# Geology and Geomorphology of Mare Fecunditatis

Subjects: Geology

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Mare Fecunditatis is a ~310,000 km2 flat basalt plain located in the low-latitude area of the Moon. Mare Fecunditatis basin was formed in the pre-Nectarian period, followed by the mare basalts eruption in the Imbrian period, and the volcanic activity continued until the early Eratosthenian period. There is no mass concentration in the center of Mare Fecunditatis, while there are positive Bouguer anomalies on the east and west sides of the basin. A diversity of geological features is found in Mare Fecunditatis.

Volcanic Tectonic Moon Mare Fecunditatis

## 1. Volcanic Features

### 1.1. Mare Basalts

Lunar mare basalt is the main volcanic product of lunar mare volcanism, originated from the partial melting of the lunar mantle and filling some of the impact basins after eruption, including Fecunditatis basin, forming Mare Fecunditatis.

The basalt in Mare Fecunditatis has an average thickness of ~500 m [1], with a thickness of up to 1500 m in the center [2]. The Multiband Imager (MI, [3]) FeO map shows that Mare Fecunditatis is 17–20 wt% in the center and 14–17 wt% in the south. The WAC $TiO_2$ map [4] shows high-Ti ($TiO_2$ > 6 wt%) and low-Ti ($TiO_2$: 2–6 wt%) basalts are mainly distributed in the center of the basin, while very low-Ti ($TiO_2$ < 2 wt%) basalts are mainly distributed in the and southern region. Interference Imaging Spectrometer (IIM, [5][6]) Al maps [7] show high-Al ($Al_2O_3$ > 11 wt%) basalts are widely distributed in the Mare Fecunditatis, except for the northeastern part; the results are similar with the compositional constraints based on FeO, $TiO_2$, and Th maps [8][9].

Luna 16 landed in the northeastern part of Mare Fecunditatis (0.7° S, 56.3° E) in 1970. All returned basalt fragments have high-Al ($Al_2O_3$ > 11 wt%) characteristics [10], with a $TiO_2$ content of 1–5 wt%, $Al_2O_3$ content of 11–20 wt%, and Mg# (Mg/(Mg+Fe) in mole percent) of 0.3–0.4 [10][11]. The isotopic ages of basalt samples show three-episode magmatic activities between ~3.14 and 3.42 Ga, but concentrate in ~3.4 Ga [12][13][14][15]. According to the mare unit map [16], the age of the unit where Luna 16 landed is 3.36 Ga, which is in good agreement with the 3.4 Ga isotopic age. The age of the low-Ti, high-Al basalt in the central and southern parts is 3.5–3.7 Ga, while the high-Ti basalt in the northeast is relatively young, at 3.34–3.36 Ga, and the magmatic activity of some basalts in the southwest continues to 3.14 Ga.

## 1.2. Sinuous Rilles

Sinuous rilles are formed by the erosion of the lunar surface or the continuous collapse of lava tubes during the flow of high-temperature lava, which usually originates from a depression, extending from high terrain to low terrain, and gradually disappears on the smooth lunar mare [17]. A short small-scale sinuous rille is found in the western part of Mare Fecunditatis, adjacent to pyroclastic deposits. This sinuous rille is 26.8 km in length, 1000 m wide, and 69 m deep. A possible 17.5 km long collapsed lava tube with 0.69 km in width and 65 m in depth is also discovered next to the sinuous rille.

## 1.3. Floor-Fractured Craters

The Taruntius crater and Goclenius crater are found in the northern and western part of the Mare Fecunditatis, respectively. Their floors are cut by concentric or polygonal fractures, known as floor-fractured craters (FFCs) [18][19][20]. There are two formation hypotheses for FFCs: (1) viscous relaxation, wherein the crater floor rebounds to fill the crater at a rate controlled by the subsurface viscosity structure, resulting in an overall amplitude shallowing of long-wavelength crater topography [21]; and (2) magma intrusions and sills form beneath the crater, and the magma lifting produces the laccolith and fractures the overlying the crater floor [18][19][20][22]. Recent numerical simulations do not support the viscous relaxation hypothesis [23], but high-resolution topographic and gravity data advocate the magma intrusion hypothesis [18][19][20].

## 1.4. Pyroclastic Deposits

Pyroclastic deposits are the products of explosive volcanism, and the characteristic richness in glass and titanium make them darker than overflow basalts [24]. They have a smooth surface and usually occur close to sinuous rilles, irregular depressions, and the boundary between the maria and highlands [25]. Two areas in Mare Fecunditatis have pyroclastic deposits: in the Taruntius crater [26] on the northern side of the center peak (5.4° N, 46.5° E), and the area connecting to the sinuous rille (3.0° S, 42.3° E).

## 1.5. Irregular Mare Patches

Irregular Mare Patches (IMPs) are enigmatic features occurring in the lunar mare. Typical IMPs (such as Ina (18.65° N, 5.30° E) and Sosigenes (8.335° N, 19.071° E) are one to several kilometers in size and composed of positive-relief mounds surrounding low rough hummocky and/or blocky floor units. The IMPs in Mare Fecunditatis are relatively small (tens to hundreds of meters in size) and only develop irregular, rough, bright, and pit features. They may be formed by (1) sublimation [27]; (2) small magma intrusion on the top of the dome [28][29][30]; (3) clearing of the overlying lunar regolith by outgassing activity within 10 Ma [31]; (4) lava flow inflation [32]; (5) basalt eruption within 100 Ma [33]; (6) pyroclastic eruption [34]; and (7) lava lake process and foamy magma extrusion [35][36][37][38]. The most fundamental scientific question of IMP is whether they are young or not. Some researchers[33] suggest that IMPs have ages younger than 100 Ma based on impact crater chronologies. Others proposed IMP formed contemporarily with the Imbrian-aged host basalts [32][35].

In the western part of Mare Fecunditatis, dozens of IMPs are identified within a length of tens to hundreds of meters. They are distributed on three small Eratosthenian-aged areas, where $TiO_2$ content is >4 wt%. Most of the IMPs are located next to the rim of craters, and a few IMPs are not connected to the crater.

### 1.6. Domes

The lunar volcanic domes are formed by (1) cooling limited lava flows [39]; (2) subsurface intrusion [40]; and combination of (2) and (1) [41]. There are at least 38 domes with a diameter of more than 500 m in the Mare Fecunditatis, mainly distributed in the center of Fecunditatis where the content of $TiO_2$ generally exceeds 3 wt%.

### 1.7. Ring-Moat Dome Structures

RMDS is a newly discovered lunar volcanic feature [42]. RMDSs are small circular mounds hundreds of meters in diameter and ~3–4 m in height, surrounded by narrow, shallow moats. Four hypotheses were proposed for the formation of RMDSs [42]: (1) high-viscous lava eruption soon after the mare basalt; (2) geologically very recent eruption; (3) small-scale squeezing features formed at the time of the mare basalt; and (4) volatility-rich magmatic foam extrusion. More than 1,600 RMDSs have been identified in the Mare Fecunditatis [43] and they are concentrated in the northern sector, where $TiO_2$ contents of the RMDS-bearing basalt are larger than 3 wt% and absolute model ages range from 3.36 to 3.67 Ga [16]. The height of RMDSs is very low (usually a few meters), which should be flattened now if RMDSs have similar ages with the surrounding mare basalts. Some RMDSs were found in the craters with a low degree of degradation (130–1500 Ma); thus, RMDSs are also potentially very young features [44][45].

## 2. Tectonic Features

### 2.1. Wrinkle Ridges

A wrinkle ridge is a linear positive relief landform on the lunar surface, which extends up to hundreds of kilometers, mainly distributed in the lunar maria. There are three main hypotheses on the formation of wrinkle ridges: (1) tectonic origins [46][47][48]; (2) magmatic origins [49][50][51]; and (3) tectonic and magmatic origins [51][52][53][54]. There are more than two hundred wrinkled ridges in Mare Fecunditatis [55]. Their lengths vary from 1 km to 250 km; most of them are less than 50 km long, mainly with an NS trend, consistent with the global trend [56].

### 2.2. Arcuate Rilles and Grabens

In addition to the sinuous rilles and floor fractures, the tectonic movement also forms long and narrow grooves, including arcuate rilles and grabens (straight rilles). Arcuate rilles are usually on the edge of the lunar mare with smooth curves [57]. The graben (straight rilles) forms under the extensional stresses, and a block of the crust cracks and drops down to create the valley floor [58][59][60].

## 3. Impact Craters

Impact craters are the most common geomorphologic features on the lunar surface. According to their size and shape, craters are divided into simple craters (<20 km, bowl-shaped), complex craters (tens to hundreds of kilometers, with terraced walls, central peaks, and flat floor), and multi-ringed basins (>290 km, with multiple peak rings) [61]. Impact craters in Mare Fecunditatis are mainly simple impact craters, with several complex impact craters on the edges. There are also some atypical craters such as elliptical craters, buried craters, and crater chains in Mare Fecunditatis.

Messier Crater (1.9° S, 47.67° E) is an elliptical crater with a major axis ~14.3 km and a minor axis of ~8.3 km, while the Messier A crater (1.97° S, 46.95° E) has a major axis ~15.8 km and a minor axis ~11 km[62]. Messier was likely formed by a low-angle westward impact, and Messier A formed following a rebound by the impacting body [63]. Major vertical rays extend over 100 km north and south from Messier and horizontal rays extend over 100 km west from Messier A. The results of Monte Carlo simulations [64] show that the simulating ray patterns by oblique impact are very similar to reality. In addition, there are at least 29 buried impact craters in the Mare Fecunditatis. The crater chains refer to a row of craters distributed linearly. Crater chains formed by secondary craters and collapse of the lava tube are identified in Mare Fecunditatis.

# 4. Other Features

## 4.1. Pit Craters

Lunar pit craters formed by the collapse of underground space. A total of 15 pit craters have been discovered on the maria and 5 on the highlands [65][66][67][68]. The underground space may be formed by the lava tube or the stoping of magma [65][68]. Recently, the underground space of the caves in Marius Hills has been detected through radar and gravity analyses [69][70]. Pit craters stay stable for at least tens of years. Some pits (such as King Crater Bridge) found at the Apollo period still show no change with the NAC data [65]. There is a pit crater (0.917° S, 48.660° E) in the center of Fecunditatis, and a highland-type pit crater (6.752° S, 42.759° E) at the southwest.

It has been employed that Integrated Software for Imagers and Spectrometers (ISIS) to make the high-resolution NAC DTM of two pit craters. The entrance to the central Mare Fecunditatis pit crater is about 125 × 100 m in size and 35 m in depth. Deposits lie on the southeast and northwest wall. The deposits on the northwest wall extend ~30 m laterally, with a slope of 20–65°. The southeast wall has collapsed severely, with a relatively gentle slope (10–35°). Most of the deposits are finer than the resolution of the NAC image (~1.1 m), with only a few meter-level rocks at the bottom of the pit crater. The bottom of the pit is relatively flat (<10°), with an area of 27 × 23 $m^2$ lower than 15°. The highland pit crater on the southwest side of Mare Fecunditatis is about 70 m in diameter, and the walls are very steep in all directions. The gentlest southwest wall is 30–60°, and the maximum slope of the northeast wall exceeds 80°. The bottom of the pit is relatively flat (<10°) with an area of 23 × 10 $m^2$.

## 4.2. Swirls

Lunar swirls are high-albedo loops and ribbons occurring in both maria and highlands associated with strong crustal magnetic fields. The formation of the swirls may be related to (1) the magnetic anomalies blocking the solar wind ion bombardment, which reduces the degree of space weathering (darkening with time) [71][72][73][74]; (2) comet impacts or micrometeoroid swarms scouring the top-most surface regolith, which exposes fresh material and imparts a remnant magnetization [75][76][77]; (3) weak electric fields attract the high-albedo, fine-grained, feldspar-rich dust [78]. The interaction between the solar wind and silicate regolith produces water (e.g., [79][80]). Moon Mineralogy Mapper ($M^3$, [81]) spectral data show that the regolith on the swirl has lower water than the surrounding area [74], which supports the hypothesis (1).

There are three swirls (identified by [82]) on the highland at the southwest side of Mare Fecunditatis with a low optical maturity , and the surface vector mapping (SVM, [83]) of magnetic field (B-flied) shows this area has a magnitude of up to 100 nT. The MI mineral data of the swirl show consistent plagioclase with the surrounding area, which contradicts hypothesis (3).

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