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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.

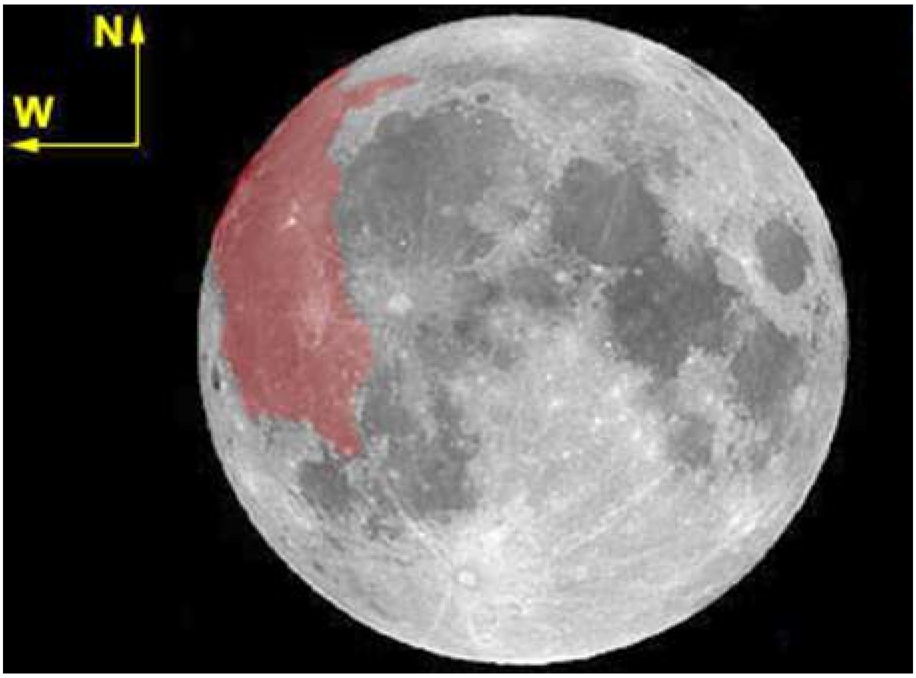

Fig. 5.1. In Oceanus Procellarum (highlighted) is the bright crater Aristarchus (https://i0.wp.com/cosmicreflections.skythisweek.info/wp-content/uploads/2020/04/oceanus_procellarum.jpg?w=840&ssl=1).

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).

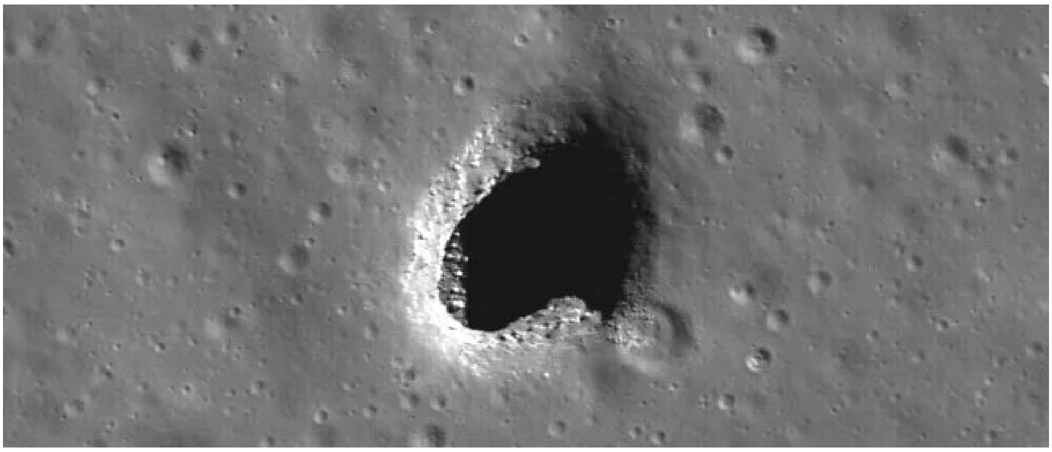

Fig. 5.2. The pit to the volcanic cave at Mare Ingenii has a diameter of about 130 meters (https://cdn.mos.cms.futurecdn.net/iSUyCz6iF6eHhqCMXPezKc-650-80.jpg.webp).

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*.

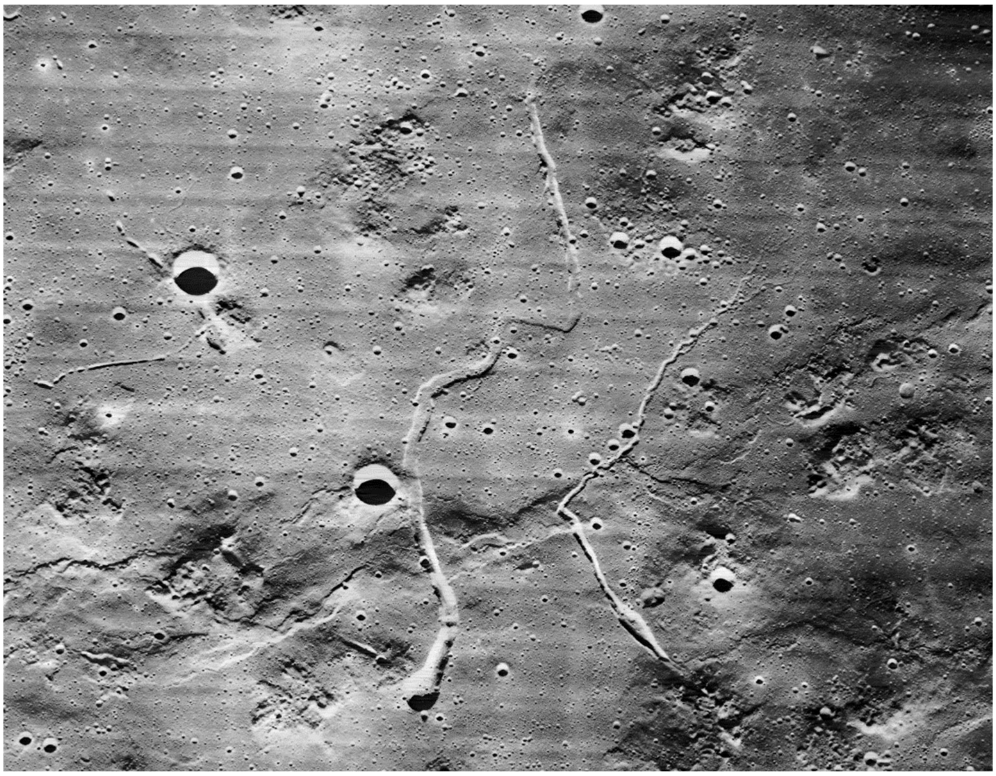

Fig. 5.3. Image of a plateau 45 km wide northwest of Marius crater on the Moon; two *Sinuous rilles* in the *Marius Hills* region cross the ridge; volcanic domes and cones are also visible (https://www.lpi.usra.edu/resources/lunarorbiter/images/preview/5213_med.jpg).

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.

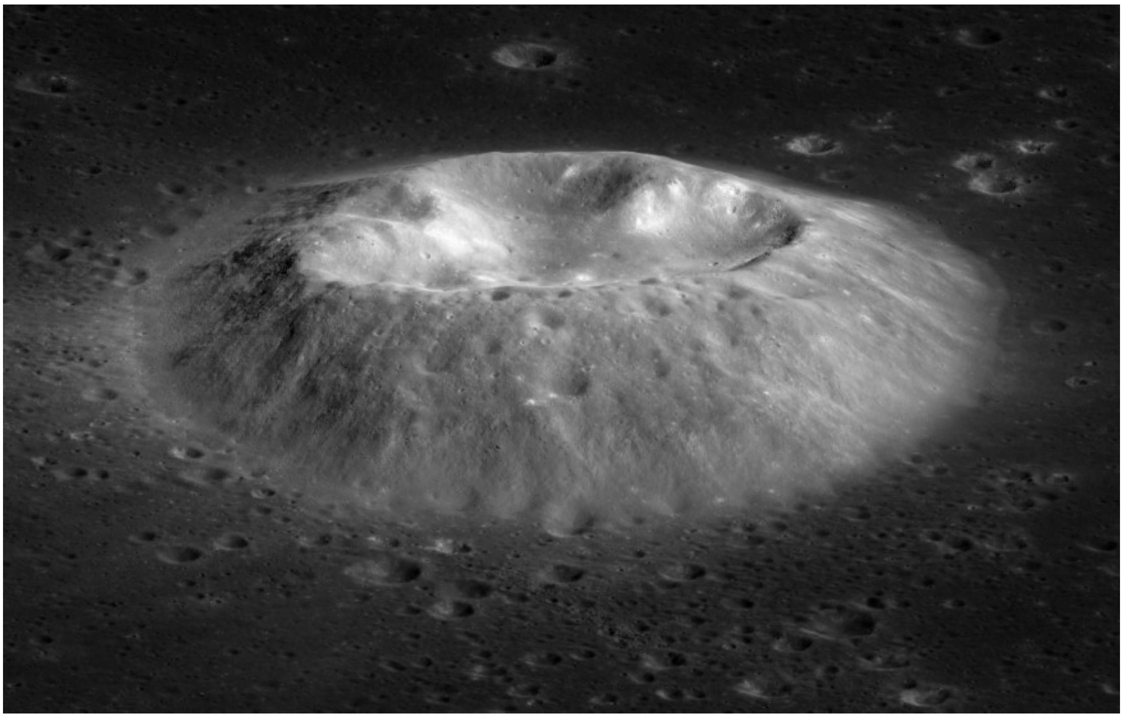

Fig. 5.4. The silicic volcano Mairan T is over 600 m high; its albedo contrasts sharply with the surrounding dark marine basalts of Oceanus Procellarum; the image width is 6.6 km (https://lroc.im-ldi.com/ckeditor_assets/pictures/1222/content_09_M1387416559_LRmos.Mairan_T_1100x1100.png).

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).

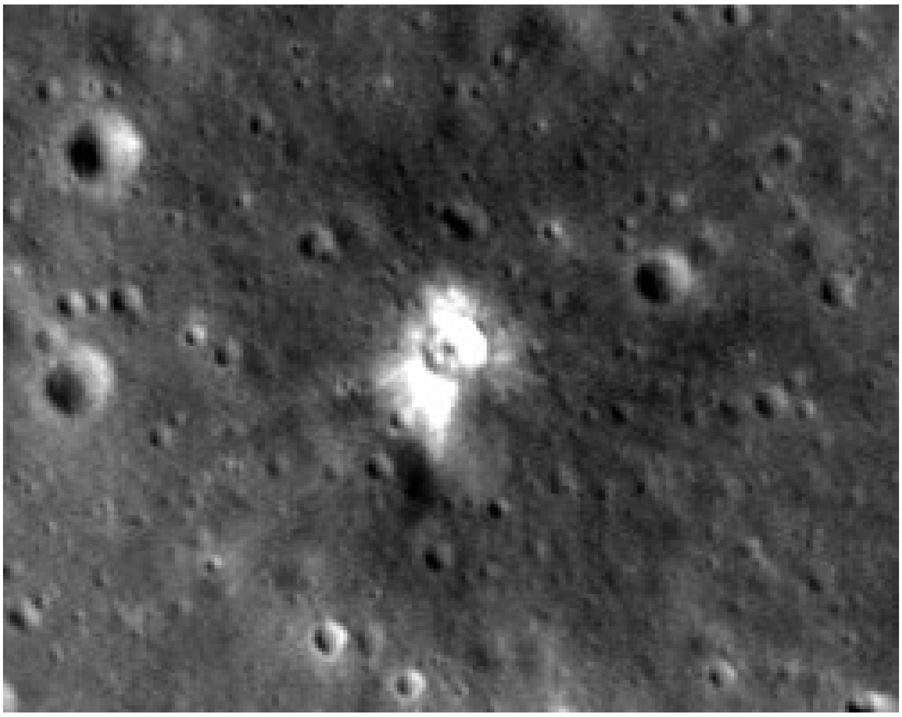

Fig. 5.5. An 18-meter crater in the Sea of Rains appeared on March 17, 2013. The flare was recorded from Earth [27] (https://upload.wikimedia.org/wikipedia/commons/a/a0/New_crater_on_the_Moon_%2817_March_2013%29.png).

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.

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