# THE STRATIGRAPHY OF LAVA FLOWS IN NORTHERN OCEANUS PROCELLARUM, MOON

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The lunar surface is composed primarily of two distinct geologic units. The bright, low titanium, low iron highlands make up the majority of the surface area and volume of lunar crust. The darker maria are high iron, high to low titanium, regions resembling terrestrial basaltic lavas and occur primarily on the near side of the Moon. The maria occur in basins, presumed to be the result of impacts which fractured the highlands crust, allowing lava to seep through the cracks and flood the surrounding highlands regions. The lunar maria are important because they tell us about the thermal history and interior composition of the Moon, and because of their relatively high concentration of useful materials [1,2].

Northern Oceanus Procellarum, a mare region on the northwestern near side of the Moon, is the area chosen for mapping in this study. The Department of Defense Clementine mission, flown in 1994, provides spectral reflectance data for the entire lunar surface, which show in high resolution (200m / pixel) the iron and titanium compositional variations of the lunar surface. These variations reveal the locations of different lava flows and differences in crater ejecta composition and density, which can be used to map the three dimensional stratigraphy of flows in the region.

**METHODS** Clementine images were used to piece together mosaics of the region of study using the ISIS software from the USGS [3]. A mosaic approximating the “true” color of the area was made with the 415 nm filter controlling the blue channel, 750 nm controlling the green, and 950 nm controlling the red channel. A false color mosaic was constructed with the 415/750 ratio controlling the blue, the 750/950 ratio controlling the green and the 750/415 ratio controlling the red channels. This exaggerated and extremely brightly colored image helps to eliminate noise caused by surface maturity, albedo, and shadowing. The result shows, in extreme contrast, the compositional differences of the lunar surface material, with highlands appearing bright red and mare materials spanning a wide range of colors.

Compositional maps of iron (FeO) and titanium ($TiO_2$) abundance were constructed using the methods described by Lucey et al. [4,5] and Blewett et al. [2]. The resulting images provide maps of Fe and Ti at 200 m/pixel resolution. This method has been calibrated using known iron and titanium concentrations from Apollo landing sites, and Lunar Prospector gamma-ray data [6].

Using compositional differences obtained from true- and false-color mosaics, as well as the iron and titanium maps, the generalized flow boundaries were located and mapped. These data provided a preliminary grouping of these units into approximately 20 generalized units, a list that was continually modified and shortened throughout the study with the arrival of new data (Table 1). A defined area of each of the flows was studied using Lunar Orbiter IV photographs to determine crater densities. Each unit was dated by comparison of crater densities with radiometrically determined ages of Apollo (Table 1). A geologic map was constructed, showing the flow units and highlands, shaded according to age (Figure 1).

Larger craters which punch through the lava layer into the highlands material produce an ejecta blanket that contains some mixture of highlands and lava materials. Once the iron concentration in the lava and the highlands iron concentration was measured, the ratio of highlands to lava material originally excavated by the impact was calculated. The total volume of excavated material was calculated using a standard model of crater geometry [e.g.,1]. These values were plotted on a map of the region, and depth contour lines drawn to produce an isopach map of the area. From these data, we calculated the mare eruption rates for this region of the Moon (Table 1).

**RESULTS AND DISCUSSION** Northern Oceanus Procellarum contains some very young flows, several of which dispute the long-held view that the Moon ceased volcanic activity around 3 Ga [7,8]. The flows in this region show a range of 2.4 billion years, from 1.2 to 3.6 billion years old (Table 1). Flow Units 1 and 3 and the Rumker area were deposited in the Late Imbrian times (3.8-3.2 Ga), and Flow Units 2, 4, 5, and 6 in the Eratosthenian era (3.2-1.1 Ga).

The lavas show little variation in iron, ranging from 19.6% to 22.1% FeO, considerably higher than the 12.9% average calculated for the highlands. A larger variation is seen in titanium, from less than 0.5% $TiO_2$, similar to the very low titanium concentration in the highlands, to a high of 6.0% $TiO_2$. The general trend in this region is for the higher Ti lavas to be younger, contradicting the generalization that the lower Ti basalts on the Moon tend to be younger than higher Ti basalts [1].

Geologic mapping in this study shows refinement over previous results. Whitford-Stark and Head [10] show some slight differences in flow boundaries and groupings compared to the results published here, and even larger differences were mapped by Wilhelms [11]. Discrepancies in both cases can be explained by the arrival of new, higher resolution Clementine compositional data in 1994 (after the previous studies [10,11] were published), which is better and more reliable for this purpose.

The lavas flows cover 462,000 km$^2$ of the study area, a significant 71% of the 653,000 km$^2$ total study area. Mare basalts cover an average of 17% of the total lunar surface [12] and the lavas in this region make up 10% of the total 6.3 x 10$^6$ km$^2$ of lava [12] on the Moon's surface. The average thickness of lava, from 232 to 1100 meters is consistent with the estimate that most maria are less than 2 km thick [12].

The total volume of lava produced, 266,000 km$^3$, represents approximately 2.7% of the total 1 x 10$^7$ km$^3$ volume of mare basalts on the Moon [12]. Based on an average crustal thickness of 53 km in the area [11], and therefore an estimate of crustal volume of 5.46 x 10$^7$ km$^3$ for the study area, the lavas make up only 1% of the total crustal volume of the study area.

The total lava volume of 266,000 km$^3$ produced over a period of 2.4 billion years, yields an average magma production rate of 1.1 x 10$^{-4}$ km$^3$ / year in this region of the Moon for the total time span of active production. This figure represents a rate that may have fluctuated during different time periods. If constant throughout the time of production, the above rate is considerably lower than the 150 x 10$^{-4}$ km$^3$ per year estimates of lunar magma production for the Late Imbrian [12], but is similar to the 1.3 x 10$^{-4}$ km$^3$ per year lunar average estimates for the Eratosthenian [12].

**REFERENCES** [1] Heiken G.H. et al. (eds.), 1991, Lunar Sourcebook. [2] Blewett D.T. et al., 1997, JGR, v.102, pp. 16319-16325. [3] ISIS documentation homepage at http://wwwflag.wr.usgs.gov /isis-bin/isis.cgi. [4] Lucey P.G. et al., 1995, Science, v. 268, pp. 1150-1153. [5] Lucey P.G. et al., 1998, JPR, v. 103, pp. 3679-3699. [6] Elphic R.C. et al., 1998, Science, v. 281, pp. 1493-1496. [7] Spudis P.D., 1996, The Once and Future Moon. [8] Schultz P.H. and Spudis P.D., 1983, Nature, v. 302, pp. 233-236. [9] Rose D.E. and Spudis P.D., 2000, LPS XXXI, CD-ROM, 1364. [10] Whitford-Stark J.L. and Head J.W.III, 1980, JGR, c. 85, pp. 6579-6609. [11] Wilhelms D.E., 1987, USGS Prof. Paper 1348. [12] Head J.W.III and Wilson L., 1992, Geochimica et Cosmochimica Acta, v. 56, pp. 2155-2175.

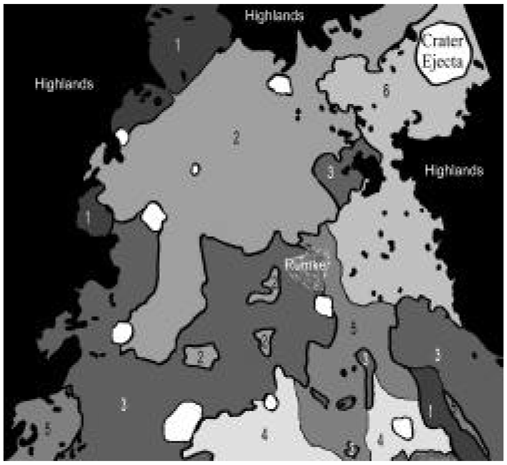
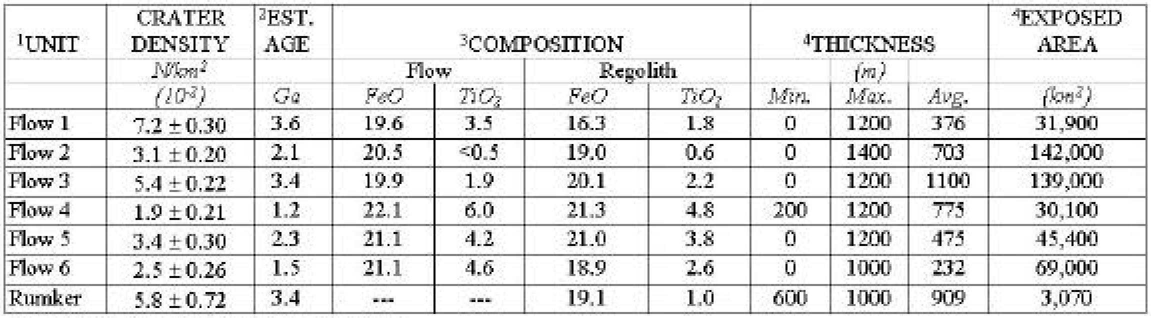


Figure 1: Geologic map of Northern Oceanus Procellarum. Gray areas are lava flows. Black areas are highlands materials and gaps in coverage. White areas are crater ejecta blankets that obscure flow boundaries. Darkest flows (i.e. #1) are oldest, and grays lighten to the youngest flows (i.e. #4). See Table 1 for unit information.

Table 1: Oceanus Procellarum Stratigraphic Unit Data



| [1]UNIT | CRATER DENSITY | [2]EST. AGE | [3]COMPOSITION | | | | [4]THICKNESS | | | [4]EXPOSED AREA |
|---|---|---|---|---|---|---|---|---|---|---|
| | N/km$^2$ | | Flow | | Regolith | | | (m) | | |
| | $(10^{-3})$ | Ga | FeO | $TiO_2$ | FeO | $TiO_2$ | Min. | Max. | Avg. | (km$^2$) |
| Flow 1 | 7.2 ± 0.30 | 3.6 | 19.6 | 3.5 | 16.3 | 1.8 | 0 | 1200 | 376 | 31,900 |
| Flow 2 | 3.1 ± 0.20 | 2.1 | 20.5 | <0.5 | 19.0 | 0.6 | 0 | 1400 | 703 | 142,000 |
| Flow 3 | 5.4 ± 0.22 | 3.4 | 19.9 | 1.9 | 20.1 | 2.2 | 0 | 1200 | 1100 | 139,000 |
| Flow 4 | 1.9 ± 0.21 | 1.2 | 22.1 | 6.0 | 21.3 | 4.8 | 200 | 1200 | 775 | 30,100 |
| Flow 5 | 3.4 ± 0.30 | 2.3 | 21.1 | 4.2 | 21.0 | 3.8 | 0 | 1200 | 475 | 45,400 |
| Flow 6 | 2.5 ± 0.26 | 1.5 | 21.1 | 4.6 | 18.9 | 2.6 | 0 | 1000 | 232 | 69,000 |
| Rumker | 5.8 ± 0.72 | 3.4 | --- | --- | 19.1 | 1.0 | 600 | 1000 | 909 | 3,070 |

1 See Figure 1 for unit locations.

2 Age interpreted by comparing crater densities with those of sampled sites and compared with calculated dates of other areas [8, 9]

3 Compositions in wt. % determined from Clementine images, using the method of Blewett et al. [2] and Lucey et al. [4,5], accurate to ± 0.5%.

4 Thickness and Exposed Area from pixel counts.