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.

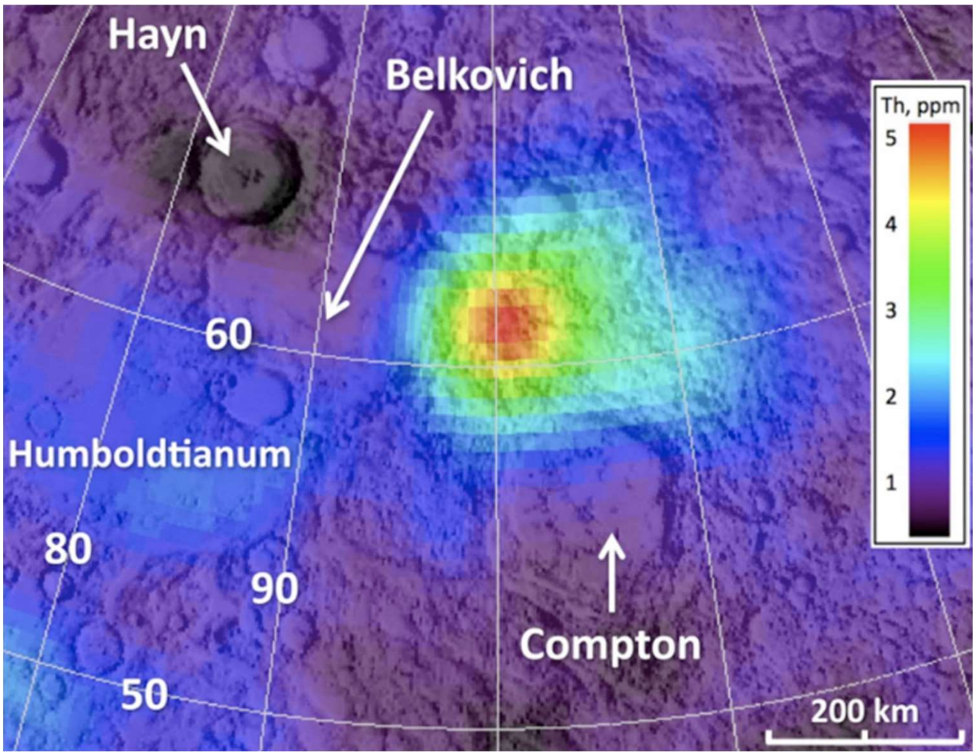

Fig. 6. 1. An image from NASA's "Lunar Reconnaissance Orbiter" shows a region on the far side of the Moon between the Compton and Belkovich craters. The colored region marks a high amount of the mineral thorium, which is thought to have been deposited by rare silicate volcanoes in the past (https://media-cldnry.s-nbcnews.com/image/upload/t_fit-1000w,f_auto,q_aut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

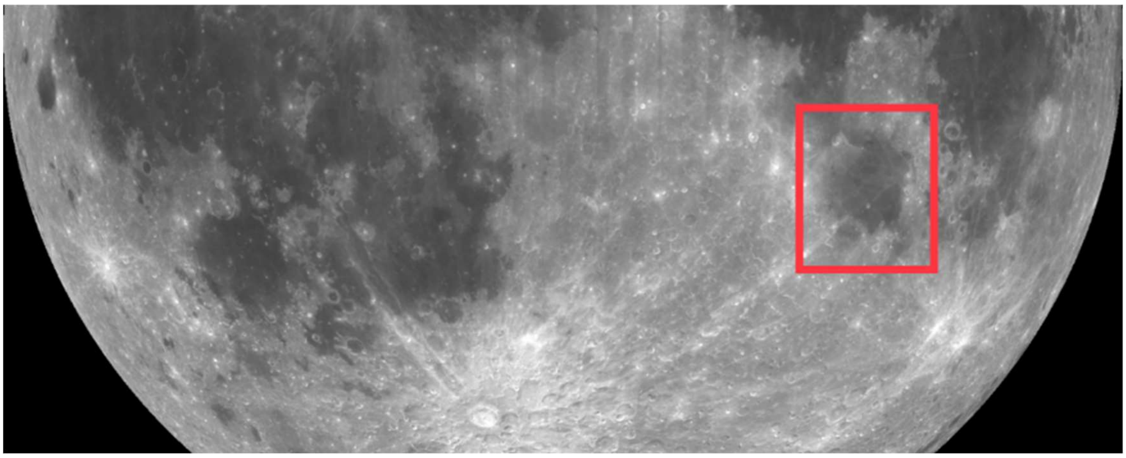

Fig 6.2. Mare Nectaris is highlighted in a red rectangle in the image of the Moon (https://lroc.im-ldi.com/news/uploads/NearsideNectarisHighlight.png).

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.

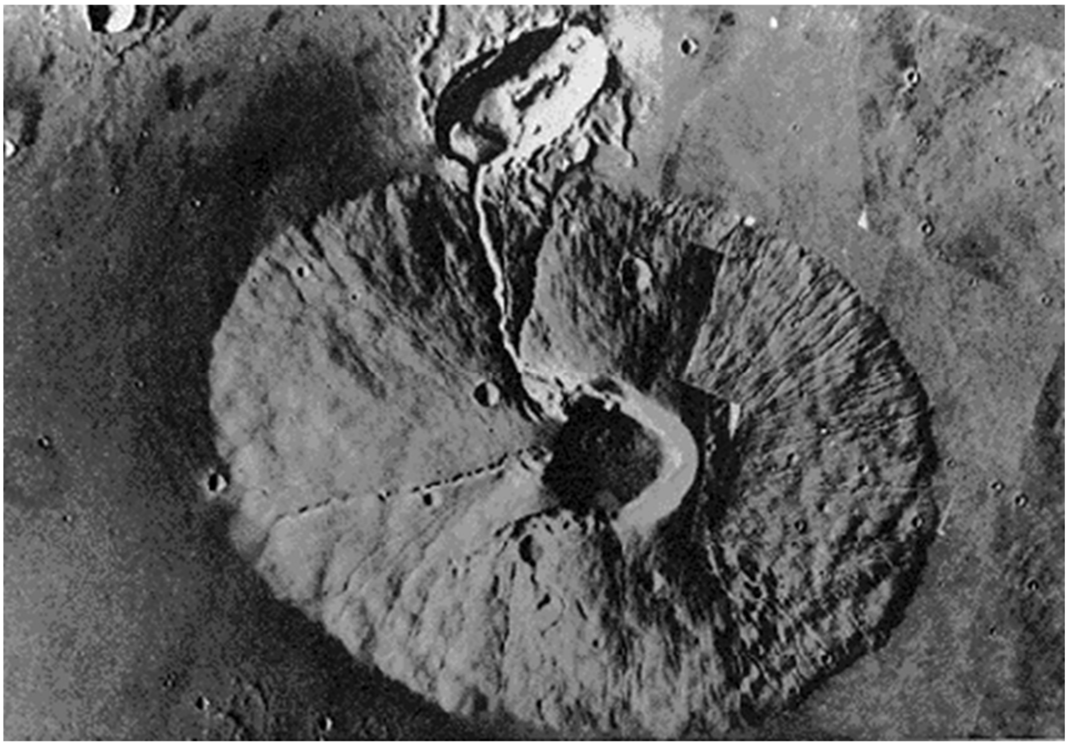

Fig. 6.3. Ceraunius Tholus is located on the edge of the Tharsis region; it is 120 km long, 95 km wide, up to 3 km high, and up to 3 billion years old (https://volcano.oregonstate.edu/sites/volcano.oregonstate.edu/files/oldroot/volcanoes/planet_volcano/mars/Cones/Ceraunius_T.gif).

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.

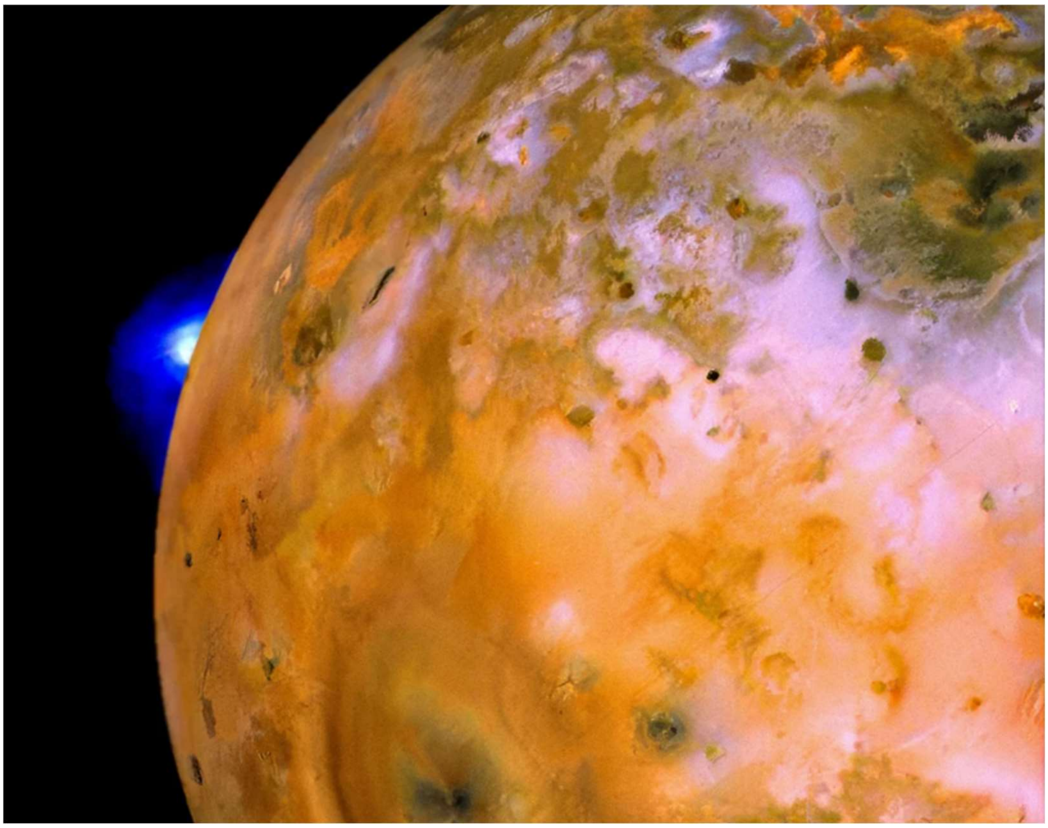

Fig. 6.4. A lava plume erupts from Io's largest volcano, Loki Patera; photo taken in 1979 by NASA's “Voyager 1" probe (https://www.quantamagazine.org/wp-content/uploads/2025/04/IoVolcanism-cr.NASA-Io-Volcano-1304x1536.webp).

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.

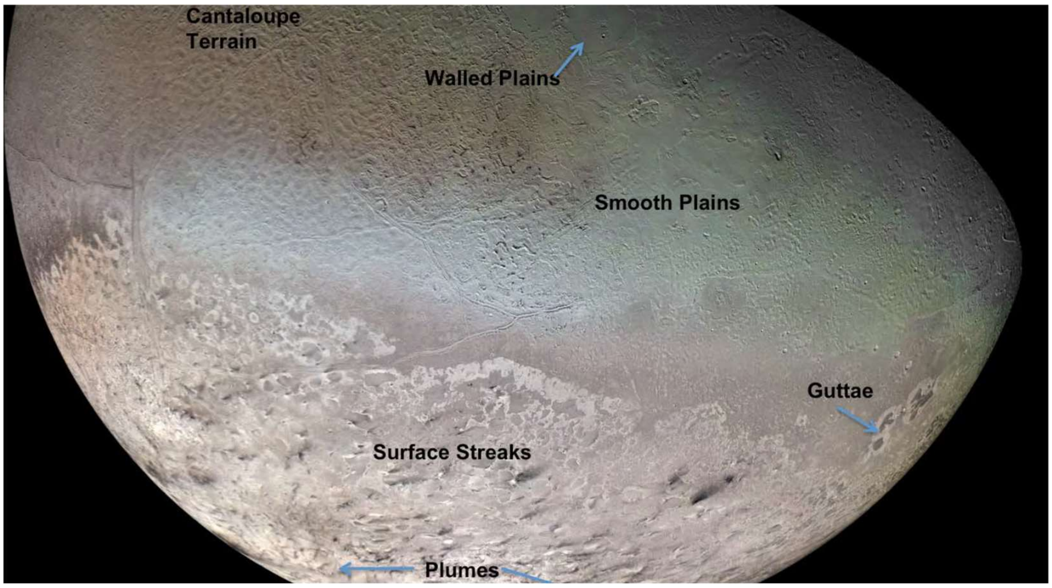

Fig. 6.5. Many of Triton's unique landforms suggest the possibility of cryovolcanism [5].

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).

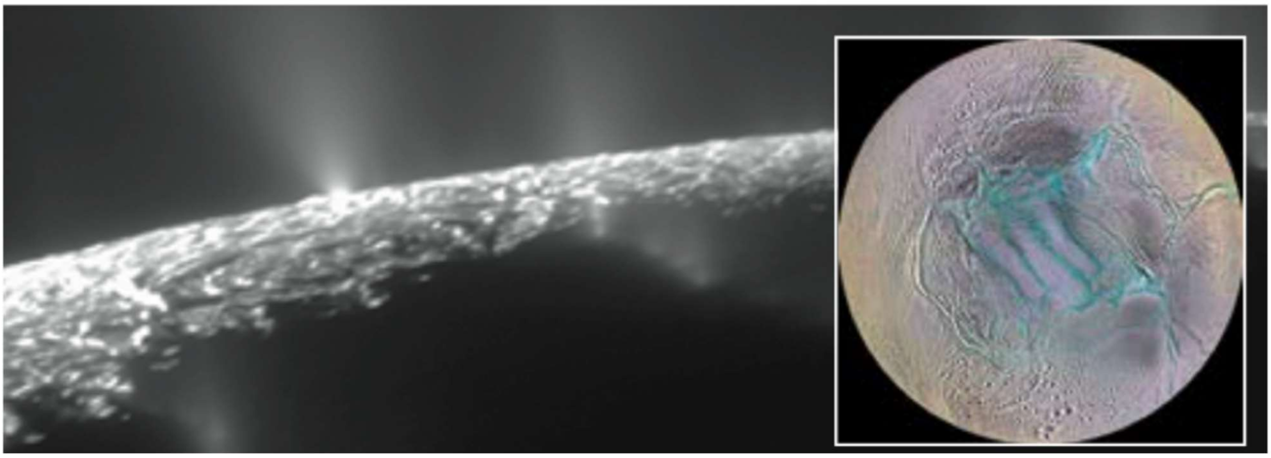

Fig. 6.6. Enceladus has a subsurface ocean with the necessary conditions to support life [3].

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.

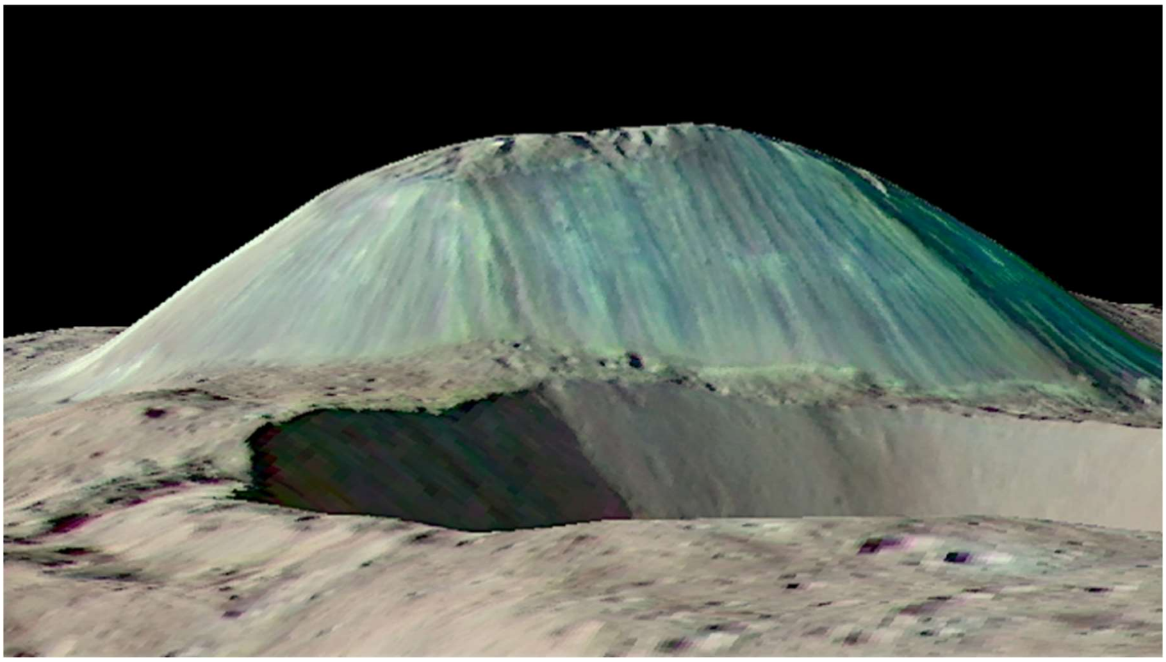

Fig. 6.7. Repeated saltwater eruptions formed the volcanic dome of Ahuna Mons near the impact crater in the foreground without exaggerating the height; the ridges on the slopes were formed by the collapse of the debris, and the faults are visible on the top (https://news.asu.edu/sites/g/files/litvpz161/files/styles/block_image_16_9_lge/public/ahuna-williams.jpg?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

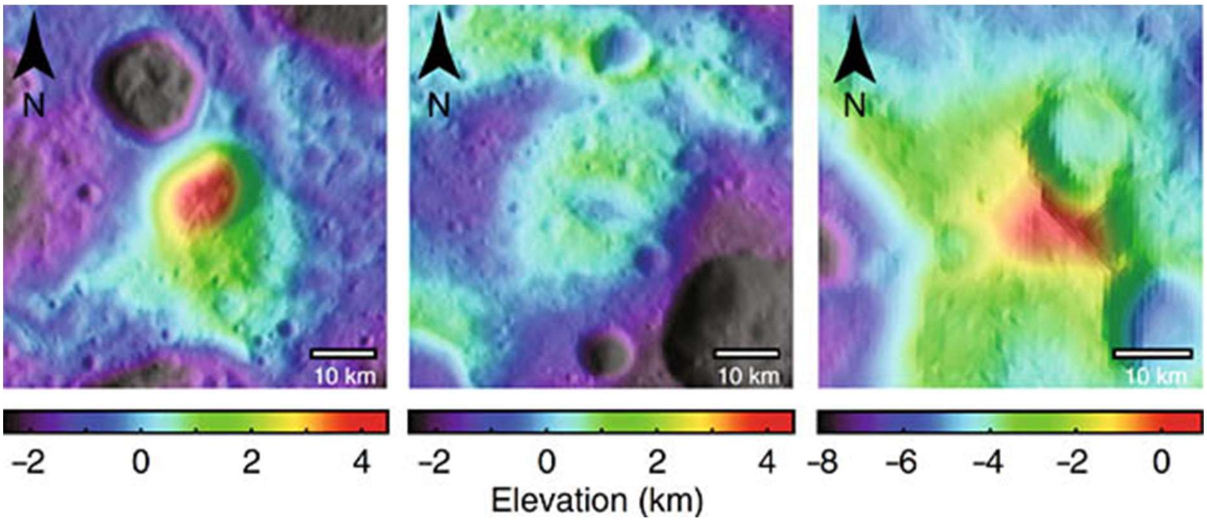

Fig. 6.8. Comparing of the relatively tall Ahuna Mons (left) with the unnamed older dome (center); Yamor Mons (right) may be about 2 billion years old, but it maintains its height due to its location near the always-cold North Pole, where ice melts much more slowly over time (https://dq0hsqwjhea1.cloudfront.net/Dmes-on-Ceres.jpg).

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].

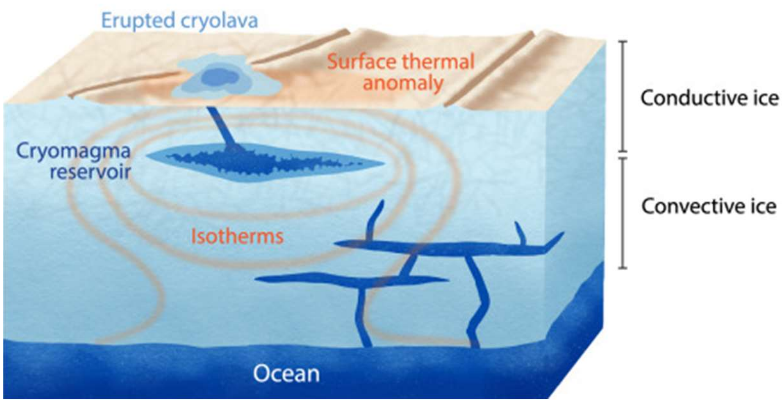

Fig. 6.9. Observed signatures for a 1 km thick reservoir of water located 1 km below Europa's surface [11].

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 tectonics	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-chronology	Using layers of volcanic ash (tephra) with a unique chemical "fingerprint" as time markers	Dating archaeological, 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.

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