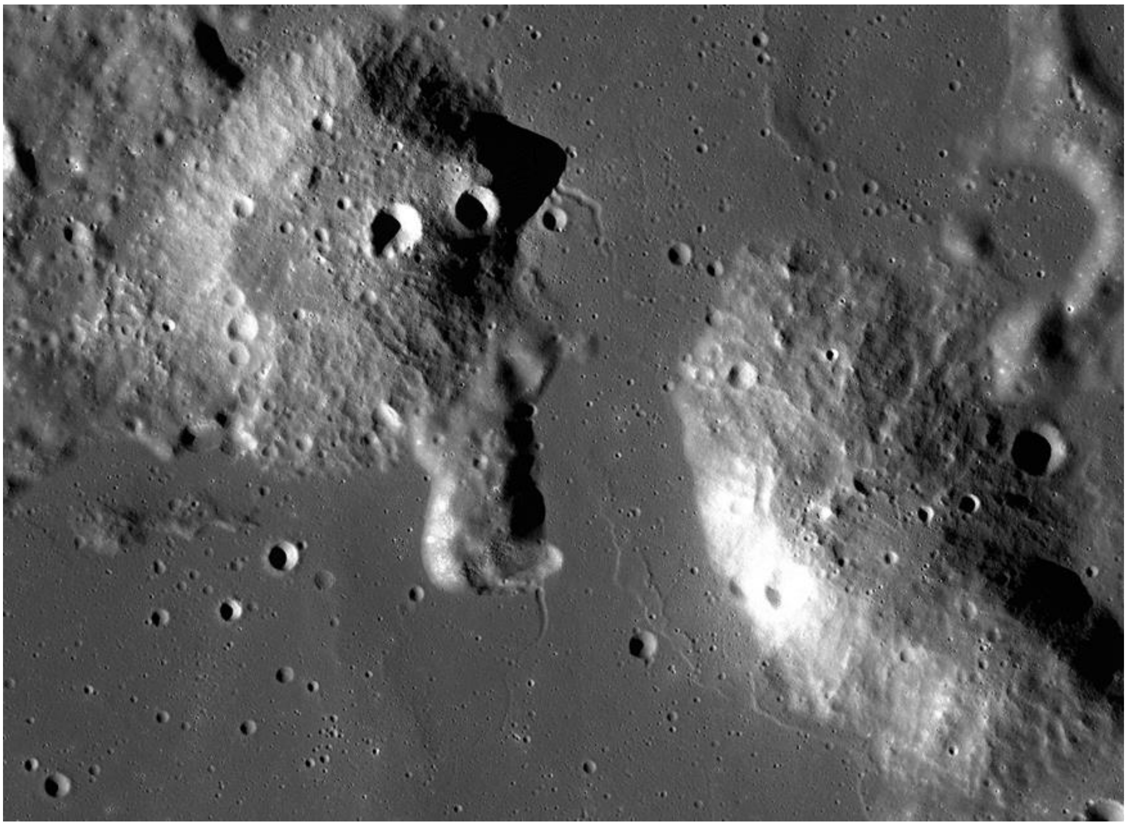

Fig. 3.6. The Gruythuizen domes were formed by eruptions of silicic lavas (https://assets.science.nasa.gov/dynamicimage/assets/science/psd/lunar-science/2023/08/Gruithuisen_Domes-1.png?w=1100&h=1100&fit=clip&crop=faces%2Cfocalpoint).

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).

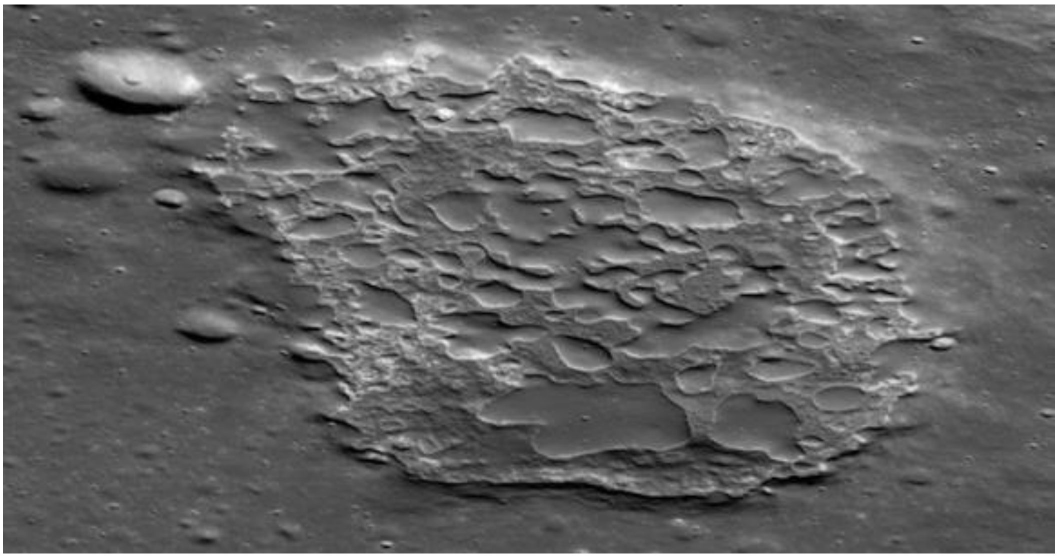

Fig. 3.7. The volcano called Ina is about 3 km long, 2 km wide, and 50 meters deep. Its floor is covered with many small, low lava mounds. The number of craters observed on the mounds indicates that the eruptions occurred about 33 million years ago (https://earthsky.org/upl/2014/10/mon-volcano-2-e1413139625498.jpg).

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.

References:

1. Binder A.B. (1998) Lunar Prospector: Overview. Science. 281(5382), p. 1475–1476.

2. Braden S.E., Stopar J.D., Robinson M.S., et al. (2014) Evidence for basaltic volcanism on the Moon within the past 100 million years. Nat. Geosci. 7 (11), p. 787–791.

3. Gagnepain-Beyneix J., Lognonné Ph., Chenet H., et al. (2006) A seismic model of the lunar mantle and constraints on temperature and mineralogy. 159(3–4), p. 140-166.

4. Head III J.W. (1976) Lunar volcanism in space and time. Reviews of Geophysics. 14(2), p. 265-300.

5. Head III J.W., Wilson L., Hiesinger H., et al. (2023) Lunar mare basaltic volcanism: Volcanic features and emplacement processes. Reviews in Mineralogy and Geochemistry, 89(1), p. 453-507

6. Jansen J.C., Andrews-Hanna J.C., Li Y., et al. (2016) Small-scale density variations in the lunar crust revealed by GRAIL. Icarus. 291, p. 107-123.

7. Jawin E. R., Besse S., Mazrouei S., et al. (2013) Spectral Signature of Lunar Pyroclastic Deposits in Moon Mineralogy (M3) data. 44th Lunar and Planetary Science Conference. 1662.pdf.

8. Morozhenko A.V., Vidmachenko A.P., Kostogryz N.M. (2015) Spectrophotometric properties of Moon's and Mars's surfaces exploration by shadow mechanism. Highlights of Astronomy. 16, p. 182-182.

9. Morozhenko O.V., Vidmachenko A.P. (2017) Possible space experiment “Mineralogical mapping of the Moon’s surface”. 17th Ukrainian Conference on Space Research, Odessa, Aug. 21- 25 2017: abstracts, p. 44.

10. Shkuratov Yu.G., Lytvynenko L.M., Shulga V.M., et al. (2003) Objectives of a prospective Ukrainian orbiter mission to the Moon. Advances in Space Research. 31(11), p. 2341-2345.

11. Snape, J. F., Nemchin, A. A., Bellucci, J. J., et al. (2016). Lunar basalt chronology, mantle differentiation and implications for determining the age of the Moon. Earth and Planetary Science Letters, 451, 149-158.

12. Steklov O.F., Vidmachenko A.P., Kolotilov M.M., et al. (2020) Moon should become a testing ground for special adaptation systems at terraforming of planets. Collection of abstracts. II International scientific-practical conference, II Shklov readings "Problems of modern natural sciences and mathematics and methods of their teaching", October 28-29, 2020, Glukhiv. P. 33-34.

13. Vid’Machenko A.P. (1995) Settling of dust in Jupiter’s atmosphere after the impact of fragments of comet Shoemaker-Levy 9. Kinematics and Physics of Celestial Bodies. 11(4), p. 14-16.

14. Vid’Machenko A.P., Morozhenko A.V. (2004) Mapping of the physical characteristics of a superficial layer of the Moon and ultra-violet polarimetry from orbital station of the Moon. 4th Ukrainian Conference on Space Research with International Participation. August 31-September 5, 2004, p. 30.

15. Vid’machenko A.P., Morozhenko A.V. (2005) Mapping of the physical characteristics and mineral composition of a superficial layer of the Moon or Mars and

ultra-violet polarimetry from the orbital station. 36th Lunar and Planetary Science Conference, March 14-18, 2005, League City, Texas, abstract #1015.

16. Vidmachenko A.P. (2014) Study of Earth-like planets. 16 International scientific conference Astronomical School of Young Scientists. Kirovohrad, Ukraine. May 29–31, 2014. P. 12-13.

17. Vidmachenko A.P. (2018) Comparative features of volcanoes on Solar system bodies. 20 International scientific conference Astronomical School of Young Scientists. May 23–24, 2018. Uman, Ukraine, p. 9-12.

18. Vidmachenko A.P. (2018) Features of volcanic activity on various bodies of the Solar system. Materials of the International Scientific and Practical Conference "The Objectives of the Sustainable Development of the Third Millennium: Challenges for Universities of Life Sciences", vol. 5, May 23-25, 2018, Kyiv, p. 41-42.

19. Vidmachenko A.P. (2018) Features of volcanoes on different Solar system bodies. Astronomical School's Report. 14(1), p. 1-14.

20. Vidmachenko A.P. (2018) Modern volcanic activity on the Moon. 20 International scientific conference Astronomical School of Young Scientists. May 23-24, 2018. Uman, Ukraine. P. 5-7.

21. Vidmachenko A.P. (2023) Volcanoes of Mars. Conference Proceedings of the VIII International Scientific and Practical Conference «Theories of world science and technology implementation» (May 08-10). Chapter 2. Osaka, Japan, p. 13-19.

22. Vidmachenko A.P., Morozhenko O.V. (2019) Physical parameters of terrestrial planets and their satellites. Kyiv, Editorial and Publishing Department of NULES of Ukraine. -468 p.

23. Vidmachenko A.P., Steklov A.F. (2020) Mineral resources can be mined on different bodies of the Solar System. 22 International scientific conference Astronomical School of Young Scientists. December 11–12 2020. Kyiv, Ukraine, p. 89-92.

24. Vidmachenko A.P., Steklov A.F. (2022) Features of lunar volcanism. International scientific innovations in human life. Proceedings of the 8th International

scientific and practical conference. Cognum Publishing House. Manchester, United Kingdom. 16-18.02.2022. P. 180-188.

25. Vidmachenko A.P., Steklov A.F. (2022) Features of volcanic structures on Venus. Proceedings of the 9th International scientific and practical conference. Modern directions of scientific research development. BoScience Publisher. Chicago, USA. 23-25.02.2022. P. 195-204.

26. Vidmachenko A.P., Steklov A.F. (2022) Modern volcanism on Venus. Proceedings of the 7th International scientific and practical conference. Innovations and prospects of world science. (March 2-4, 2022). Chapter 19. Perfect Publishing. Vancouver, Canada. P. 119-129.

27. Vidmachenko A.P., Steklov O.F. (2023) Features of volcanic activity on the surface of Venus. Basics of learning the latest theories and methods. Proceedings of the IX International Scientific and Practical Conference. (March 07 – 10, 2023). Chapter 7. Boston, USA. International Science Group, p. 39-46.

28. Vidmachenko A.P., Steklov O.F. (2025) Evidence and forms of volcanic activity on Venus. In book: Vidmachenko A. P., Ovsak O. S., Kuznetsova J. G., Steklov O. F. The influence of volcanic activity on the formation of the Venus surface. Chapter: 4. Publisher: Primedia eLaunch, Boston, USA. -101 p. P. 71-84.

29. Vidmachenko A.P., Vidmachenko H.A. (2007) Is it dangerous asteroids? Astronomical almanac. 53, p. 195-207.

30. Weber R.C. (2014) Interior of the Moon. In book: Encyclopedia of the Solar System (Third Edition). Chapter 24. P. 539-554.

31. Weber R.C., Garcia R., Johnson C.L., et al. (2010) The use of deep moonquakes for constraining the internal structure of the Moon. American Geophysical Union, Fall Meeting 2010, abstract id. U51B-0037.

32. Weber R.C., Lin P.-Y., Garnero E.J., et al. (2011) Seismic Detection of the Lunar Core. Science. 331(6015), p. 309.

33. Wieczorek M. A., Neumann G. A., Nimmo F., Zuber M. T. (2012) The crust of the moon as seen by GRAIL. Science, 339(6120), p. 671-675.

34. Wieczorek M. A., Zuber M. T. (2001) The composition and origin of the lunar crust: Constraints from central peaks and crustal thickness modeling. Geoph. Research Letters, 28(21), p. 4023-4026.

35. Wieczorek, M. A., Phillips, R. J. (2000). The “Procellarum KREEP Terrane”: Implications for mare volcanism and lunar evolution. Journal of Geophysical Research: Planets, 105(E8), 20417-20430.

36. Williams D.B., Ramsey M.S. (2024) Infrared spectroscopy of volcanoes: from laboratory to orbital scale. Frontiers in Earth Science. Vol. 12, id.1308103.

37. Yatskiv Ya.S., Vidmachenko A.P., Morozhenko O.V., Sosonkin M.G. (2007) Design and ultraviolet UV spektrofotopolyarymetra CFP remote mineralogical mapping of the surface layer of the moon aboard the lunar orbiter ("Ukrselena-satellite"). 7 Ukrainian Conference on Space Research. September 2-9, 2007. The program and abstracts. Evpatoria, Ukraine. - P. 173.

38. Zhang D., Li X., Li Q., et al. (2014) Lunar surface heat flow mapping from radioactive elements measured by Lunar Prospector. Acta Astronautica. 99(1), p. 85–91.

DOI: 10.46299/979-8-90214-588-2.4

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.

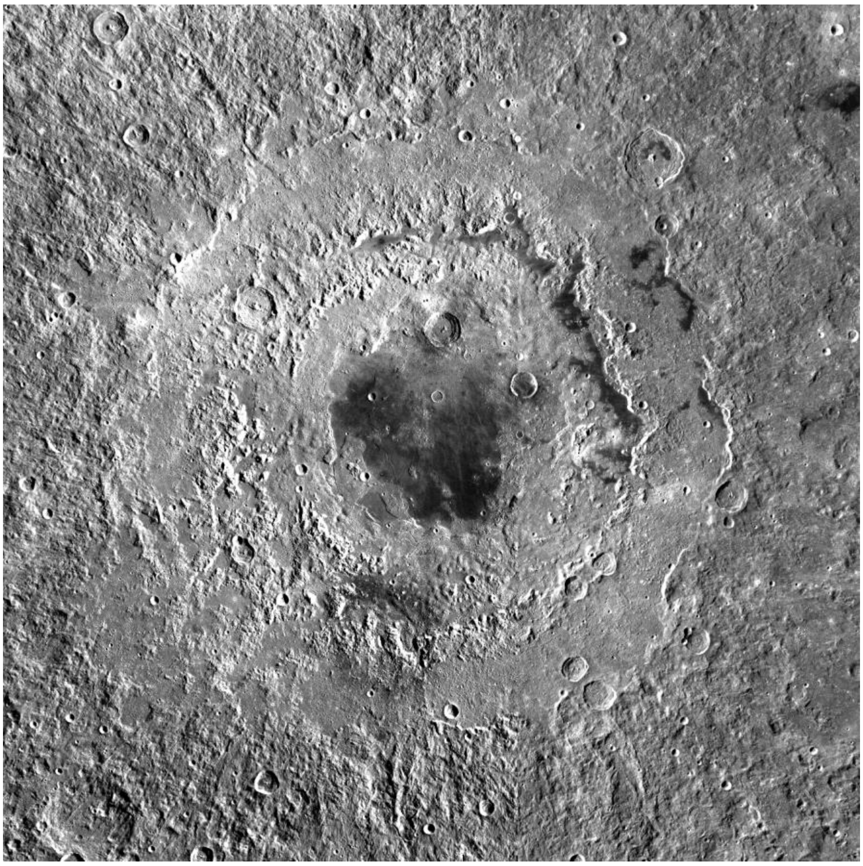

Fig. 4.2. Mare Orientale is the youngest of the large lunar basins, formed 3.8 billion years ago; its outer ring has a diameter of up to 1000 km; unlike most basins, it was not completely filled with lava (https://upload.wikimedia.org/wikipedia/commons/3/32/Mare_Orientale_%28LRO%29.png).

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.

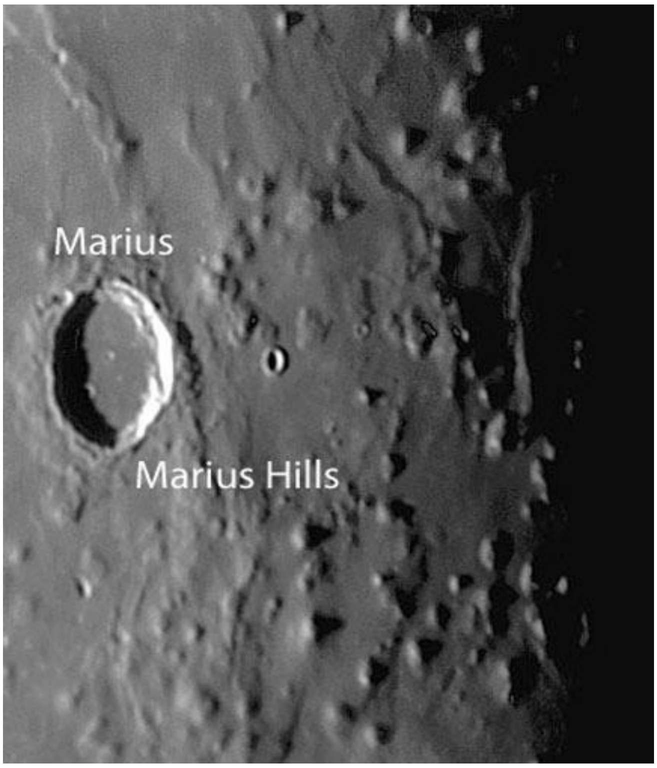

Fig. 4.4. Marius Hills is a wide field near Marius Crater with many domes between 200 and 500 m high. Marius Hills is a wide field near Marius Crater with many domes between 200 and 500 m high (https://skyandtelescope.org/wp-content/uploads/Domes-Marius-wide-Jim-Phillips_edited-1.jpg).

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 features* 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.

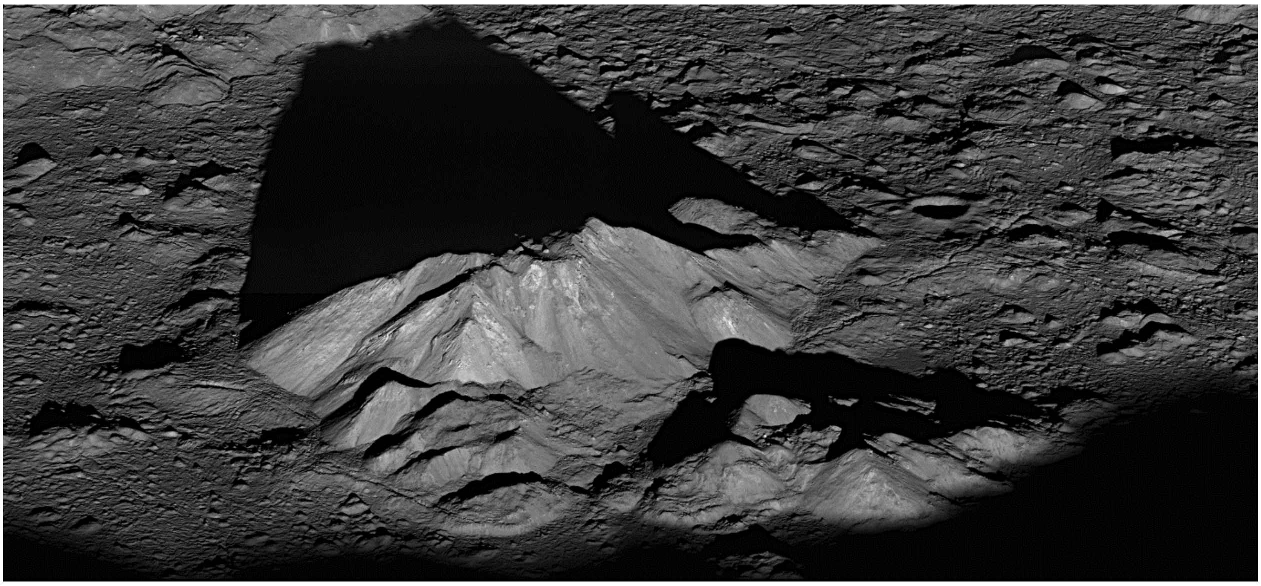

Fig. 4.5. The central peak of Tycho Crater in the image is about 15 km wide (left to right in this image) (https://lroc.im-ldi.com/news/uploads/M162350671LE.small2.png).

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.

References:

1. Allen C.C., Greenhagen B.T., DonaldsonHanna K.L., et al. (2011) Analysis of Lunar Pyroclastic Glass Deposit FeO Abundances by LRO Diviner. Lunar Exploration Analysis Group. Houston, TX, United States, November 7-9, JSC-CN-24714.

2. Besse S., Jawin E.R., Mazrouei S. et al. (2013) Spectral Signature of Lunar Pyroclastic Deposits in Moon Mineralogy (M3) data. 44th Lunar and Planetary Science Conference. 1662.pdf.

3. Braden, S. E., Stopar, J. D., Robinson, M. S., et al. (2014) Evidence for basaltic volcanism on the Moon within the past 100 million years. Nat. Geosci. 7 (11), p. 787–791.

4. Elkins-Tanton L.T., Burgess S., Yin Q.Z., et al. (2011) The lunar magma ocean: Reconciling the solidification process with lunar petrology and geochronology. Earth Planet. Sci. Lett. 304, p. 326–336.

5. Farrand W.H., Trang D., Li Sh. (2023) Dark mantles over domes and rilles on the Moon: Evidence for pyroclastic materials. Icarus. 406, December 2023, Article 115759.

6. Haruyama J., Hioki K., Shirao M., et al. (2009) Possible lunar lava tube skylight observed by SELENE cameras. Geophysical Research Letters. 36(21), p. L21206-1-5.

7. Head III J.W., Wilson L., Hiesinger H., et al. (2023) Lunar mare basaltic volcanism: Volcanic features and emplacement processes. Reviews in Mineralogy and Geochemistry, 89(1), p. 453-507. https://doi.org/10.2138/rmg.2023.89.11

8. Hiesinger H., Head J., Wolf U., et al. (2011) Ages and stratigraphy of lunar mare basalts: A synthesis. Geological Society of America Special Papers. 477, p. 1-51.

9. Hiesinger, H. V., Van Der Bogert, C. H., Pasckert, J. H., et al. (2012) How old are young lunar craters? Journal of Geophysical Research: Planets. 117(E00H10), p. 1-15.

10. Jawin E. R., Besse S., Mazrouei S., et al. (2013) Spectral Signature of Lunar Pyroclastic Deposits in Moon Mineralogy (M3) data. 44th Lunar and Planetary Science Conference. 1662.pdf.

11. Lawson S.L., Feldman W.C., Lawrence D.J. et al. (2005) Recent outgassing from the lunar surface: The Lunar Prospector Alpha Particle Spectrometer. Journal of geophysical research. 10(E09009), p. 1-8.

12. Lin Y., Tronche E.J., Steenstra E.S., van Westrenen W. (2017) Experimental constraints on the solidification of a nominally dry lunar magma ocean. Earth Planet. Sci. Lett. 471, p. 104–116.

13. Morozhenko A.V., Vid'machenko A.P. (2006) Mapping of physical characteristics of a superficial layer of the Moon and ultra-violet polarimetry from orbital lunar station. 36th COSPAR Scientific assembly. The second world space congress. Huston, Texas, USA, 12-21 October 2006, p. 54-55.

14. Morozhenko A.V., Vidmachenko A.P. (2004) Moon Base and Problems of Global Changes on the Earth. Journal of Automation and Information Sciences. 36(11), p. 27-31.

15. Morozhenko A.V., Vidmachenko A.P., Kostogryz N.M. (2015) Spectrophotometric properties of Moon's and Mars's surfaces exploration by shadow mechanism. Highlights of Astronomy. 16, p. 182-182.

16. Morozhenko O.V., Vidmachenko A.P. (2017) Features of the method for mapping of physical characteristics of lunar surface according to the data of ultraviolet polarimetry. 17th Ukrainian Conference on Space Research, Odessa, Aug. 21- 25 2017: abstracts, p. 43.

17. Neal C.R., Taylor L.A. (1992) Petrogenesis of mare basalts: A record of lunar volcanism. Geochimica et Cosmochimica Acta. 56, p. 2177-2211.

18. Pieters C.M., Goswami J.N., Clark R.N., et al. (2009) Character and Spatial Distribution of OH/H2O on the Surface of the Moon Seen by M3 on Chandrayaan-1. Science, 326(5952), 568-572.

19. Schultz P.H., Staid M.I., Pieters C.M. (2006) Lunar activity from recent gas release. Nature. 444(7116), p. 184–186.

20. Shkuratov Yu.G., Lytvynenko L.M., Shulga V.M., et al. (2003) Objectives of a prospective Ukrainian orbiter mission to the Moon. Advances in Space Research. 31(11), p. 2341-2345.

21. Snape, J. F., Nemchin, A. A., Bellucci, J. J., et al. (2016) Lunar basalt chronology, mantle differentiation and implications for determining the age of the Moon. Earth and Planetary Science Letters, 451, 149-158.

22. Steklov E.A., Vidmachenko A.P., Steklov A.F. (2019) The water resource of the Moon is sufficient for its colonization. 6-th Gamow International Conference in Odessa "New Trends in Astrophysics, Cosmology and HEP after Gamow" and 19-th Gamow Summer School "Astronomy and beyond: Astrophysics, Cosmology, Radioastronomy and Astrobiology", Ukraine, Odessa, August 11-18, 2019, p. 43.

23. Su B., Yuan J., Chen Y., et al. (2022) Fusible mantle cumulates trigger young mare volcanism on the cooling Moon. Sci Adv. 8(42), eabn2103.

24. Trang D., Gillis-Davis J.J., Lemelin M., et al. (2017) The compositional and physical properties of localized lunar pyroclastic deposits. Icarus. 283, p. 232-253.

25. Vid'Machenko A.P. (1995) Settling of dust in Jupiter's atmosphere after the impact of fragments of comet Shoemaker-Levy 9. Kinematics and Physics of Celestial Bodies. 11(4), p. 14-16.

26. Vid'Machenko A.P., Morozhenko A.V. (2004) Mapping of physical characteristics of the Moon's superficial layer and ultra-violet polarimetry from a lunar orbital station. Kosmichna Nauka i Tekhnologiya. 10(5/6), p. 21-27.

27. Vid'Machenko A.P., Morozhenko A.V. (2004) Mapping of the physical characteristics of a superficial layer of the Moon and ultra-violet polarimetry from orbital station of the Moon. 4th Ukrainian Conference on Space Research with International Participation. August 31-September 5, 2004, p. 30.

28. Vid’Machenko A.P., Morozhenko A.V. (2006) The application of the brewster angle data for the lunar surface mapping by the real part of the refractive index. Solar System Research. 40(6), p. 462-467.

29. Vidmachenko A.P. (2012) The magnetic field of planets, satellites and asteroids. Astronomical School's Report. 8(2), p. 136-148.

30. Vidmachenko A.P. (2014) Study of Earth-like planets. 16 International scientific conference Astronomical School of Young Scientists. Kirovohrad, Ukraine. May 29–31, 2014. P. 12-13.

31. Vidmachenko A.P. (2016) Activity of processes on the visible surfaces of Solar System bodies. Astr. School’s Report 12 (1), p. 14-26.

32. Vidmachenko A.P. (2018) Comparative features of volcanoes on Solar system bodies. 20 International scientific conference Astronomical School of Young Scientists. May 23–24, 2018. Uman, Ukraine, p. 9-12.

33. Vidmachenko A.P. (2018) Features of volcanic activity on various bodies of the Solar system. Materials of the International Scientific and Practical Conference "The Objectives of the Sustainable Development of the Third Millennium: Challenges for Universities of Life Sciences", vol. 5, May 23-25, 2018, Kyiv, p. 41-42.

34. Vidmachenko A.P. (2018) Features of volcanoes on different Solar system bodies. Astronomical School’s Report. 14(1), p. 1-14.

35. Vidmachenko A.P. (2018) Modern volcanic activity on the Moon. 20 International scientific conference Astronomical School of Young Scientists. May 23-24, 2018. Uman, Ukraine. P. 5-7.

36. Vidmachenko A.P. (2023) Volcanoes of Mars. Conference Proceedings of the VIII International Scientific and Practical Conference «Theories of world science and technology implementation» (May 08-10). Chapter 2. Osaka, Japan, p. 13-19.

37. Vidmachenko A.P., Morozhenko A.V. (2013) Will there be Ukraine on the moon? 13 Ukrainian Conference on Space Research with International Participation. September 2-6, 2013, Yevpatoria, Ukraine, p. 219.

38. Vidmachenko A.P., Morozhenko O.V. (2019) Physical parameters of terrestrial planets and their satellites. Kyiv, Editorial and Publishing Department of NULES of Ukraine. -468 p.

39. Vidmachenko A.P., Mozgovyi A.V., Steklov O.F. (2021) The Moon and its water resources. Astronomy and the present: materials of the 10th All-Ukrainian scientific conference, April 12, 2021, Vinnytsia / ed.: V.F. Zabolotny, O.V. Mozgovyi. - Vinnytsia: LLC "TVORY", p. 58-59.

40. Vidmachenko A.P., Steklov A.F. (2020) Mineral resources can be mined on different bodies of the Solar System. 22 International scientific conference Astronomical School of Young Scientists. December 11–12 2020. Kyiv, Ukraine, p. 89-92.

41. Vidmachenko A.P., Steklov A.F. (2020) Minerals will be mined on the Moon. 22 International scientific conference Astronomical School of Young Scientists. December 11–12 2020. Kyiv, Ukraine, p. 94-95.

42. Vidmachenko A.P., Steklov A.F. (2022) Features of lunar volcanism. International scientific innovations in human life. Proceedings of the 8th International scientific and practical conference. Cognum Publishing House. Manchester, United Kingdom. 16-18.02.2022. P. 180-188.

43. Vidmachenko A.P., Steklov A.F. (2022) Features of volcanic structures on Venus. Proceedings of the 9th International scientific and practical conference. Modern directions of scientific research development. BoScience Publisher. Chicago, USA. 23-25.02.2022. P. 195-204.

44. Vidmachenko A.P., Steklov A.F. (2022) Modern volcanism on Venus. Proceedings of the 7th International scientific and practical conference. Innovations and prospects of world science. (March 2-4, 2022). Chapter 19. Perfect Publishing. Vancouver, Canada. P. 119-129.

45. Vidmachenko A.P., Vidmachenko H.A. (2007) Is it dangerous asteroids? Astronomical almanac. 53, p. 195-207.

46. Weber R.C., Garcia R., Johnson C.L., et al. (2010) The use of deep moonquakes for constraining the internal structure of the Moon. American Geophysical Union, Fall Meeting 2010, abstract id. U51B-0037.

47. Weber R.C., Lin P.-Y., Garnero E.J., et al. (2011) Seismic Detection of the Lunar Core. Science. 331(6015), p. 309.

48. Wieczorek M. A., Neumann G. A., Nimmo F., Zuber M. T. (2012) The crust of the moon as seen by GRAIL. Science, 339(6120), p. 671-675.

49. Wieczorek M. A., Zuber M. T. (2001) The composition and origin of the lunar crust: Constraints from central peaks and crustal thickness modeling. Geoph. Research Letters. 28(21), p. 4023-4026.

50. Wieczorek, M. A., & Phillips, R. J. (2000). The "Procellarum KREEP Terrane": Implications for mare volcanism and lunar evolution. Journal of Geophysical Research: Planets, 105(E8), p. 20417-20430.

51. Williams D.B., Ramsey M.S. (2024) Infrared spectroscopy of volcanoes: from laboratory to orbital scale. Frontiers in Earth Science. Vol. 12, id.1308103.

52. Yatskiv Ya.S., Vidmachenko A.P., Sosonkin M.G., Lapchuk V.P. (2009) Development of the onboard devices for Moon research. 9 Ukrainian Conference on Space Research with International Participation. August 31-September 5, 2009. The program and abstracts. Yevpatoria, Ukraine. P. 37.

53. Zhang D., Li X., Li Q., et al. (2014) Lunar surface heat flow mapping from radioactive elements measured by Lunar Prospector. Acta Astronautica. 99(1), p. 85–91. DOI: 10.1016/j.actaastro.2014.01.020.

DOI: 10.46299/979-8-90214-588-2.5

5. Lunar volcanism: types of formations, research methods and historical evolution

Introduction

Volcanism, as a fundamental geological process, plays a key role in the formation and evolution of the surfaces of planets, moons, and other solid celestial bodies in the Solar System. This process involves the release of molten rock, known as magma (or lava after eruption onto the surface), as well as gases and solid particles from the interior of a celestial body onto its surface or into the atmosphere.

The Moon, our closest neighbor in space. It shows abundant evidence of intense volcanic activity in its distant past, which has significantly influenced its present appearance. The study of volcanism on the Moon [38-40] is extremely important for understanding not only its own geological history and thermal evolution, but also for comparison with volcanic processes on other bodies in the Solar System, including Earth, Venus [33, 51-53], Mars [41], the moon Io, etc. The study of lunar volcanoes helps to reveal the secrets of the formation and evolution of rocky planets and moons and may also have practical significance for future exploration and possible development of the Moon [9, 14, 16].

5.1. Types of volcanic formations on the surface of the Moon

The surface of the Moon exhibits a variety of volcanic formations, which testify to its rich magmatic history. These formations are mainly of silicate origin, formed by eruptions of molten rock [1]. The surface of the Moon is not homogeneous and contains a variety of volcanic formations, which testify to different stages and styles of volcanic activity in its history. Among the most noticeable and important volcanic features of the Moon are lunar seas, volcanic domes and cones, lava tubes, pyroclastic deposits, and rilles.

Mare Basalts are large, dark, basaltic plains [6, 8, 18] that cover over 17% of the Moon's surface, mostly on the near side. They are the most obvious volcanic features on the Moon visible to the naked eye. These lava flows are hundreds of meters thick and are similar to basaltic lava flows on Earth. The lunar mare appears darker than the surrounding mountainous areas. They got their name in ancient times when they were mistaken for bodies of water. In fact, the lunar mare is a vast expanse of solidified basaltic lava flows that filled ancient impact basins.

Among the most famous and largest lunar mare is the *Oceanus Procellarum*, which is the largest formation of its type on the Moon, reaching a diameter of about 2590 km. Other significant seas include *Mare Imbrium*, with a diameter of about 1,123 km, formed by a giant impact; *Mare Tranquillitatis*, known as the site of the first human landing on the Moon, with a diameter of about 873 km; and Mare Crisium, an isolated circular sea with a diameter of about 418 km. Also worth mentioning are *Mare Fecunditatis, Mare Frigoris, Mare Humorum, Mare Nubium), Mare Serenitatis, Mare Vaporum, Mare Nectaris, Mare Marginis, Mare Smythii, Mare Humboldtianum, Mare Moscoviense (on the reverse side, Mare Orientale (partly on the reverse side), Mare Australe*, and other smaller formations.

The lunar seas are composed mainly of basalt, which is an igneous rock rich in iron and magnesium, with a low viscosity. This allowed the lava to spread over great distances, filling the depressions of the impact basins.

The age of the lunar maria, determined by radiometric dating of samples returned to Earth by the “Apollo” and “Luna” missions, ranges from 4.2 to 3.16 billion years. Crater-counting dating [7] also indicates the possible existence of younger lava flows, up to 1.2 billion years old. Interestingly, the Chang'e-5 mission found basalts that are about 2.03 billion years old; this indicates a longer period of volcanic activity on the Moon than previously thought. The predominant location of the lunar maria on the near side of the Moon is a significant asymmetry. This phenomenon may be related to the different crustal thickness between the near and far sides of the Moon, as well as to the concentration of heat-generating elements such as potassium, rare earth elements and phosphorus (KREEP) in certain regions, particularly in *Oceanus Procellarum* (Fig. 5.1) and in Mare Imbrium.

Fig. 5.1. In Oceanus Procellarum (highlighted) is the bright crater Aristarchus (https://i0.wp.com/cosmicreflections.skythisweek.info/wp-content/uploads/2020/04/oceanus_procellarum.jpg?w=840&ssl=1).

The difference in age between the oldest and youngest seas indicates a long period of volcanic activity on the Moon, which may reflect the gradual cooling of its interior [4, 11, 17, 55, 56] and changes in magma sources over billions of years. Marine basalts formed from eruptions of low-viscosity basaltic lava that filled basins and craters [36, 37]. The energy source for their formation must have been radiogenic heating in the primordial lunar interior.

Lunar basalts differ from terrestrial basalts in that they have a higher iron content and a lower silicon and aluminum content; this 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 marine basalts to be classified by TiO_2 (very low Ti, low Ti, and high Ti), Al_2O*3*, and K. For example, basalts with high Ti contents were found at the “Apollo 11” and “Apollo 17” landing sites. These studies have shown that the lunar mantle is significantly depleted in rare earth elements beneath the widely spaced landing sites; this supports a global differentiation process.

5.2. Morphological features associated with seas

Lava tubes are tunnels formed by the cooling of the outer part of a lava flow, allowing the inner lava to continue flowing. That is, lava tubes are subsurface cavities formed by the flow of lava beneath the frozen surface of a lava flow. When the lava stops flowing and the top of the flow has solidified, a tunnel or tube forms. Lava tubes on the Moon are sometimes detected by skylights, openings formed by the collapse of the tube ceiling, providing access to the underground cavity [5] (Fig. 5.2).

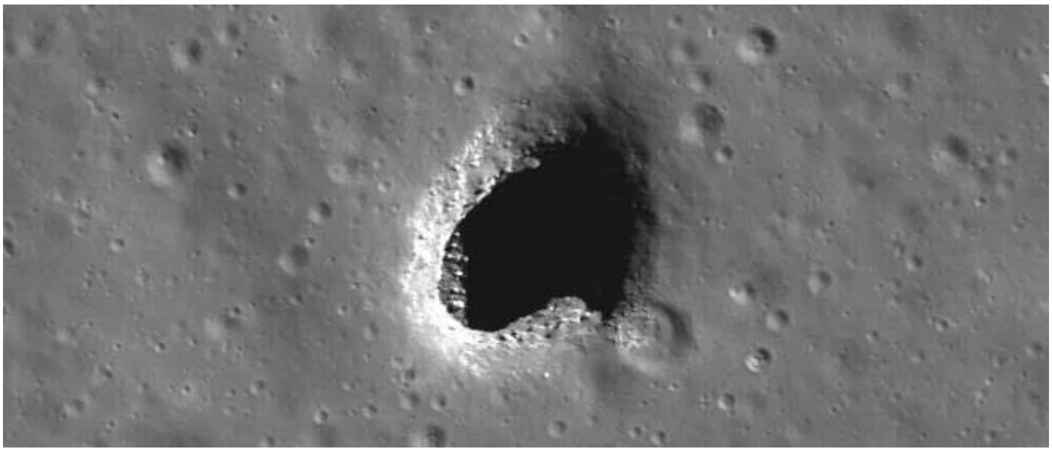

Fig. 5.2. The pit to the volcanic cave at Mare Ingenii has a diameter of about 130 meters (https://cdn.mos.cms.futurecdn.net/iSUyCz6iF6eHhqCMXPezKc-650-80.jpg.webp).

Known lava tube locations include the *Marius Hills* area, *Mare Tranquillitatis*, and possibly *Mare Serenitatis*. Lunar lava tubes can be of considerable size, reaching over 300 meters in diameter and more than 40 m deep below the surface. These subsurface cavities have been considered as potential sites for future lunar bases [19-25, 34, 43], as they may provide protection from cosmic and solar radiation, meteorites, and extreme temperatures. Lava tubes form during effusive basaltic volcanism, when lava flows over considerable distances, cooling from above and forming a solid crust. The extensive network of lava tubes may indicate long-term and large-scale eruptions of basaltic lava in the past [50]. The study of lava tubes can provide valuable information about the physical properties of lunar lava (viscosity, temperature), as well as the possibility of preserving water ice in them, especially in shaded areas.

Rilles are channel-like structures formed by lava flows. They are long, narrow depressions on the lunar surface that resemble canals. They come in several types, including sinuous, arcuate, and linear (Fig. 5.3).

Sinuous rilles have a curved, sinuous shape and are thought to be solidified lava channels or collapsed lava tubes. They often start from small craters that may be former volcanic vents. The most famous is *Schroter's Valley*, which stretches for hundreds of kilometers.

Arcuate rilles have a more gentle curvature and are located mainly at the edges of lunar seas. They are thought to have formed as lava flows cooled and compressed, causing deformation of the surface.

Linear rilles are straight in shape and are usually associated with tectonic faults in the lunar crust, indicating the stretching or shifting of crustal blocks. Examples include *Rima Hyginus* and *Rima Ariadaeus*.

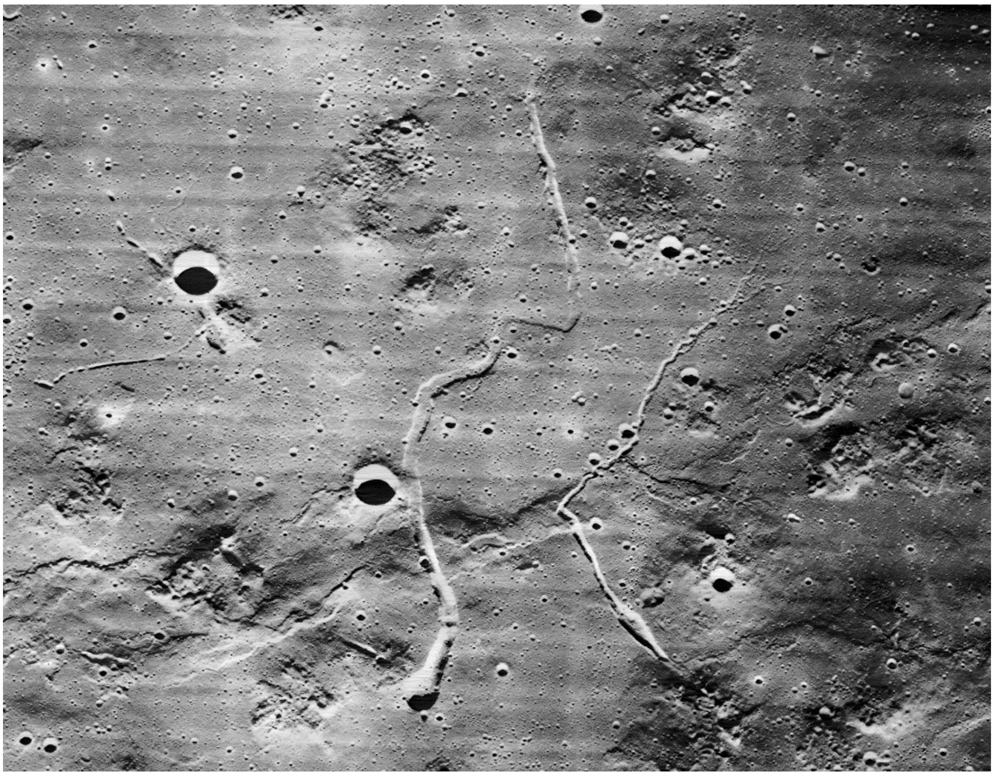

Fig. 5.3. Image of a plateau 45 km wide northwest of Marius crater on the Moon; two *Sinuous rilles* in the *Marius Hills* region cross the ridge; volcanic domes and cones are also visible (https://www.lpi.usra.edu/resources/lunarorbiter/images/preview/5213_med.jpg).

The morphology of arcuate rilles (their length, width, depth, and presence of meanders) can provide information about the viscosity of the lava, its flow velocity, and the volume of the eruption that produced them. Arcuate rilles can indicate processes of subsidence and deformation of the edges of lunar basins under the weight of lava.

Studying the direction and distribution of rilles can help reconstruct the paleogeography of lunar lava fields, determine the locations of former volcanic centers, and understand the mechanisms of lava transport on the lunar surface.

Domes and Cones. Numerous small, rounded or oval elevations, known as volcanic domes [3] and cones, can be observed on the surface of lunar mare. Due to the low gravity (one-sixth that of Earth), eruptions can eject material much further, forming wide, thin layers around the vent, rather than steep cones as on Earth.

These formations are considered shield volcanoes, formed by the eruption of more viscous lava or by intrusive processes where magma does not reach the surface but causes it to rise. The size of the domes can vary but is usually 8–12 km in diameter and rises a few hundred meters above the surrounding plain. Some domes have small, cratered depressions on their summits, evidence of former lava outflows.

Notable clusters of basalt domes include *Marius Hills*, one of the largest volcanic complexes on the Moon, 330 km in diameter with dozens, perhaps hundreds, of domes and cones; *Mons Rümker*, a somewhat smaller complex similar in appearance to *Marius Hills*, is 70 km in diameter with about 30 domes reaching heights of up to 1300 m. Some domes, such as *Manilius 1*, have low circular polarization coefficients, indicating smooth, rock-poor surfaces or possibly pyroclasts.

The *Gruithuisen Domes* are two large domes, 20 km and 13 km in diameter, which are distinct from basaltic domes and may have a different composition. There are also isolated domes, such as the 30 km *Valentine dome* and a few others. The composition of most domes is thought to be basaltic, similar to lunar sea lava, but the discovery of domes with a higher silica content, such as the *Gruithuisen Domes* and the *Mairan T dome* (Fig. 5.4), suggests a variety of magmatic processes on the Moon. Clustering of domes in certain regions may indicate localized sources of magma or features of the crustal tectonic structure that contributed to their formation. Differences in morphology (e.g., steepness of slopes) between different domes may reflect differences in the viscosity of the lava at the time of eruption or different mechanisms of their formation (extrusive versus intrusive). The discovery of silicate domes, whose composition is similar to rhyolite or dacite on Earth, raises questions about magmatic differentiation processes on the Moon that could have led to the formation of more viscous lava in the absence of water and plate tectonics typical of Earth.

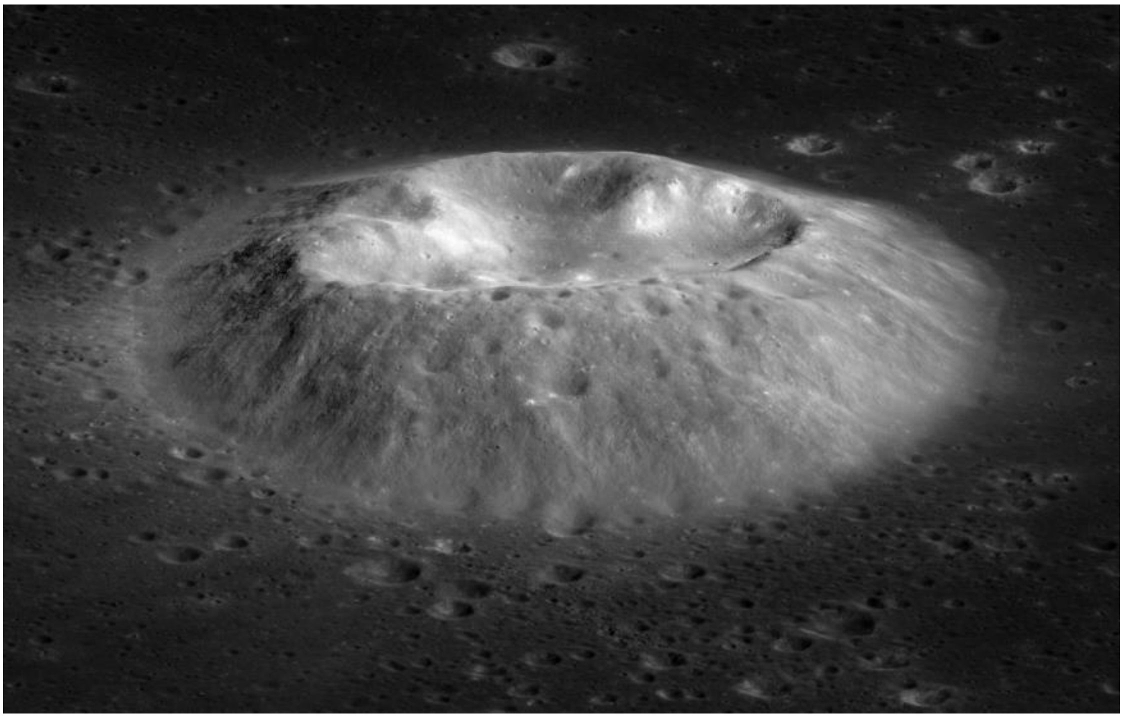

Fig. 5.4. The silicic volcano Mairan T is over 600 m high; its albedo contrasts sharply with the surrounding dark marine basalts of Oceanus Procellarum; the image width is 6.6 km (https://lroc.im-ldi.com/ckeditor_assets/pictures/1222/content_09_M1387416559_LRmos.Mairan_T_1100x1100.png).

Dark Mantle Deposits – DMDs – formed by lava fountain eruptions, when molten lava, driven by dissolved gases, was ejected high above the surface and cooled rapidly, forming small spheres of solidified lava glass. These deposits consist primarily of orange and black glass spheres rich in iron and titanium. The largest known pyroclastic deposits are located along the edges of lunar seas or in craters, including large areas near Taurus Littrow, Sinus Estuum, Aristarchus Plateau, and other regions on the near side of the Moon. Due to the lower gravity on the Moon, pyroclasts could be scattered over much greater distances, forming extensive deposits that can cover thousands of square kilometers and reach a thickness of up to 10–20 meters.

The presence of pyroclastic deposits suggests that lunar magma contained dissolved gases (probably carbon monoxide and dioxide), although their concentrations were much lower than in terrestrial magma, leading to less powerful explosive eruptions. The location of these deposits is often associated with cracks and faults in the lunar crust that served as channels for magma to escape. Pyroclastic deposits may be a valuable source of oxygen and may also contain other useful elements such as hydrogen and helium-3, making them important for planning future lunar missions and possible development of lunar resources.

These *Dark Mantle Pyroclastic Deposits* are low-albedo areas ranging in size from 10 km^2 to over 50,000 km^2; they are covered by fine-grained material. These areas often host sinusoidal rilles, irregular depressions, craters with fissures in the floor, and impact craters located around seas.

Larger DMDs, such as those at *Taurus-Littrow* and *Mare Vaporum*, are known to contain glass beads rich in iron and titanium. Smaller DMDs are typically composed of iron-bearing *mafic minerals* such as pyroxene and olivine. *Chromite-spinel* was recently discovered in a large DMD at *Sinus Aestuum*.

Pyroclastic glasses are the deepest and most primitive basalts on the Moon, originating directly from the lunar mantle. Recent analyses have documented the presence of water in this glass, suggesting that the lunar interior is much richer in volatiles than previously thought.

Wrinkle ridges are tectonic features that form in areas of compression, often in the center of impact basins, where the surface bends around features beneath the lava, such as old impact craters.

Irregular Mare Patches (IMPs) are enigmatic volcanic features on the lunar surface, as the absence of impact craters [28, 54] and their distinct appearance suggest that they formed less than 100 million years ago; that is, about 1 billion years after the previously expected cessation of lunar volcanism.

Although their young appearance may be the result of a recent eruption, it has also been suggested that they may be ancient volcanic deposits that appear young because of the high porosity of the material or because of collapse or drainage processes into subsurface cavities. The most famous example is *Ina*, a small structure photographed by Apollo 15 in 1971, the origin of which is still debated.

5.3. Historical changes in volcanic features on the lunar surface

The history of the Moon is divided into five generally recognized geological periods, reflecting the evolution of its volcanic activity.

Table 5.1.

Lunar geological time scale and associated volcanic activity

Period/Epoch	Age (billion years ago)	Defining events	Characteristics of volcanism
Pre-Nectarian	4.5 – 3.92	Formation of the lunar crust (~4.42 Ga), formation of 30 impact basins (e.g., South Pole–Aitken basin)	Lack of significant marine basalts; early crustal differentiation.
Nectarian	3.92 – 3.85	Formation of 12 multi-ring impact basins (e.g., Serenitatis, Crisium)	Early marine volcanism begins, but less extensive than in the Imbrian period.
Early Imbrian	3.85 – 3.80	Formation of the Imbrium and Orientale basins	Intense marine volcanism begins, filling large basins.
Late Imbrian	3.80 – 3.2	Completion of large basin formation	Peak of marine volcanism, formation of most visible seas.
Eratosthenian	3.2 – 1.1	Craters almost destroyed by erosion (impact cratering)	Significantly fewer basaltic eruptions; activity possible until 1.2 Ga.
Copernican	1.1 – Present	Presence of bright ray systems around craters	Very rare, small-scale volcanic events; activity possible until 50-120 Ma.

The Moon has been volcanically active for most of its history, with the first volcanic eruptions occurring around 4.2 billion years ago. The peak of marine volcanism occurred between 3.8 and 3.2 billion years ago. This activity was long thought to have ceased around 1 billion years ago.

However, more recent evidence suggests a longer and more complex history:

Young basalts are volcanic rocks returned by the "Chang'e-5" mission, which were dated to 2.03 billion years ago, making them the youngest samples recovered from the Moon. This extends the known duration of lunar volcanism by about 800–900 million years. Among the thousands of glass beads in the soil samples returned by "Chang'e-5", three *young glass beads*, C, were identified as volcanic and were only 120 million years old. *Irregular marine spots* (IMPs) also appear young, with ages less than 100 million years [2]. This also suggests potentially recent volcanism.

This extension of the known duration of lunar volcanism has profound implications for understanding the entire 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 could be the presence of radioactive elements underground that could generate enough heat to form magma.

Despite significant progress, it remains a mystery why the far side of the Moon, which always faces away from Earth, is so radically different from the near side, with a thicker crust and an almost complete absence of seas from ancient lava oceans. These differences point to a complex and possibly asymmetric thermal and geological evolution of the Moon.

5.4. Data underlying inferences about volcanic changes

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

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 (called the half-life). The more of the daughter nuclide present relative to the parent nuclide, the more time has passed since the decay clock was "started". This method is applicable to a variety of volcanic materials.

Samples returned by the “Apollo” and “Luna” missions, as well as lunar meteorites, have allowed the establishment of a geological chronology on the Moon. Radiometric dating of lunar sea samples has yielded an age range of 3.16 to 4.2 billion years. 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 is a method of estimating the age of the surface of a planet, 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 young ages of about 1.2 billion years for some marine sediments.

Despite their value, crater counting has limitations and uncertainties. Reliability can vary considerably, especially for very young surfaces, where counts are often limited to craters of smaller diameter. Smaller craters may be less reliable for age estimation because their size-frequency distribution is more prone to change. Factors that affect accuracy include the following features:

Impact velocity, where the size-frequency distribution of impactors is not fully known, and there may be variations in impact velocity over time.

Heterogeneity of crater formation, where secondary craters formed by ejecta from primary impacts and secondary craters formed by the impact of "new" meteoroids can "contaminate" crater populations; these features of crater formation affect age determinations.

Properties of the object under study, such as differences in the strength of the material on the surface of the object, affect the formation of craters. After the formation of craters, they undergo a kind of modification under the influence of erosion, when deposition and diffusion creep can change the original morphology of the craters, making their surface somewhat younger than it actually is.

Statistical and observational biases also impose certain limitations on the number of craters formed and their counting; there is an influence from changes in lighting conditions and the resolution of the resulting images that can affect the identification of craters and the accuracy of their age (Fig. 5.5).

Fig. 5.5. An 18-meter crater in the Sea of Rains appeared on March 17, 2013. The flare was recorded from Earth [27] (https://upload.wikimedia.org/wikipedia/commons/a/a0/New_crater_on_the_Moon_%2817_March_2013%29.png).

Geological mapping and stratigraphy of the Moon, based on principles of stratigraphy (such as the law of superposition), allows us to order geological events in time. The identification of impact basins such as Nectaris and Imbrium as stratigraphic markers has allowed us to create a relative chronology of lunar events. Modern geological maps of the Moon synthesize data from the Apollo missions and recent satellite missions.

Compositional analysis of the chemical and mineralogical composition of lunar samples (marine basalts, pyroclastic glass, etc. [48, 49]) and remote sensing data using spectral [13, 58] and polarimetric [12, 15, 29-32, 57] measurements provide critical information about magma sources, mantle melting processes, the degree of lunar differentiation, and the presence of volatiles [26, 47]. For example, the discovery of water in lunar pyroclastic glass has changed the understanding of the volatile content of the lunar interior.

Conclusion

Lunar volcanism is a key element in understanding the geological evolution of the Moon and, more broadly, the entire inner Solar System [35, 44-46]. From vast basaltic seas that formed billions of years ago to mysterious irregular seamounts and young volcanic samples, the Moon preserves a rich record of magmatic activity.

Data obtained through sample-return missions ("Apollo", "Luna", "Chang'e-5") and advanced remote sensing have allowed scientists not only to identify and classify volcanic formations, but also to date them precisely, revealing a dynamic history that extends much further than previously thought. A combination of radiometric dating, crater counting, and geological mapping provides the basis for these conclusions, providing both absolute and relative chronological frameworks.

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.

References:

1. Bischoff A., Horstmann M., Barrat J.-A., et al. (2014) Trachyandesitic volcanism in the early Solar System. Earth, Atmospheric, and Planetary Sciences 111(35), p. 12689-12692.

2. Braden, S. E., Stopar, J. D., Robinson, M. S., et al. (2014) Evidence for basaltic volcanism on the Moon within the past 100 million years. Nat. Geosci. 7 (11), p. 787–791.

3. Farrand W.H., Trang D., Li Sh. (2023) Dark mantles over domes and rilles on the Moon: Evidence for pyroclastic materials. Icarus. 406, December 2023, Article 115759.

4. Garcia, R.F., Khan, A., Drilleau, M. et al. (2019) Lunar Seismology: An Update on Interior Structure Models. Space Sci Rev. 215, P. 50. https://doi.org/10.1007/s11214-019-0613-y.

5. Haruyama J., Hioki K., Shirao M., et al. (2009) Possible lunar lava tube skylight observed by SELENE cameras. Geophysical Research Letters. 36(21), p. L21206-1-5.

6. Head J.W., Wilson L., Hiesinger H., et al. (2023) Lunar mare basaltic volcanism: Volcanic features and emplacement processes. Reviews in Mineralogy and Geochemistry, 89(1), p. 453-507.

7. Hiesinger H.V., Van Der Bogert C.H., Pasckert J.H., et al. (2012) How old are young lunar craters? Journal of Geophysical Research: Planets. 117(E00H10), p. 1-15.

8. Hiesinger, H., Head III, J. W., Wolf, U., et al. (2010) Ages and stratigraphy of lunar mare basalts in Mare Frigoris and other nearside maria based on crater size-frequency distribution measurements. Journal of Geophysical Research: Planets, 115(E3).

9. Kuznyetsova Y.G., Vidmachenko A.P., Steklov A.F. (2020) Astrobiology aspect of Moon’ study in the process of colonization. 20-th Gamow International Astronomical Conference-School "Astronomy and beyond: astrophysics, cosmology and gravitation, high energy physics, astroparticle physics, radioastronomy and astrobiology", Ukraine, Odessa, August 9-16, p. 21-22.

10. Li Q.L., Zhou Q., Liu Y., et al. (2021) Two-billion-year-old volcanism on the Moon from Chang'e-5 basalts. Nature. 600(7887), p. 54-58.

11. Lognonne P., Kobayashi N., Garcia R., et al. (2012) Lunar interior as seen by seismology: from Apollo to future missions. 39th COSPAR Scientific Assembly. Held 14-22 July 2012, in Mysore, India. Abstract D2.6-11-12, p.1102.

12. Morozhenko A.V., Vid'machenko A.P. (2006) Mapping of physical characteristics of a superficial layer of the Moon and ultra-violet polarimetry from orbital lunar station. 36th COSPAR Scientific assembly. The second world space congress. Huston. Texas. USA. 12-21 October 2006. - P. 54-55.

13. Morozhenko A.V., Vidmachenko A.P., Kostogryz N.M. (2015) Spectrophotometric properties of Moon's and Mars's surfaces exploration by shadow mechanism. Highlights of Astronomy. 16, p. 182-182.

14. Morozhenko O.V., Vid'Machenko A.P. (2004) An observing base on the Moon and the global ecological problem of the Earth. 4th Ukrainian Conference on Space Research with International Participation. August 31-September 5, 2004, Kyiv, Ukraine, p. 29.

15. Morozhenko O.V., Vidmachenko A.P. (2017) Features of the method for mapping of physical characteristics of lunar surface according to the data of ultraviolet polarimetry. 17th Ukrainian Conference on Space Research, Odessa, Aug. 21- 25 2017: abstracts, p. 43.

16. Morozhenko O.V., Vidmachenko A.P. (2017) Possible space experiment "Mineralogical mapping of the Moon's surface". 17th Ukrainian Conference on Space Research, Odessa, Aug. 21- 25 2017: abstracts, p. 44.

17. Neal C.R. (2006) Why the next generation of Moon exploration needs a global seismic network. European Planetary Science Congress 2006. Berlin, Germany, 18 - 22 September 2006, p. 291.

18. Snape J.F., Nemchin A.A., Bellucci J.J., et al. (2016) Lunar basalt chronology, mantle differentiation and implications for determining the age of the Moon. Earth and Planetary Science Letters, 451, p. 149-158.

19. Steklov A.F., Vidmachenko A.P. (2019) Creation and standardization of self-digging endoplanetary systems for Moon, Mars and Mercury. 7th International conference "Space technologies: present and future", 21-24 may 2019, p. 113.

20. Steklov A.F., Vidmachenko A.P. (2020) Ways to colonize the Moon. 22 International scientific conference Astronomical School of Young Scientists. December 11–12 2020. Kyiv, Ukraine, p. 84-85.

21. Steklov A.F., Vidmachenko A.P., Dashkiev G.N. (2019) On the creation of technology for a comfortable human life on the Moon. Lunar ISRU 2019. Developing a New Space Economy Through Lunar Resources and Their Utilization, July 15-17, 2019, Columbia, Maryland, id. 5033.

22. Steklov A.F., Vidmachenko A.P., Miniaylo D.M. (2019) Methods of heating areas for human living under the surface of the Moon. Lunar ISRU 2019. Developing a New Space Economy Through Lunar Resources and Their Utilization, July 15-17, 2019, Columbia, Maryland, LPI Contribution No 2152, id. 5107.

23. Steklov A.F., Vidmachenko A.P., Miniaylo D.N. (2019) Methods of heating areas where a person lives below the surface of the Moon. 6-th Gamow International Conference in Odessa “New Trends in Astrophysics, Cosmology and HEP after Gamow” and 19-th Gamow Summer School “Astronomy and beyond: Astrophysics, Cosmology, Radioastronomy and Astrobiology”, Ukraine, Odessa, August 11-18, 2019, p. 57-58.

24. Steklov A.F., Vidmachenko A.P., Miniaylo D.N. (2019) Ways of human survival on the Moon. 6-th Gamow International Conference in Odessa “New Trends in Astrophysics, Cosmology and HEP after Gamow” and 19-th Gamow Summer School “Astronomy and beyond: Astrophysics, Cosmology, Radioastronomy and Astrobiology”, Ukraine, Odessa, August 11-18, 2019, p. 57.

25. Steklov A.F., Vidmachenko A.P., Minyailo D.M. (2020) Heat engineering systems for comfortable human habitation on the Moon. Collection of abstracts. II International scientific-practical conference, II Shklov readings "Problems of modern natural sciences and mathematics and methods of their teaching", October 28-29, 2020, Glukhiv. P. 41-42.

26. Steklov E.A., Vidmachenko A.P., Steklov A.F. (2019) The water resource of the Moon is sufficient for its colonization. 6-th Gamow International Conference in Odessa “New Trends in Astrophysics, Cosmology and HEP after Gamow” and 19-th

Gamow Summer School “Astronomy and beyond: Astrophysics, Cosmology, Radioastronomy and Astrobiology”, Ukraine, Odessa, August 11-18 2019, p. 43.

27. Suggs R.M., Moser D.E., Cooke W.J., Suggs R.J. (2014) The flux of kilogram-sized meteoroids from lunar impact monitoring. Icarus, 238, p. 23-36.

28. Vid’Machenko A.P. (1995) Settling of dust in Jupiter’s atmosphere after the impact of fragments of comet Shoemaker-Levy 9. Kinematics and Physics of Celestial Bodies. 11(4), p. 14-16.

29. Vid’Machenko A.P., Morozhenko A.V. (2004) Mapping of physical characteristics of the Moon's superficial layer and ultra-violet polarimetry from a lunar orbital station. Kosmichna Nauka i Tekhnologiya. 10(5/6), p. 21-27.

30. Vid’Machenko A.P., Morozhenko A.V. (2004) Mapping of the physical characteristics of a superficial layer of the Moon and ultra-violet polarimetry from orbital station of the Moon. 4th Ukrainian Conference on Space Research with International Participation. August 31-September 5, 2004, p. 30.

31. Vid’machenko A.P., Morozhenko A.V. (2005) Mapping of the physical characteristics and mineral composition of a superficial layer of the Moon or Mars and ultra-violet polarimetry from the orbital station. 36th Lunar and Planetary Science Conference, March 14-18, 2005, League City, Texas, abstract #1015.

32. Vid’Machenko A.P., Morozhenko A.V. (2006) The application of the brewster angle data for the lunar surface mapping by the real part of the refractive index. Solar System Research. 40(6), p. 462-467.

33. Vidmachenko A.P., Steklov O.F. (2023) Features of volcanic activity on the surface of Venus. Basics of learning the latest theories and methods. Proceedings of the IX International Scientific and Practical Conference. (March 07 – 10, 2023). Chapter 7. Boston, USA. International Science Group, p. 39-46.

34. Vidmachenko A.P. Steklov A.F. Miniaylo D.N. Kolotilov N.N. (2022) The Moon Should Become the Main Testing Ground for the Development and Testing of Thermal and Gravitational Adaptation Systems for Terraforming of Planets and Planetoids. 53rd Lunar and Planetary Science Conference, held 7-11 March 2022 at The Woodlands, Texas. LPI Contribution No. 2678, 2022, id.1054.

35. Vidmachenko A.P. (2014) Study of Earth-like planets. 16 International scientific conference Astronomical School of Young Scientists. Kirovohrad, Ukraine. May 29–31, 2014. P. 12-13.

36. Vidmachenko A.P. (2016) Activity of processes on the visible surface of planets of Solar system. 18 International scientific conference Astronomical School of Young Scientists. National Aviation University, Kyiv, Ukraine, May 26-27, 2016. P. 23-27.

37. Vidmachenko A.P. (2016) Activity of processes on the visible surfaces of Solar System bodies. Astr. School's Report 12 (1), p. 14-26.

38. Vidmachenko A.P. (2018) Features of volcanic activity on various bodies of the Solar system. Materials of the International Scientific and Practical Conference "The Objectives of the Sustainable Development of the Third Millennium: Challenges for Universities of Life Sciences", vol. 5, May 23-25, 2018, Kyiv, p. 41-42.

39. Vidmachenko A.P. (2018) Features of volcanoes on different Solar system bodies. Astronomical School's Report. 14(1), p. 1-14.

40. Vidmachenko A.P. (2018) Modern volcanic activity on the Moon. 20 International scientific conference Astronomical School of Young Scientists. May 23-24, 2018. Uman, Ukraine. P. 5-7.

41. Vidmachenko A.P. (2023) Volcanoes of Mars. Conference Proceedings of the VIII International Scientific and Practical Conference «Theories of world science and technology implementation» (May 08-10). Chapter 2. Osaka, Japan, p. 13-19.

42. Vid'Machenko A.P., Morozhenko A.V. (2004) Mapping of the physical characteristics of a superficial layer of the Moon and ultra-violet polarimetry from orbital station of the Moon. 4th Ukrainian Conference on Space Research with International Participation. August 31-September 5, 2004, p. 30.

43. Vidmachenko A.P., Morozhenko A.V. (2013) Will there be Ukraine on the moon? 13 Ukrainian Conference on Space Research with International Participation. September 2-6, 2013, Yevpatoria, Ukraine, p. 219.

44. Vidmachenko A.P., Morozhenko A.V. (2014) The study Earth-like planets using spacecraft. Ast. School's Rep. 10(1), 6-19.

45. Vidmachenko A.P., Morozhenko O.V. (2014) The physical characteristics of surface Earth-like planets, dwarf and small (asteroids) planets, and their companions, according to distance studies. MAO NAS of Ukraine, NULES of Ukraine. Kyiv, Publishing House "Profi". -388 p.

46. Vidmachenko A.P., Morozhenko O.V. (2019) Physical parameters of terrestrial planets and their satellites. Kyiv, Editorial and Publishing Department of NULES of Ukraine. -468 p.

47. Vidmachenko A.P., Mozgovyi A.V., Steklov O.F. (2021) The Moon and its water resources. Astronomy and the present: materials of the 10th All-Ukrainian scientific conference, April 12, 2021, Vinnytsia / ed.: V.F. Zabolotny, O.V. Mozgovyi. - Vinnytsia: LLC "TVORY", p. 58-59.

48. Vidmachenko A.P., Steklov A.F. (2020) Mineral resources can be mined on different bodies of the Solar System. 22 International scientific conference Astronomical School of Young Scientists. December 11–12 2020. Kyiv, Ukraine, p. 89-92.

49. Vidmachenko A.P., Steklov A.F. (2020) Minerals will be mined on the Moon. 22 International scientific conference Astronomical School of Young Scientists. December 11–12 2020. Kyiv, Ukraine, p. 94-95.

50. Vidmachenko A.P., Steklov A.F. (2022) Features of lunar volcanism. International scientific innovations in human life. Proceedings of the 8th International scientific and practical conference. Cognum Publishing House. Manchester, United Kingdom. 16-18.02.2022. P. 180-188.

51. Vidmachenko A.P., Steklov A.F. (2022) Features of volcanic structures on Venus. Proceedings of the 9th International scientific and practical conference. Modern directions of scientific research development. BoScience Publisher. Chicago, USA. 23-25.02.2022. P. 195-204.

52. Vidmachenko A.P., Steklov A.F. (2022) Modern volcanism on Venus. Proceedings of the 7th International scientific and practical conference. Innovations and prospects of world science. (March 2-4, 2022). Chapter 19. Perfect Publishing. Vancouver, Canada. P. 119-129.

53. Vidmachenko A.P., Steklov O.F. (2025) Evidence and forms of volcanic activity on Venus. In book: Vidmachenko A. P., Ovsak O. S., Kuznetsova J. G., Steklov O. F. The influence of volcanic activity on the formation of the Venus surface. Chapter: 4. Publisher: Primedia eLaunch, Boston, USA. 101 p. P. 71-84.

54. Vidmachenko A.P., Vidmachenko H.A. (2007) Is it dangerous asteroids? Astronomical almanac. 53, p. 195-207.

55. Weber R.C., Garcia R., Johnson C.L., et al. (2010) The use of deep moonquakes for constraining the internal structure of the Moon. American Geophysical Union, Fall Meeting 2010, abstract id. U51B-0037.

56. Weber R.C., Lin P.-Y., Garnero E.J., et al. (2011) Seismic Detection of the Lunar Core. Science. 331(6015), p. 309.

57. Yatskiv Ya.S., Vidmachenko A.P., Morozhenko O.V., Sosonkin M.G. (2007) Design and ultraviolet UV spektrofotopolyarymetra CFP remote mineralogical mapping of the surface layer of the moon aboard the lunar orbiter ("Ukrselena-satellite"). 7 Ukrainian Conference on Space Research. September 2-9, 2007. The program and abstracts. Evpatoria, Ukraine. - P. 173.

58. Yatskiv Ya.S., Vidmachenko A.P., Sosonkin M.G., Lapchuk V.P. (2009) Development of the onboard devices for Moon research. 9 Ukrainian Conference on Space Research with International Participation. August 31-September 5, 2009. The program and abstracts. Yevpatoria, Ukraine. P. 37.

DOI: 10.46299/979-8-90214-588-2.6

6. Comparative analysis of volcanic activity on the Moon and in the Solar System

Introduction

The early history of the Moon was characterized by intense volcanism associated with the cooling of a primordial magma ocean, which led to the formation of a lunar crust composed mainly of anorthosite.

The first volcanic eruptions on the Moon occurred about 4.2 billion years ago. The period of most active basaltic volcanism, which led to the formation of most lunar mare, occurred between 3.8 and 3 billion years ago. During this period, about 70% of all lunar basaltic material was erupted. It was believed that major volcanic activity on the Moon gradually decreased and ceased about 1 billion years ago. However, recent studies, including analysis of samples returned by the "Chang'e-5" mission and the study of small volcanic formations known as *Irregular Mare Patches* (IMPs), indicate volcanic activity that lasted much longer, possibly up to 100 million years ago and even later. The age of the lunar seas has been determined by various methods, including radiometric dating of samples and impact crater counting.

There are hypotheses about the possibility of modern volcanic activity on the Moon [25], associated with the so-called *transient lunar phenomena* (TLPs) - short-term changes in brightness or color on the lunar surface, although their nature remains controversial.

The discovery of late volcanic activity, in particular basalts about 2 billion years old and IMPs that show signs of a young age (less than 100 million years) [2], casts doubt on traditional models of the thermal evolution of the Moon. These findings suggest that the Moon's interior may have cooled more slowly than previously thought, or that there were localized heat sources that supported magmatic activity for a longer period [43].

Detailed age distribution studies of the various types of volcanic features on the Moon, including lunar mare, domes, pyroclastic deposits, and IMPs, can help reconstruct a more accurate chronology of geological processes on the Moon and better understand its internal structure and composition, as well as compare the rates of volcanic activity at early and late stages of its evolution.

6.1. Introduction to Planetary Volcanism

Volcanism is defined as the geological process by which molten rock (magma) or volatiles (cryomagma) from the interior of a planet are erupted onto its surface. This process is fundamental to the geological evolution of planetary bodies, providing critical information about the composition and structure of their mantles, the location and duration of internal melting, and the nature of convection and thermal evolution. Volcanic activity is essential during crustal growth, as evidenced by the ubiquitous basaltic rocks on various planetary bodies. It shapes landscapes by forming volcanic cones, lava flows, and other features that encode information about subsurface magma transport and surface processes.

Volcanism in the Solar System is divided into two main types: silicate and cryovolcanism. Silicate volcanism involves the eruption of molten silicate rock, which is the predominant type of volcanism on rocky bodies such as Earth, the Moon, Mars, and Venus. Mafic (magnesium- and iron-rich) lavas, usually basaltic, are common and tend to form broad, gently sloping shield volcanoes and large lava plains. Silica-rich lavas are more viscous and tend to form steeper stratovolcanoes. In contrast, cryovolcanism involves the extrusion of liquids and vapors composed of volatile compounds such as water, ammonia, and methane. These substances would be frozen on the surface of icy bodies in the outer Solar System but may exist in liquid or slushy form below the surface.

The Moon plays a unique and invaluable role in understanding the early history of the Solar System. It preserves ancient geological processes that have been largely erased or greatly altered on more active terrestrial planets such as Earth and Venus. As the only extraterrestrial body from which samples have been returned from known geological contexts (the “Apollo” and “Luna” missions), the Moon provides crucial quantitative insight into its history. This allows for the calibration of dating methods applied to other planetary surfaces, making it key to establishing an absolute chronology for the inner Solar System.

6.2. Location and distribution of volcanic formations

Most of the large volcanic plains (lunar seas) are located on the near side of the Moon, occupying a significant portion of its surface. There are significantly fewer seas on the far side. Volcanic domes and cones are also mainly concentrated within the lunar seas, especially in regions such as the Marius Hills and Mount Rümker, which are located on the near side of the Moon. Pyroclastic deposits formed by explosive eruptions are often found along the edges of lunar seas or in craters, on both the near and far sides. Rills, both sinuous and arc-shaped, are also mainly associated with lunar seas, reflecting lava flow channels or tectonic processes that occurred at their edges. Small areas of relatively young volcanism have been found exclusively within lunar seas on the near side of the Moon.

The far side of the Moon has much less volcanic activity, which may be due to the greater thickness of the crust and other features of its geological structure. However, there are some volcanic structures, such as the Compton-Belkovich complex (Fig. 6.1), which is a unique non-marine volcanic formation on the far side [8]. The heterogeneous distribution of volcanism on the Moon (predominance on the near side) may indicate an asymmetry in the internal structure of the Moon, such as a difference in crustal thickness between the near and far sides, or a peculiar distribution of heat-generating elements in its mantle. Detailed mapping and analysis of the location of different types of volcanic features on the Moon can help reveal patterns in lunar magmatic activity, identify potential sources of magma, and understand the influence of global and local geological processes on the distribution of volcanism.

6.3. Volcanic history of the Moon

The entire history of the Moon is divided into several generally accepted geological periods: Pre-Nectarian, Nectarian, Early Imbrium, Late Imbrium, Eratosthenian, and Copernican.

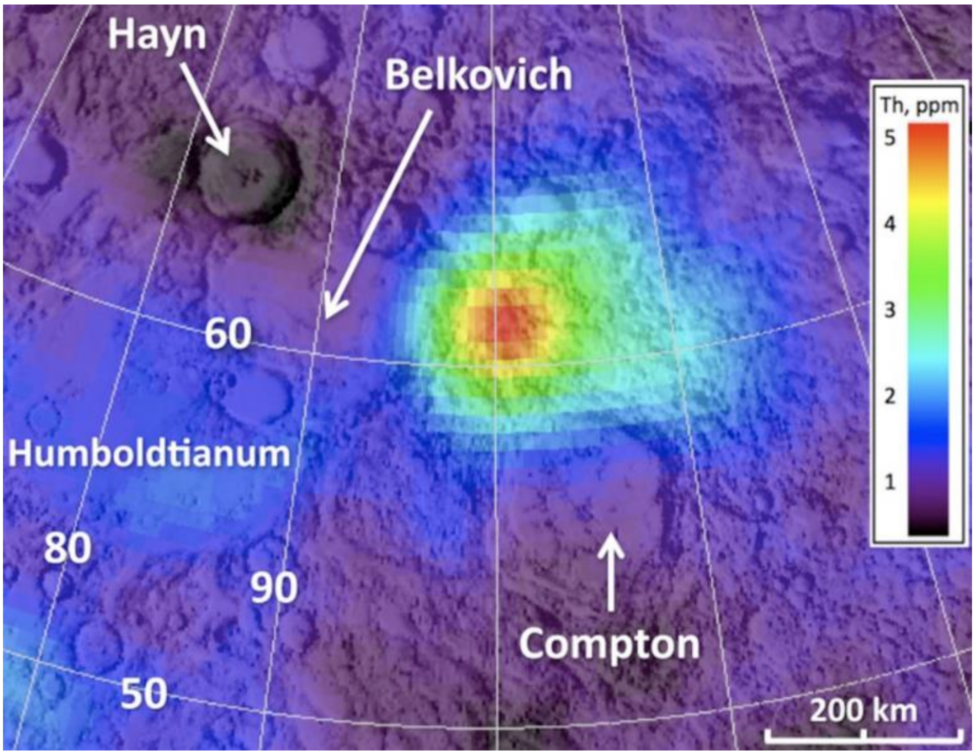

Fig. 6. 1. An image from NASA's "Lunar Reconnaissance Orbiter" shows a region on the far side of the Moon between the Compton and Belkovich craters. The colored region marks a high amount of the mineral thorium, which is thought to have been deposited by rare silicate volcanoes in the past (https://media-cldnry.s-nbcnews.com/image/upload/t_fit-1000w,f_auto,q_auto:best/MSNBC/Components/Photo/_new/110726-VMoonPhoto-hmed-1120a.jpg).

This time scale is based on standard stratigraphic principles, such as the law of superposition, applied to surface features modified primarily by impact cratering [16] and volcanism.

Lunar geological time scale and major volcanic epochs.

Pre-Nectarian period (from the formation of the lunar crust to ~3.92 billion years ago). This period is defined from the formation of the lunar crust (estimated at about 4.2 billion years ago) to the Mare Nectaris formation event (Fig. 6.2). It is characterized by the presence of 30 impact basins, the oldest of which is the South Pole–Aitken basin.

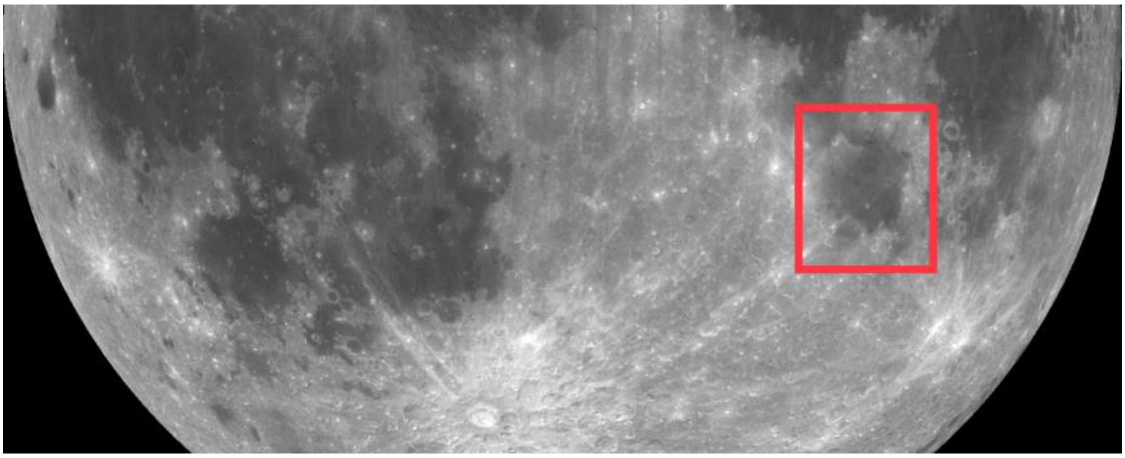

Fig 6.2. Mare Nectaris is highlighted in a red rectangle in the image of the Moon (https://lroc.im-ldi.com/news/uploads/NearsideNectarisHighlight.png).

The lunar crust [42] evolved rapidly during this phase, with approximately 80% of its final mass formed within the first 150 million years. The rapid formation of the lunar crust and the presence of numerous large impact basins during the Pre-Nectarian period indicate an early lunar surface with significant internal heat and intense bombardment. This early history is important because the formation of the large basins would have created significant topographic depressions that later became sites for extensive marine volcanism. This establishes a fundamental causal relationship between the early impact history and the subsequent distribution of lunar volcanism.

Nectarian period (~3.92 billion years ago to ~3.85 billion years ago). This period encompasses all events that occurred between the formation of the Nectaris and Mare Imbrium impact basins. Twelve multi-ringed impact basins are recognized in the Nectarian period, including Mare Serenitatis and Mare Crisium. The age of Mare Nectaris is somewhat controversial, with the most commonly cited figures being 3.92 billion years ago, and less commonly 3.85 billion years ago. This uncertainty in the dating of Mare Nectaris highlights the challenges in establishing a precise chronology of early lunar events, especially until widespread sample returns are available that would allow reliable radiometric dating.

Imbrian period (~3.85 billion years ago to ~3.2 billion years ago). This period is divided into early and late epochs. Early Imbrian, the period is defined as the time between the formation of the Mare Imbrium and Mare Orientale impact basins. The

Mare Imbrium basin is thought to have formed 3.85 billion years ago, although a minority of opinion dates this event to 3.77 billion years ago. The age of the Mare Orientale basin has not been directly determined, but it must be older than 3.72 billion years ago and may be as old as 3.84 billion years ago. The Imbrian period was a time of maximum volume output of marine volcanism, occurring between 3.8 and 3.2 billion years ago. Most basalts [6] erupted during the Late Imbrian period, approximately 3.6–3.8 billion years ago. This period is key to understanding lunar volcanism, as it was then that most of the large basins were flooded with basaltic lavas, forming the dark lunar seas we see today. It also indicates that the Moon's internal heat was intense enough to support large-scale eruptions for a long time after its formation.

Eratosthenian period (~3.2 billion years ago to ~1.1 billion years ago). It is named after the typical crater of this period, the crater Eratosthenes. The base of the Eratosthenian period is defined by the time when craters on a geological unit of a certain size have been almost completely destroyed by erosional processes, mainly by impact cratering itself. During this period, there were significantly fewer basaltic eruptions than during the Imbrian period.

Copernican period (~1.1 billion years ago to present). This is the youngest geological period of the Moon, continuing to the present. Initially, the presence of a bright ray system around the Copernicus impact crater was used to define Copernican units, but this is complicated by the presence of bright ray systems. The base of the Copernican period does not correspond to the formation of the Copernicus impact crater. The age of the base of the Copernican period is not well constrained, but a commonly quoted figure is 1.1 billion years ago.

Table 5.1 presents a generalized chronology of the lunar geologic timescale and associated volcanic activity.

6.4. Marine basalts: formation, composition and morphology

Lunar seas are large basaltic plains covering over 15% of the Moon's surface [14], mostly on the near side. They are the most obvious volcanic features on the Moon, appearing as dark topographic features visible to the naked eye. These lava flows are hundreds of meters thick and are similar to basaltic lava flows on Earth, such as those in Hawaii.

The petrogenesis of sea basalts involves partial melting and hybridization at depth, accompanied by equilibrium between hybrid fluids and local olivine-pyroxenite residue. The energy source for the formation of sea basalts is radiogenic heating in the primordial lunar interior. Lunar basalts formed from eruptions of low-viscosity basaltic lava that filled basins and craters. They 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 seafloor basalts by TiO_2 (very low Ti, low Ti, high Ti), Al_2O_3, and K. For example, basalts with high Ti contents were found at the "Apollo 11" and "Apollo 17" landing sites, while basalts with low Ti contents were found at the "Apollo 12, -9, -14, -15", and "Luna 16" missions. These studies have shown that the lunar mantle is significantly depleted in rare earth elements beneath widely spaced landing sites, supporting a global differentiation process. Marine basalts are the only direct window into the composition of the lunar interior, as they formed from partial melting of mantle material. Their analysis reveals significant information about lunar volcanism and the nature of the mantle, as well as the processes that occurred after magma formation. This allows scientists to reconstruct the thermal and chemical evolution of the Moon. Recall that morphological features associated with marine basalts include the following.

Lava tubes, which are tunnels formed by the cooling of the outer part of a lava flow, allowing the inner lava to continue flowing.

Rilles, which are channel-like structures formed by lava flows.

Wrinkle ridges, which 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.

Domes and *cones*, which are small volcanic formations. On the Moon, due to its low gravity (one-sixth that of Earth), eruptions can eject material much further, forming broad, thin layers around the vent, rather than cones as on Earth. Most lunar domes and cones appear to be composed of basalt. Examples include the *Marius Hills* and *Mons Rümker*, which are large volcanic complexes. Some domes, such as *Manilius 1*, have low circular polarization coefficients, indicating smooth, rock-poor surfaces or perhaps pyroclasts. [4]

Irregular marine spots (IMPs) are rather mysterious volcanic features on the Moon's surface, the absence of craters and the clear appearance of which indicate that they formed less than 100 million years ago, about 1 billion years after the expected cessation of lunar volcanism. Although their youthful appearance may be the result of recent eruptions, it is also suggested that they are ancient volcanic deposits that appear young due to the high porosity of the material or to processes of collapse or drainage into subsurface cavities. This discussion of the age of IMPs highlights unresolved questions about the duration of lunar volcanism and its potential mechanisms in later stages.

Lunar *pyroclastic deposits*, also known as *Dark Mantle Deposits* (DMDs), are low-albedo regions composed of fine-grained material, with areas ranging from 10 km^2 to over 50,000 km^2. These deposits are often associated with sinusoidal ridges, irregular depressions, fissured craters, and impact craters located around seas.

The composition of DMDs can vary considerably. Larger DMDs, such as those at *Taurus-Littrow* and *Mare Vaporum*, are known to contain iron- and titanium-rich glass beads [7]. Smaller DMDs are typically composed of iron-bearing mafic minerals such as pyroxene and olivine, in both juvenile and non-juvenile volcanic components. Recently, chromite-spinel was found in a large DMD at *Sinus Aestuum*. The spectral characteristics of these deposits show differences, for example, larger DMDs containing iron- and titanium-rich orange and black beads have distinct spectral slopes compared to smaller DMDs.

Pyroclastic deposits are important for several reasons. Petrological experiments and modeling have shown that pyroclastic glasses are the deepest and most primitive basalts on the Moon [1]. This means that they originate directly from the lunar mantle, providing direct information about its composition and thermal state. Recent analyses have documented the presence of water in these glass beads, suggesting that the lunar interior is much richer in volatiles than previously thought. This discovery has profound implications for understanding lunar evolution and potential resources. In addition, these iron-rich pyroclastic glasses release the highest percentage of oxygen of all Apollo soils, making these deposits promising lunar resources for future missions.

6.5. Dating lunar volcanic surfaces

Two main methods are used to determine the age of lunar volcanic surfaces: radiometric dating of samples and crater counting.

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. The more daughter nuclide is present 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 ages ranging from 3.16 to 4.2 billion years. The youngest crystallization age recorded for lunar basalts by radiometric dating is 2.03 billion years for samples returned by the “Chang'e-5” mission, extending the known duration of lunar volcanism by about 800–900 million years. This discovery is critically important because it expands our understanding of the thermal evolution of the Moon, showing that its interior remained hot enough to support volcanism for much longer than previously thought [12].

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 highlands are older than dark lava plains). Crater counting on the Moon has shown a young age of about 1.2 billion years for some marine sediments.

Despite its value, crater counting has limitations and uncertainties. Reliability can vary considerably, especially for very young surfaces, where counts are often limited to craters of smaller diameter. Smaller craters may be less reliable for age estimation because their size-frequency distribution is more prone to change [43]. Factors that affect accuracy include:

Impact velocity. Incomplete knowledge of the size-frequency distribution of impactors, as well as possible variations in impact velocity over time.

Atmospheric filtration. The presence of an atmosphere (on other bodies) can affect crater formation.

Heterogeneity of crater formation. Secondary craters (formed by ejecta from primary impacts) and secondary craters themselves can contaminate crater populations, affecting age determinations.

Subject properties. Differences in the strength of the material of the body under study affect crater formation.

Modification of craters after formation. Erosion, deposition, and diffusion creep can alter crater morphology, making the surface appear younger than it actually is.

Statistical and observational biases. Limited crater numbers or limited counting areas, as well as lighting conditions and image resolution, can affect crater identification and age accuracy. The complementary nature of radiometric dating and crater counting is critical to lunar geology. Radiometric dating provides absolute calibration points, while crater counting allows these ages to be extrapolated to wider, unsampled areas. New samples, such as those returned by “Chang'e-5” [12], are crucial for validating and calibrating the impact crater counting chronology, which is the basis for dating most geological units of other bodies in the inner Solar System.

6.6. Evolution and duration of lunar volcanism

The Moon has been volcanically active for most of its history, with the first volcanic eruptions occurring around 4.2 billion years ago. The peak of marine volcanism occurred between 3.8 and 3.2 billion years ago. This activity was long thought to have ceased around 1 billion years ago. However, more recent evidence suggests that small-scale volcanism may have occurred over the past 50 million years. In particular, volcanic rocks returned by the "Chang'e-5" mission were dated to 2 billion years ago, making them the youngest samples ever recovered from the Moon. Furthermore, among the thousands of glass beads in soil samples returned by the Chang'e-5 probe, three were identified as volcanic and were only 120 million years old, although this discovery remains to be verified.

This extension of the known duration of lunar volcanism has profound implications for understanding the thermal evolution of the Moon. This 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 could be the presence of radioactive elements underground, which can generate enough heat to form magma and are known to be common in certain areas of the Moon. However, not all early volcanism can be explained in this way, as the "Chang'e-5" volcanic rocks and some of the 2.8-billion-year-old volcanic rocks from the far side returned by "Chang'e-6" come from sources not enriched in these elements.

Despite significant progress, questions remain. For example, the origin and purpose of the unusual small structure called Ina, photographed by "Apollo 15" in 1971, remain unknown. Although some theories suggest that Ina is a caldera formed by a post-eruption collapse or explosive gas release, its relatively young age (possibly less than 100 million years) remains a matter of debate. Furthermore, it remains a mystery why the far side of the Moon, which always faces away from Earth, is so radically different from the near side, with a thicker crust and an almost complete absence of seas from ancient lava oceans. These differences indicate a complex and possibly asymmetric thermal and geological evolution of the Moon.

6.7. Comparative volcanism in the Solar System

Volcanic activity in the Solar System exhibits a wide range of forms, from silicate volcanism on rocky planets to cryovolcanism on icy bodies.

6.7.1. Silicate volcanism on rocky bodies

Earth. Volcanism on Earth is active and extremely diverse, including different types of volcanoes (shield, stratovolcanoes, cinder cones), a wide range of magma compositions (from basaltic to rhyolitic), powerful driving forces (plate tectonics, mantle plumes), and a long history of activity that continues to this day.4 Lunar volcanism, in contrast, has been predominantly basaltic, shield-type (in the form of seas and domes), has been characterized by lower gas content in the magma, and has occurred in the absence of active plate tectonics.

Mars is known for its colossal volcanoes, which are generally much larger than those on Earth [22-24]. Olympus Mons, the largest volcano in the Solar System [17, 18], is approximately 27 kilometers high and 600 kilometers in diameter, dwarfing even the highest mountains on Earth. Martian volcanic features are mainly concentrated in two regions: the Pharsis Dome and the Elysium Region, where sixteen significant volcanoes have been identified.

Unlike Earth, Mars has a much thicker and more rigid crust, which limits tectonic activity [26]. This is due to the lack of plate tectonics, which allows magma to accumulate in the same places for long periods of time, and to the lower gravity. Therefore, volcanoes there grow larger and for longer periods of time. This lack of plate tectonics is a key difference that explains the scale of Martian volcanoes. Martian volcanoes operate similarly to Earth's, with eruptions occurring through central tunnels and lateral vents, but they form vast lava plains that can extend hundreds of kilometers from their bases due to the lack of obstructions.

Mars also has a wide range of other volcanic features, including large volcanic cones, unusual patera structures (shallow saucer-shaped formations with large calderas, such as *Biblis Patera* and *Ulysses Patera*), and volcanoes with steeper slopes (such as Ceraunius Tholus, Fig. 6.3). Two possible lava channels are visible on *Ceraunius Tholus*. One is a large channel at the top center. It appears to feed a volcanic cone in an old impact crater near its base. The second example is a chain of moon-shaped pits to the left of center. This chain of pits connects to a channel down the slope and likely reflects the collapse of a lava tube. Both of these structures closely resemble the winding channels on the Moon.

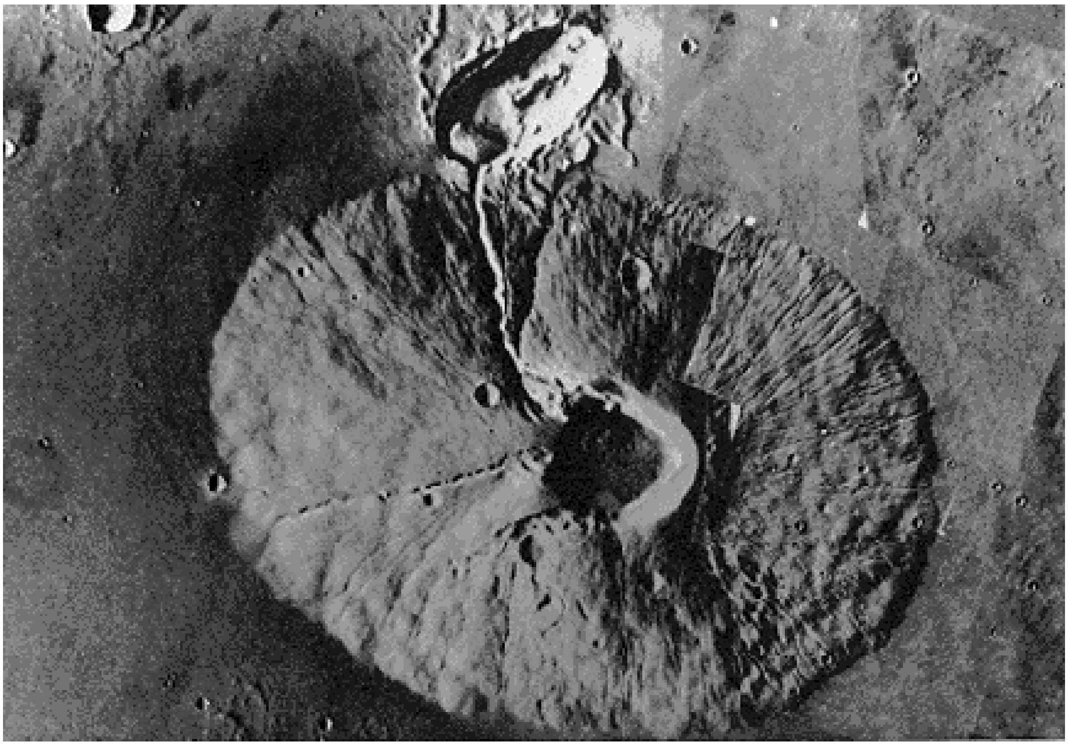

Fig. 6.3. Ceraunius Tholus is located on the edge of the Tharsis region; it is 120 km long, 95 km wide, up to 3 km high, and up to 3 billion years old (https://volcano.oregonstate.edu/sites/volcano.oregonstate.edu/files/oldroot/volcanoes/planet_volcano/mars/Cones/Ceraunius_T.gif).

Martian lava plains are similar in age to the lunar seas, about 3–3.5 billion years ago. Mars also shows evidence of both effusive (lava flows) and explosive (pyroclastic deposits) volcanism, although the latter was less common there than on Earth. Volcanism on Mars in the high-altitude poteras and plains ceased 3 billion years ago, but some smaller shield and cone volcanoes erupted only 2 billion years ago. Giant shield volcanoes are even younger, forming between 1 and 2 billion years ago. The youngest lava flows on Olympus Mons are only 20–200 million years old. The concentration and duration of volcanism in these two regions (Pharsis and Elysium) are explained by the evolution of a long-lived mantle hotspot.

Venus is known for its extreme volcanic landscape, characterized by a variety of volcanic features formed by its unique geological processes. More than 80% of Venus's surface is covered in volcanic rocks, with vast lava flows extending for hundreds of kilometers [31, 34, 36, 40]. The planet has over 1,600 large volcanic features, mostly shield volcanoes such as *Gula Mons* and *Sif Mons*. In addition to shield volcanoes, Venus is home to distinctive structures called coronae and pancake domes. A *coronae* is a large, ring-shaped tectonic structure formed by the uplift of the crust by hot mantle material. *Pancake domes* are smaller, flatter volcanic features that are likely formed from highly viscous lava. Their characteristic flat-topped, steep-sided shape is the result of viscous flows spreading under the influence of gravity and interacting with the elastic lithosphere. The high atmospheric pressure on Venus (about 90 times that of Earth) also likely contributed to the formation of this flat, steep-sided shape. This high pressure, combined with the almost complete absence of water, explains the lack of explosive, ash-producing eruptions on Venus. Venusian lavas require a much higher gas content than Earth's lavas to erupt explosively.

Venus' volcanoes are still active. Evidence, such as variations in the level of sulfur dioxide in the atmosphere, suggests potential volcanic activity. Recent studies using radar images taken by the "Magellan" spacecraft in 1991 have revealed a volcanic vent on the massive *Maat Mons*, the planet's tallest volcano, that has changed shape and appeared to be overflowing with molten rock over an eight-month period. This is considered the most convincing direct evidence of ongoing volcanic activity on Venus [31, 36]. Understanding the volcanism of Venus is crucial to understanding the geological differences between the terrestrial planets, especially since Venus does not exhibit plate tectonics like Earth.

Io (a moon of Jupiter) is the most volcanically active body in the Solar System. Volcanic activity on the moon was first detected in 1979 by the "Voyager 1" spacecraft. Observations of Io have revealed over 150 active volcanoes [33], and estimates suggest that there may be as many as 400 (Fig. 6.4). Io's primary source of internal heat comes from tidal forces generated by Jupiter's gravitational pull. Unlike Earth, where most of its internal heat is released by the decay of radioactive isotopes, tidal heating is dominant on Io.

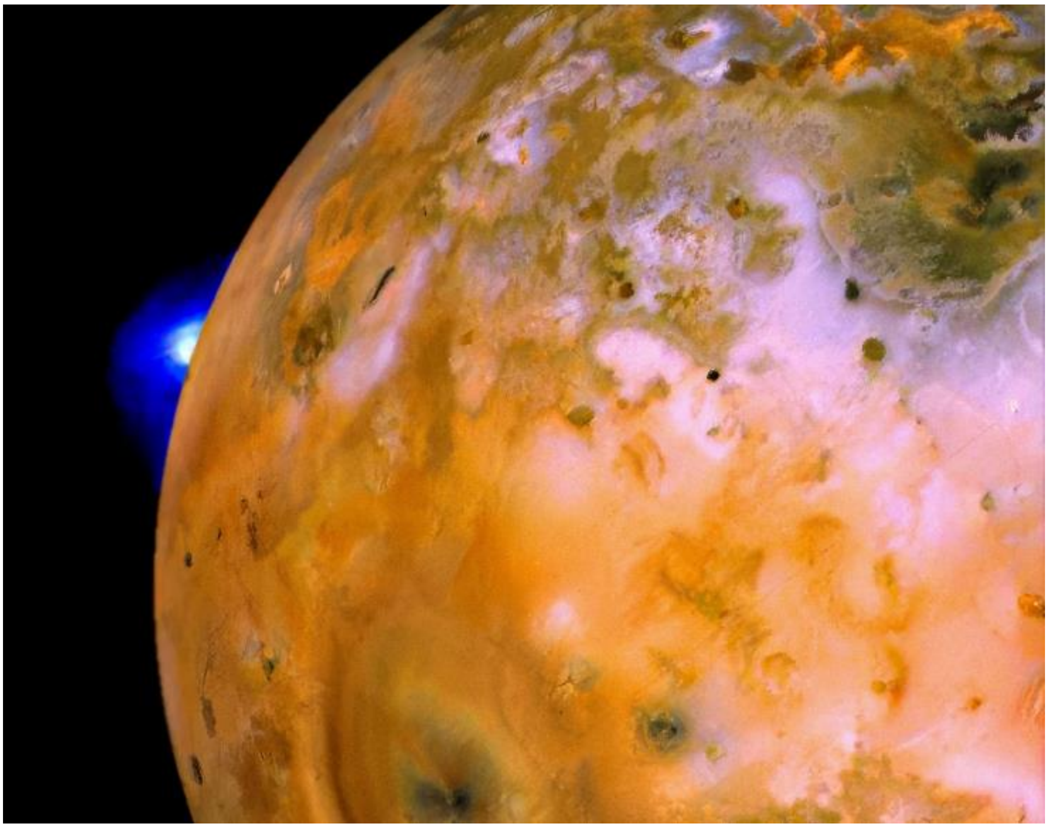

Fig. 6.4. A lava plume erupts from Io's largest volcano, Loki Patera; photo taken in 1979 by NASA's “Voyager 1" probe (https://www.quantamagazine.org/wp-content/uploads/2025/04/IoVolcanism-cr.NASA-Io-Volcano-1304x1536.webp).

Because Io orbits Jupiter in an elliptical orbit, the gravitational pull of Jupiter on Io varies with the moon's distance from the gas giant [27]. This gravitational fluctuation creates a constant stretching and compression of Io's interior, generating enormous amounts of heat due to friction. This process makes Io a unique natural laboratory for studying tidal heating and its effects on planetary interiors [13].

Io's volcanism has resulted in the formation of hundreds of volcanic centers and extensive lava flows. Three different types of volcanic eruptions have been identified: eruptions occur within volcanic depressions known as paterae. Flow-dominated eruptions (so-called Promethean volcanism), which produce lava flows tens or even hundreds of kilometers long. There are also explosion-dominated eruptions (so-called Pillan volcanism), which eject sulfur, sulfur dioxide gas, and pyroclastic material into space to heights of up to 500 km, forming large umbrella-shaped volcanic plumes.

Lava flows on Io are predominantly basaltic in composition, similar to lavas observed on Earth from shield volcanoes. However, lava flows composed of sulfur and sulfur dioxide have also been observed. Eruption temperatures have reached 1600 K, which can be explained by the eruption of high-temperature ultramafic silicate lavas. This moon of Jupiter is the most volcanically active body in the Solar System. Its intense volcanism, which includes numerous active volcanoes, lava lakes, and sulfur emissions, is driven by the powerful tidal forces of Jupiter and the other Galilean moons.

The lack of active plate tectonics on the Moon and Mars has led to the formation of very large shield volcanoes over stationary mantle plumes, in contrast to Earth, where the movement of lithospheric plates leads to the formation of volcanic chains at subduction zones.

6.7.2. Cryovolcanism on Icy Bodies

Cryovolcanism is a geological process involving the extrusion of liquids and vapors of materials that would be frozen at the surface temperatures of icy bodies in the outer Solar System. It differs from traditional volcanism, which involves the eruption of molten rock, and involves the eruption of volatile compounds such as water, ammonia, and methane in the form of ice particles or vapor. This process provides information about the internal composition and geological processes of icy bodies.

Triton (a moon of Neptune) exhibits cryovolcanic activity, characterized by the presence of geysers that eject plumes of ice particles into space. These geysers were first observed by the Voyager 2 spacecraft in 1989. Voyager 2 observations revealed numerous geyser-like eruptions (Fig. 6.5) of nitrogen or water gas and entrained dust from beneath Triton's surface in plumes up to 8 km high. The exact mechanism behind Triton's plumes is not yet fully understood. One hypothesis is that Triton's plumes are caused by solar heating beneath a transparent or translucent layer of nitrogen ice, creating a kind of "hard greenhouse effect." As solar radiation heats the darker material beneath, this causes a rapid increase in pressure as the nitrogen begins to sublimate until enough pressure builds up to erupt through the translucent layer.

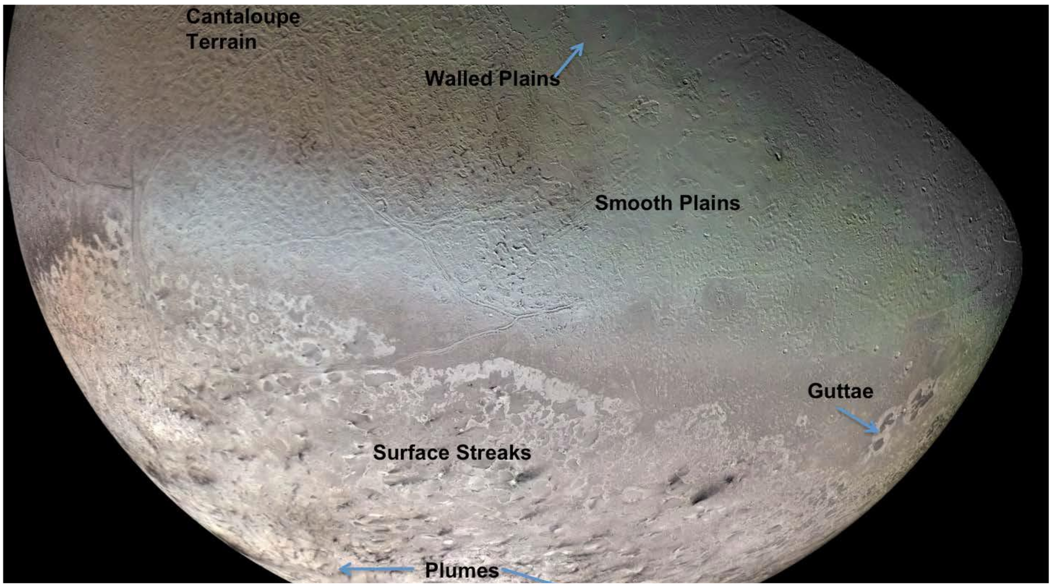

Fig. 6.5. Many of Triton's unique landforms suggest the possibility of cryovolcanism [5].

This model is largely supported by the observation that Triton was near the peak of its southern summer during the "Voyager 2" flyby, which provided prolonged sunlight on its southern polar cap. Another hypothesis suggests that Triton's cryovolcanism [39] is fueled by internal heat generated by tidal forces from Neptune, particularly due to Triton's eccentric and retrograde orbit, which results in tidal braking. This internal heat can support a subsurface ocean and fuel cryovolcanism.

Triton's surface is geologically very young, with regions ranging in age from 6 to 50 million years. It is characterized by unique cryovolcanic features, such as *Leviathan Patera* (a caldera-like structure about 100 km in diameter) and icy lava lakes composed primarily of water ice with small amounts of ammonia. These features, along with dark streaks left by geyser emissions, suggest a dynamic geological history.

Enceladus (a moon of Saturn) exhibits intense cryovolcanic activity. The "Cassini" mission discovered a complex system of geysers near the south pole that spew plumes of water vapor and ice particles into space [35]. These plumes originate from four subparallel linear depressions known as "tiger stripes," which have elevated surface temperatures, indicating ongoing cryovolcanism [37, 38, 41].

Cryovolcanism on Enceladus is largely driven by tidal heating. The moon's eccentric orbit around Saturn generates tidal forces that heat its interior through friction between its rocky core and icy crust. This heat supports a subsurface ocean 30–40 km below the ice shell (Fig. 6.6).

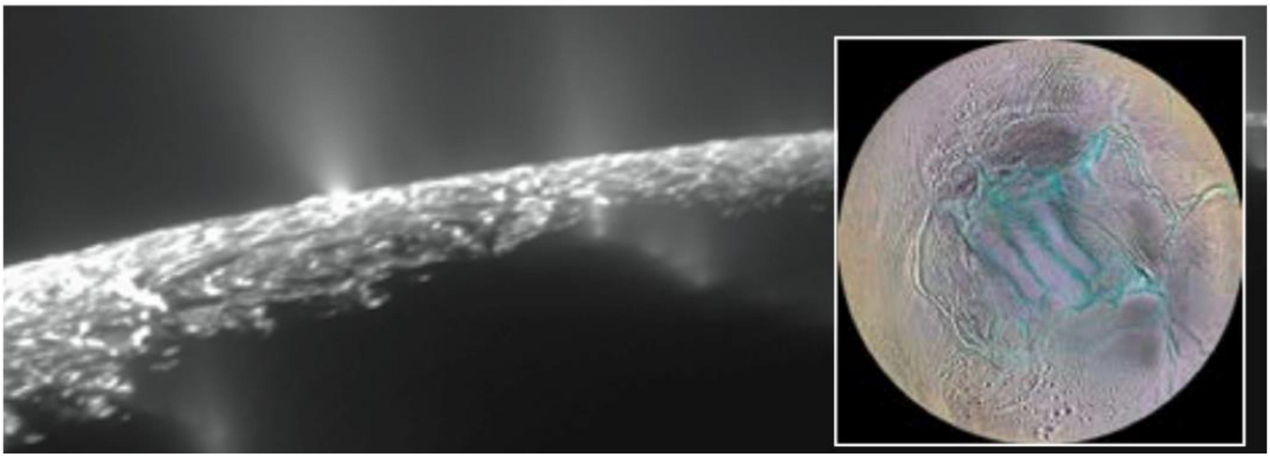

Fig. 6.6. Enceladus has a subsurface ocean with the necessary conditions to support life [3].

The plumes erupted by geysers contain a complex mixture of water vapor, ice particles, organic molecules, salts, and other volatiles. The presence of complex organic molecules and salts suggests a subsurface ocean in contact with the rock and a potentially complex geochemical cycle. This makes Enceladus one of the most promising places to search for life beyond Earth.

Ceres (a dwarf planet) is the largest object in the Main Asteroid Belt; it also shows evidence of cryovolcanism. The most prominent cryovolcanic feature is Ahuna Mons, up to 4 km high and with a base up to 20 km (Fig. 6.7).

The many older, more rounded mountains on Ceres may also be ancient cryovolcanoes (Fig. 6.8), which may indicate a long history of volcanism. Cryovolcanoes on Ceres erupt liquid or gaseous volatiles such as water, ammonia, or methane, rather than molten rock. Salt water is likely the main component of cryolava on Ceres.

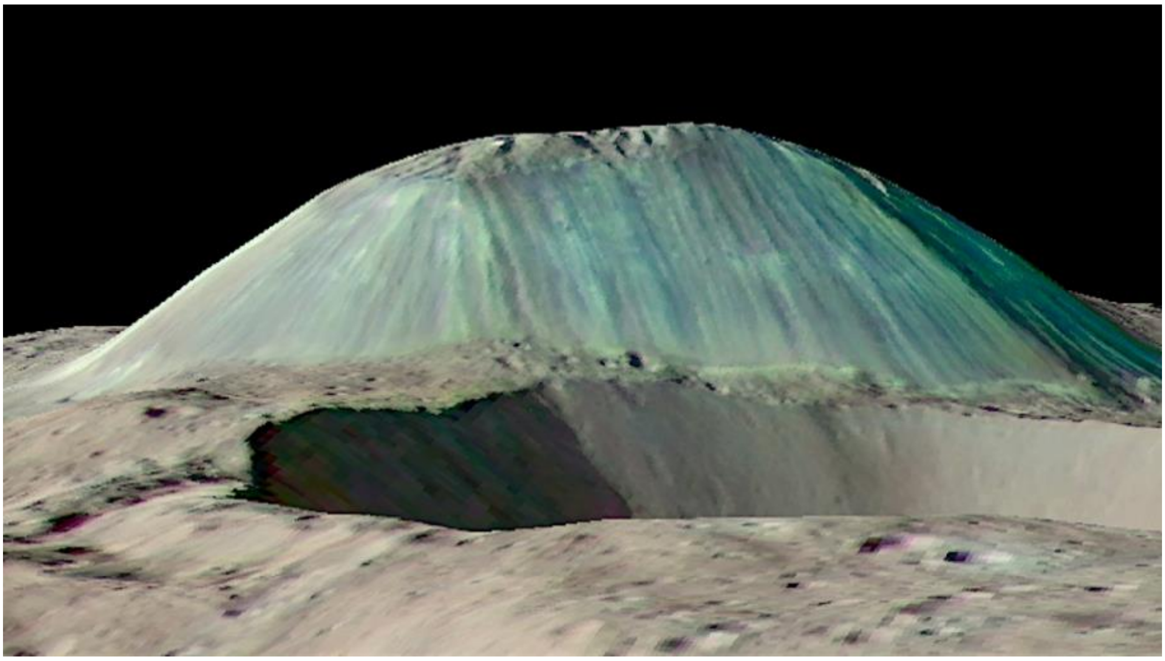

Fig. 6.7. Repeated saltwater eruptions formed the volcanic dome of Ahuna Mons near the impact crater in the foreground without exaggerating the height; the ridges on the slopes were formed by the collapse of the debris, and the faults are visible on the top (https://news.asu.edu/sites/g/files/litvpz161/files/styles/block_image_16_9_lge/public/ahuna-williams.jpg?itok=J5rHntn1).

Analysis of images from the Dawn spacecraft has shown that Ceres has experienced cryovolcanism throughout its geological history, with an average surface extrusion rate of about 10,000 cubic meters per year, orders of magnitude lower than the rate of basaltic volcanism on the terrestrial planets. *Ahuna Mons* [19-21] has only a few impact craters on its surface, indicating a geologically young age of no more than 240 million years.

The prolonged cryovolcanism on Ceres, despite its small size and expected rapid cooling, is a fascinating discovery. The most likely internal energy source for cryovolcanic processes on Ceres is the radioactive decay of certain isotopes in the rocky parts of the dwarf planet. This suggests that Ceres's internal heat was maintained long enough for liquid water or brines to exist, allowing volcanic activity on the surface in recent geological time.

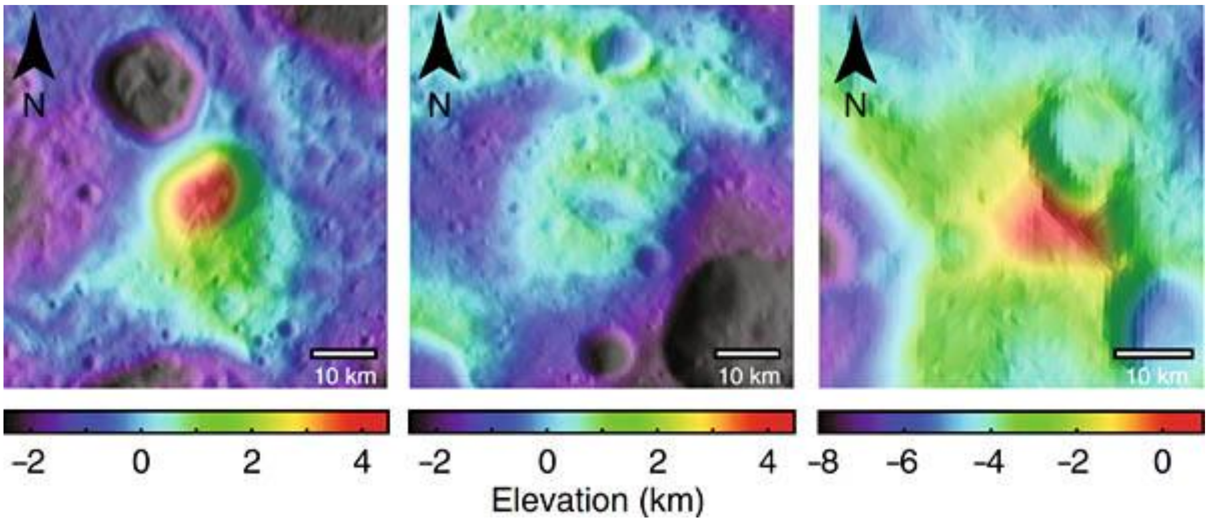

Fig. 6.8. Comparing of the relatively tall Ahuna Mons (left) with the unnamed older dome (center); Yamor Mons (right) may be about 2 billion years old, but it maintains its height due to its location near the always-cold North Pole, where ice melts much more slowly over time (https://dq0hsqwjhea1.cloudfront.net/Dmes-on-Ceres.jpg).

Europa (a moon of Jupiter) is an icy moon of Jupiter. It is considered a prime target for the search for life in the outer Solar System due to its apparent activity. Although direct observations of active eruptions have been rare, there is a strong suspicion of cryovolcanism [29, 30]. It has been suggested that periodic eruptions of water from Europa's interior may provide a window into the study of the moon's interior conditions and habitability [15].

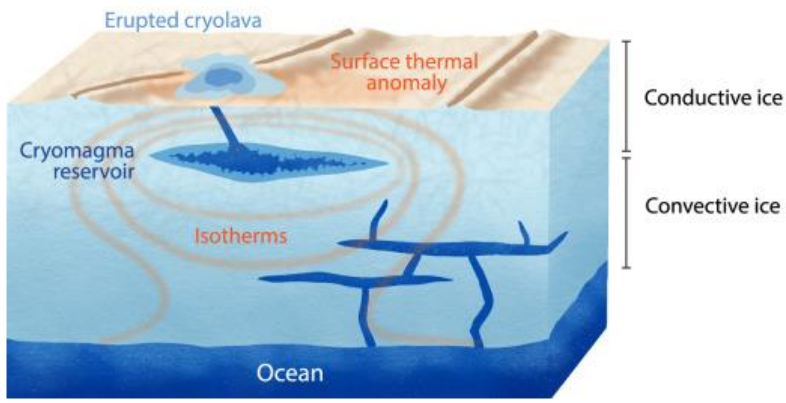

Fig. 6.9. Observed signatures for a 1 km thick reservoir of water located 1 km below Europa's surface [11].

Surface features such as chaotic areas, lenses, double ridges, and central depressions in impact craters are likely explained by liquid brine reservoirs ("cryomagma") in Europa's shallow ice shell [10, 28]. Freezing of cryomagma is expected to increase pressure in the reservoirs, potentially triggering eruptions. Studies show that it is possible to distinguish between water erupting from the deep ocean or from shallow liquid reservoirs using combined measurements of material salinity, surface temperature, and ice shell thickness.

Future missions such as the "Europa Clipper" (NASA) and the "Jupiter Icy Moons Explorer" (JUICE) (ESA), which will begin observing Europa's surface, studying its internal structure, and characterizing the space environment around 2030, are crucial to confirming and understanding cryovolcanism on Europa [32]. These missions will provide new insights into Europa's habitability and the evolution of its ice shell.

Table 6.1 provides a comparison of volcanic features and mechanisms on various bodies in the Solar System.

Table 6.1.

Comparative Volcanic Features and Mechanisms in the Solar System

Body	**Type of volcanism**	**Main features**	**Heat source**	**Plate tecto-nics**	**Duration of volcanism**	**Notes**
Moon	Silicate	Marine basalt plains, pyroclastic deposits, arable lands, wrinkle ridges, domes, IMPs	Radioactive decay	None	4.2 Ga – 1.2 Ga (main), possible up to 50-120 Ma	Unique early SS record, dating calibration.
Mars	Silicate	Giant shield volcanoes, paterae, toli, mare-like plains	Radioactive decay, long-lived mantle hotspot	None	3.5 Ga – 20-200 Ma	Volcanoes larger due to lack of plate tectonics.
Venus	Silicate	Shield volcanoes, pancake domes, crowns, vast lava plains	Radioactive decay, mantle plumes	None	300-500 Ma ago (active), possible current	High atmospheric pressure and lack of water suppress explosive eruptions.

Body	Type of volcanism	Main features	Heat source	Plate tecto-nics	Duration of volcanism	Notes
Io	Silicate	Hundreds of active volcanoes, lava flows, explosive plumes	Intense tidal heating from Jupiter	None	Current	Most active SS volcanic body, unique tidal heating laboratory.
Triton	Cryovol-canism	Geysers (nitrogen, ice), cryolava lakes, plains	Solar heating ("hard greenhouse effect"), tidal braking	None	Current (young surface)	Two possible heat sources, unique icy landscapes.
Ence-ladus	Cryovo-lcanism	Tiger-striped geysers, plumes (water, ice, organic matter, salts)	Tidal heating from Saturn	None	Current	Subsurface ocean, potential habitability.
Ceres	Cryovol-canism	Ahuna Mons, older domes, flat craters	Radioactive decay	None	Long-lived (until recent)	Prolonged cryovolcanism for a small body, evidence of subsurface brines.
Europa	Cryovol-canism	Water plumes, chaotic areas, double ridges	Tidal heating from Jupiter	None	Possible current	Future missions will explore subsurface ocean and habitability.

6.8. Driving factors and unifying themes in planetary volcanism

Volcanic activity on various planetary bodies is driven by a number of interrelated factors, including *internal heat sources, planetary characteristics*, and *environmental influences*.

6.8.1. Internal heat sources. The main sources of internal heat that fuel volcanism is the following.

The radioactive decay of radioactive isotopes such as uranium, thorium, and potassium are a significant source of heat for most rocky bodies, including the Earth, Moon, Mars, and Ceres. This residual heat from accretion and differentiation, as well as the ongoing heat from isotope decay, supports mantle convection and magma generation.

Tidal heating is the process by which the gravitational pull of a larger body (the host planet) on a satellite causes periodic deformations, generating frictional energy that heats its interior. This mechanism is the dominant source of heat for volcanism on Io, Enceladus, Triton, and Europa. Io is the most prominent example where intense tidal heating supports persistent and extremely active volcanic activity.

Planetary characteristics. Size, mass, and internal structure. These factors influence the internal heat budget and the potential for volcanic activity. Larger planets tend to retain heat longer and have a higher probability of ongoing volcanic processes. The thickness and composition of the mantle and crust also affect the distribution and intensity of volcanism. For example, the Moon has an asymmetric crustal thickness, which may explain the difference in the distribution of marine basalts between the near and far sides.

The *composition* of the planetary body (mantle and crust) affects the nature and extent of volcanic activity. The presence of volatile compounds can lead to explosive eruptions, while the silica content affects the viscosity of the magma. Io, for example, has lavas rich in sulfur compounds due to its unique composition. Ceres erupts salt water, ammonia, or methane, reflecting its volatile-rich interior.

6.8.2. Environmental Influences

Atmospheric pressure greatly influences the behavior of erupting magma and the volcanic landforms formed. On Venus, the high atmospheric pressure (90 times that of Earth) suppresses explosive eruptions, as they require a much higher gas content in the lava. This leads to the dominance of effusive flows and the formation of unique pancake domes.

Surface gravity. The lower gravity on the Moon and Mars allows eruptions to eject material much farther than on Earth, influencing the morphology of volcanic structures.

Presence/absence of plate tectonics. Earth's plate tectonics concentrates volcanic activity along plate boundaries. In contrast, on single-plate planets such as Mars and Venus, volcanism is more diffuse and often centered around long-lived mantle hotspots, allowing volcanoes to grow to enormous sizes. Table 6.2 summarizes the key methods for dating planetary surfaces, their principles, applications, and limitations.

Table 6.3.

Key methods for dating planetary surfaces

Dating Method	Principles	Application	Limitations
Radiometric dating	Measuring the ratio of "parent" radioactive isotopes to "daughter" decay products; known decay rate (half-life)	Determining the absolute age of igneous rocks; calibrating other dating methods (e.g., crater counting)	Requires return of physical samples; cannot date surfaces without igneous rocks; possible contamination or loss of isotopes
Crater counting	Estimating the age of the surface from the density of impact craters; assuming a known rate of crater formation	Dating unsampled regions on the Moon and other planetary surfaces; determining the relative age of different sites	Depends on calibration with radiometric dates; sensitive to secondary craters, erosion, sediments, target properties; less reliable for small craters and young surfaces
Tephro-chrono-logy	Using layers of volcanic ash (tephra) with a unique chemical "fingerprint" as time markers	Dating archaeolo-gical, geological, and paleo-ecological sequences; correlating events at different locations	Requires accurate geochemical "fingerprint"; tephra chemistry can change over time; mainly used on Earth

6.9. Unresolved issues and future directions

Despite significant progress in understanding volcanism on the Moon and other bodies in the Solar System, a number of fundamental questions remain that will shape future research directions. Regarding lunar volcanic evolution, one of the major mysteries is the confirmation and full understanding of very young activity. The discovery of 2 billion year old volcanic rocks by the “Chang'e-5” mission and potentially 120 million year old volcanic glass beads challenge long-held beliefs about rapid cooling of the Moon. This requires further research to determine whether these events were isolated "eructations" or evidence of a longer, albeit small-scale, volcanism, perhaps fueled by localized radioactive elements.

Furthermore, it remains unclear why the far side of the Moon has a significantly thicker crust and is almost completely devoid of large marine basalts compared to the near side. Understanding this crustal dichotomy is key to unraveling the full thermal and geological history of the Moon. In comparative planetology of volcanism, the question of active volcanism on Venus remains an open one. Although recent Magellan observations of Maat Mons provide the most convincing direct evidence of ongoing eruptions, the frequency and extent of this activity are still unknown.

Future missions, such as “VERITAS” (NASA) and “EnVision” (ESA), aim to map the surface of Venus in detail, which will allow for higher resolution images and topography to better understand its volcanic history and current activity.

Regarding the icy worlds, while active cryovolcanism has been confirmed on Io, Enceladus, and Triton, the nature of Europa's plumes is the subject of intense research. Determining whether these plumes originate directly from a deep subsurface ocean or from shallow liquid reservoirs in the ice shell is of great importance for assessing Europa's habitability. Future missions such as “Europa Clipper” and “JUICE” will use combined measurements of salinity, surface temperature, and ice shell thickness to distinguish between these scenarios. These unresolved questions have profound implications for broader planetary science topics, including the search for life beyond Earth. Active cryovolcanism on Enceladus, which releases water, organic molecules, and salts from its subsurface ocean, makes it a prime target for astrobiological research. Understanding these processes on the Moon and other bodies also helps us better understand our own planet, Earth, and its evolution.

Conclusions

The Moon, with its well-preserved geological record, serves as a key to understanding early volcanism and the evolution of the inner Solar System.

Its history of volcanic activity, spanning billions of years, from large-scale marine eruptions to potentially recent, small-scale events (Tables 6.3, 6.4), provides invaluable data for calibrating time scales and modeling planetary processes.

Table 6.3.

Major lunar seas.

Sea Name	Average Diameter (km)	Coordinates (center)	Age (billion years)
Ocean of Storms	~2590	18° N, 57° W	3.7-1.2
Sea of Rain	~1123	32° N, 15° W	3.9-3.3
Sea of Calm	~873	8° N, 31° E	3.8-3.1
Sea of Crisis	~418	17° N, 59° E	3.7-3.2
Sea of Fertility	~909	7° S, 53° E	3.9-3.2
Sea of Cold	~1596	56° N, 1° E	3.8-3.5
Sea of Moisture	~389	24° S, 38° W	3.8-3.5
Sea of Clouds	~715	21° S, 16° W	3.8-3.1
Sea of Clarity	~707	28° N, 17° E	3.8-3.4
Sea of Vapors	~245	13° N, 3° E	3.8-3.2
Sea of Nectar	~333	15° S, 34° E	3.9-3.2
Sea of the Land	~420	13° N, 86° E	3.8-3.0
Sea of Smith	~373	1° N, 87° E	3.8-3.1
Sea of Humboldt	~273	56° N, 81° E	3.8-3.5
Sea of Moscow	~277	27° N, 147° E	3.9-3.0
Sea of the East	~327	19° S, 92° W	3.8-3.0
Sea of the South	~603	38° S, 93° E	3.9-3.5
Sea of the Known	~376	10° S, 22° W	3.8-3.5
Sea of Islands	~513	7° N, 30° W	3.8-3.2
Sea of Waves	~243	7° N, 68° E	3.8-3.0
Sea of Foam	~139	1° N, 65° E	3.8-3.2

Table 6.4.

Characteristics of prominent lunar domes and cones.

Name Formation	**Type**	**Diameter (km)**	**Height (m)**	**Coordinates (center)**	**Features**
Marius Hills	Domes	~330	200-500	14° N, 52° W	Large number of domes and cones
Rümker Mountain	Domes	~70	200-1300	40° N, 58° W	Plateau with numerous domes
Gruythuizen Domes	Domes	~20 & ~13	~1800	36° N, 40° W	Non-basalt composition (possibly silicate)
Valentine's Dome	Dome	~30	~900	30° N, 10° E	Large effusive dome
Arago Domes α and β	Domes	~24 & ~23	~300	6° N, 20° E	Two relatively large domes
Gardner Dome	Dome	~70	~800	17° N, 35° E	A "megadome" of overlapping structures

Name Formation	Type	Diameter (km)	Height (m)	Coordinates (center)	Features
Cauchy Domes ω & τ	Domes	~10 & ~14	~300	7° N, 37° E	A pair of prominent domes
Milichia Dome π	Dome	~4	~300	10° N, 31° W	A dome with relatively high vertical relief
Capuan Dome	Dome	~7	~200	34° S, 26° W	A low dome in a crater
Kiza Dome π	Dome	~11	~250	26° S, 24° W	A prominent dome near Kiza crater

Volcanism in the Solar System is extremely diverse and dynamic, reflecting the unique conditions of each body (Table 6.5). From the giant silicate shield volcanoes of Mars, which form in the absence of plate tectonics, to the mysterious pancake domes of Venus, which arise under extreme atmospheric pressure, and the continuous tidal heating eruptions of Io, each body offers a unique perspective on volcanic mechanisms.

Table 6.5.

Comparison of lunar volcanism with other bodies

Characteristics	Moon	Earth	Mars	Io (Jupiter's moon)
Types of Volcanoes	Volcanoes Shield (seas, domes), cones, rilles	Shield, stratovolcanoes, cinder cones, calderas	Shield, paterae, possible stratovolcanoes	Active volcanoes, calderas, lava lakes, cryovolcanoes
Main Composition of Eruptions	Basalt	Basalt, andesite, rhyolite	Basalt	Mostly sulfur and silicates
Plate Tectonics	None	Active	None (mostly vertical movements)	None
Energy Source	Residual heat, radioactive decay	Residual heat, radioactive decay Tidal forces	Residual heat, radioactive decay	Tidal forces of Jupiter and other moons
Current Activity	Probably very low or absent	Active	Possibly very low	Extremely high

Cryovolcanism on icy moons such as Triton, Enceladus, Ceres, and Europa reveals complex interactions between internal heat, volatile composition, and surface processes that are critical to the search for subsurface oceans and potential habitability. Ongoing studies, supported by new missions and improved dating methods, continue to reveal new aspects of these geological processes. Resolving outstanding questions about the duration of lunar volcanism, the activity of Venus, and the nature of Europa's plumes will not only deepen our understanding of individual bodies, but also contribute to a more holistic view of the formation, evolution, and potential for life throughout the Solar System.

References:

1. Allen C.C., Greenhagen B.T., Donaldson Hanna K.L., et al. (2011) Analysis of Lunar Pyroclastic Glass Deposit FeO Abundances by LRO Diviner. Lunar Exploration Analysis Group. Houston, TX, United States, November 7-9, JSC-CN-24714.
2. Braden S.E., Stopar J.D., Robinson M.S., et al. (2014) Evidence for basaltic volcanism on the Moon within the past 100 million years. Nat. Geosci. 7(11), p. 787–791.
3. Davila A., McKay Ch.P., Willson D., et al. (2018) Follow the plume: Organic molecules and habitable conditions in the subsurface ocean of Enceladus. Lunar And Planetary Science And Exploration. Astrobiology Science Strategy for the Search for Life in the Universe. Irvine, United States, January 16-18, 2018. P. 1-6.
4. Farrand W.H., Trang D., Li Sh. (2023) Dark mantles over domes and rilles on the Moon: Evidence for pyroclastic materials. Icarus. 406, December 2023, Article 115759.
5. Hansen C.J., Grundy W., Hofgartner J., et al. (2021) Triton: Fascinating Moon, Likely Ocean World, Compelling Destination! The Planetary Science Journal. 2(4), id.137, 12 p.
6. Head J.W., Wilson L., Hiesinger H., et al. (2023) Lunar mare basaltic volcanism: Volcanic features and emplacement processes. Reviews in Mineralogy and Geochemistry, 89(1), p. 453-507.

7. Jawin E.R., Besse S., Mazrouei S., et al. (2013) Spectral Signature of Lunar Pyroclastic Deposits in Moon Mineralogy (M3) data. 44th Lunar and Planetary Science Conference. 1662.pdf.

8. Jolliff B.L., Tran T.N., Lawrence S.J., et al. (2011) Compton-Belkovich: Nonmare, Silicic Volcanism on the Moon's Far Side. 42 Lunar and Planetary Science Conference.

9. Kargel J.S. (1994) Cryovolcanism on the icy satellites. Earth Moon Planet. 67, p. 101–113.

10. Klyanchin A.I., Vidmachenko A.P., Morozhenko A.V., et al. (2011) The asymmetry of the reflective properties of hemispheres of the Jovian satellite Europa. 13 International scientific conference Astronomical School of Young Scientists, May 12–14, 2011. The program and abstracts. Chernigiv, Ukraine. – P. 29-30.

11. Lesage E, Howell SM, Neveu M, et al. (2025) Identifying signatures of past and present cryovolcanism on Europa. Nat Commun. 16(1), p. 1886.

12. Li Q.L., Zhou Q., Liu Y., et al. (2021) Two-billion-year-old volcanism on the Moon from Chang'e-5 basalts. Nature. 600(7887), p. 54-58.

13. Matsuyama I.N., Steinke T., Nimmo F. (2022) Tidal Heating in Io. Elements. 18(6), p. 374–378.

14. Morozhenko A.V., Vidmachenko A.P., Kostogryz N.M. (2015) Spectrophotometric properties of Moon's and Mars's surfaces exploration by shadow mechanism. Highlights of Astronomy. 16, p. 182-182.

15. Steklov A.F., Vidmachenko A.P. (2018) On possible colonization of Ceres. 20 International scientific conference Astronomical School of Young Scientists. May 23–24 2018. The program and abstracts. Uman, Ukraine, p. 63-65.

16. Vid'Machenko A.P. (1995) Settling of dust in Jupiter's atmosphere after the impact of fragments of comet Shoemaker-Levy 9. Kinematics and Physics of Celestial Bodies. 11(4), p. 14-16.

17. Vidmachenko A.P. (2014) Study of Earth-like planets. 16 International scientific conference Astronomical School of Young Scientists. Kirovohrad, Ukraine. May 29–31, 2014. P. 12-13. 30

18. Vidmachenko A.P. (2016) Activity of processes on the visible surfaces of Solar System bodies. Astr. School's Report 12 (1), p. 14-26.

19. Vidmachenko A.P. (2017) Features of the structure of the Ceres surface. 19 International scientific conference Astronomical School of Young Scientists. May 24–25 2017. The program and abstracts. – Bila Tserkva, Ukraine. P. 13-15.

20. Vidmachenko A.P. (2017) Features of the structure of Ceres surface. Astronomical School's Report. 13(1), p. 11-21.

21. Vidmachenko A.P. (2017) Features of the surface of Ceres. Astronomical almanac. 64, p. 231-248.

22. Vidmachenko A.P. (2018) Comparative features of volcanoes on Solar system bodies. 20 International scientific conference Astronomical School of Young Scientists. May 23–24, 2018. Uman, Ukraine, p. 9-12.

23. Vidmachenko A.P. (2018) Features of volcanic activity on various bodies of the Solar system. Materials of the International Scientific and Practical Conference "The Objectives of the Sustainable Development of the Third Millennium: Challenges for Universities of Life Sciences", vol. 5, May 23-25, 2018, Kyiv, p. 41-42.

24. Vidmachenko A.P. (2018) Features of volcanoes on different Solar system bodies. Astronomical School's Report. 14(1), p. 1-14.

25. Vidmachenko A.P. (2018) Modern volcanic activity on the Moon. 20 International scientific conference Astronomical School of Young Scientists. May 23-24, 2018. Uman, Ukraine. P. 5-7.

26. Vidmachenko A.P. (2023) Volcanoes of Mars. Conference Proceedings of the VIII International Scientific and Practical Conference «Theories of world science and technology implementation» (May 08-10). Chapter 2. Osaka, Japan, p. 13-19.

27. Vidmachenko A.P., Morozhenko O.V. (2017) The physical characteristics of the surface of the satellites and rings of giant planets. Kyiv: Editorial and publishing department of NUBiP of Ukraine. -412 p.

28. Vidmachenko A.P., Morozhenko A.V., Klyanchin A.I., et al. (2011) Asymmetry of reflective properties of the hemispheres of Jupiter satellite Europa. Astronomical School's Report. 7(1), p. 133-144.

29. Vidmachenko A.P., Morozhenko A.V., Klyanchin A.I. (2011) Features of morphology and geology of surface of Jupiter satellite Europe. Astronomical School's Report. 7(1), p. 117-132.

30. Vidmachenko A.P., Morozhenko A.V., Klyanchyn A.I. (2011) The morphology and geology of the surface features of Jupiter's satellite Europa. 13 International scientific conference Astronomical School of Young Scientists, May 12–14, 2011. The program and abstracts. Chernigiv, Ukraine. - P. 15-16.

31. Vidmachenko A.P., Ovsak O.S., Kuznetsova J.G., Steklov O.F. (2025) The influence of volcanic activity on the formation of the Venus surface. Primedia eLaunch, Boston, USA. -101 p.

32. Vidmachenko A.P., Steklov A.F. (2020) Tectonic activity on the Europa satellite. 22 International scientific conference Astronomical School of Young Scientists. December 11–12 2020. Kyiv, Ukraine, p. 15-17.

33. Vidmachenko A.P., Steklov A.F. (2022) Activity of volcanic processes on Jupiter's Moon Io. Proceedings of IX International Scientific and Practical Conference. International scientific innovations in human life. (March 16-18, 2022). Chapter 12. Cognum Publishing House, Manchester, United Kingdom. P. 80-89.

34. Vidmachenko A.P., Steklov A.F. (2022) Features of volcanic structures on Venus. Proceedings of the 9th International scientific and practical conference. Modern directions of scientific research development. BoScience Publisher. Chicago, USA. 23-25.02.2022. P. 195-204.

35. Vidmachenko A.P., Steklov A.F. (2022) Geysers in the southern polar region of Saturn's moon Enceladus. Proceedings of the 11th International scientific and practical conference. Innovations and prospects of world science (22-24 June, 2022). Chapter 43. Perfect Publishing. Vancouver, Canada. P. 286-292.

36. Vidmachenko A.P., Steklov A.F. (2022) Modern volcanism on Venus. Proceedings of the 7th International scientific and practical conference. Innovations and prospects of world science. (March 2-4, 2022). Chapter 19. Perfect Publishing. Vancouver, Canada. P. 119-129.

37. Vidmachenko A.P., Steklov A.F. (2022) Temperature anomalies in the southern polar region of Enceladus. Proceedings of the 12th International scientific and practical conference. Science, innovations and education: problems and prospects (June 28-30, 2022). Chapter 50. CPN Publishing Group. Tokyo, Japan. P. 345-354.

38. Vidmachenko A.P., Steklov A.F. (2022) The relationship between Enceladus geysers and Saturn's rings and magnetosphere. Proceedings of the 13th International scientific and practical conference. Modern directions of scientific research development (15-17 June 2022). Chapter 68. BoScience Publisher. Chicago, USA. P. 424-432.

39. Vidmachenko A. P., Steklov A. F. (2022) Volcanoes on Triton among the kingdom of ice. Proceedings of the 11th International scientific and practical conference. Modern directions of scientific research development. Chapter 19. BoScience Publisher. Chicago, USA. P. 141-150.

40. Vidmachenko A.P., Steklov A.F., Hrudynin B.O. (2022) Seasonal activity of "tiger" stripes on Enceladus. Proceedings of the 12th International scientific and practical conference. International scientific innovations in human life (08-10 June, 2022). Ch. 60. Cognum Publishing House. Manchester, United Kingdom. P. 365-375.

41. Vidmachenko A.P., Steklov O.F. (2023) Features of volcanic activity on the surface of Venus. Basics of learning the latest theories and methods. Proceedings of the IX International Scientific and Practical Conference. (March 07 – 10, 2023). Chapter 7. Boston, USA. International Science Group, p. 39-46.

42. Wieczorek M. A., Neumann G. A., Nimmo F., Zuber M. T. (2012) The crust of the moon as seen by GRAIL. Science, 339(6120), p. 671-675.

43. Williams J.-P., van der Bogert C.H., Pathare A.V., et al. (2017) Dating very young planetary surfaces from crater statistics: A review of issues and challenges. Meteoritics & Planetary Science. 53(4), p. 1-29.