Ancient Lava Flows in Mare Imbrium: Estimations of Extent and Rheologic Properties using LROC Images.

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Introduction: The surface of the near side of the Moon is pock-marked by large, pseudo-round areas known as mare. Formed as a result of extensive eruption of low viscosity, mafic lavas into low-lying impact basins, these mare are composed of basaltic rock, whose age in the study area of Mare Imbrium falls between 2.01 and 3.57 Ga. [1]. At least three distinct generations of Imbrian to Erasthotenian age [1] basalt- forming flows have been recognized and mapped within the basin, originating between 18°N - 23°N and 28°W - 32°W, extending distances of approximately 1200, 600, and 400 km respectively [2]. Recent, high resolution images obtained by the Lunar Reconnaissance Orbiter Camera (LROC) currently in orbit around the Moon show these lobate flows in extensive detail, including in areas without previous high resolution images, such as those provided by orbital photographs taken during the Apollo 15 and 17 missions, which were the basis for the initial mapping of the flows in the region by Schaber [2].

We use these new data to measure flow geometry and calculate the rheologic properties of the lavas represented by the flows, gain an understanding of how these may vary along the extent of a single flow, and to provide preliminary insight into the rates at which these lavas were extruded.

Methods: This study employed remote sensing techniques to locate, map, and measure individual lava flows within Mare Imbrium, primarily focusing on those regions previously mapped by Schaber using Apollo orbital photography [2]

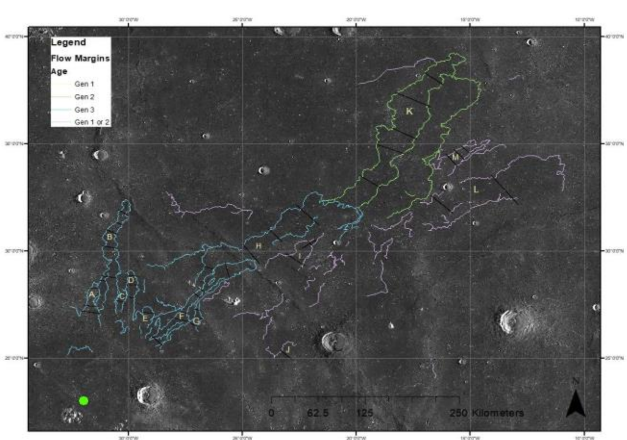

Figure 1: Distribution of flows and location of cross sections. The approximate origin is marked in green.

Using ArcGIS and images obtained by LROC at low sun illumination [3], flow margins were located and mapped by observing subtle variations in illumination and shadow. These variations indicate the presence of a flow scarp delineated by a relatively sharp change in slope.

Once these were mapped, locations along these flows with well-defined scarps were chosen to obtain cross-sections from accompanying Digital Elevation Model (DEM) data [4]. These cross sections were normalized by removing any trend in the data to account for variations as a result of flow across a regional slope, then measured to obtain flow height and width, along with the width of any channels, if present.

These data were then utilized to calculate the yield strength of the lava by the following equations, assuming the flow to be a Bingham material with a finite yield strength [5]:

(1) $Y = \rho\, g\, H \sin\theta$ [5]

(2) $Y = \rho\, g\, H^2 / W$ [6]

(3) $Y = \rho\, g\, (W-w) \sin^2 \theta$ [5]

where $\sin\theta$ is the topographic gradient, H is the flow thickness, W the horizontal width, and w the channel width for any channelized flows, and taking the acceleration due to lunar gravity, g, as 1.625 m/s^2, and the average density of lunar basalt, ρ, to be 3149 kg/m^3 [7].

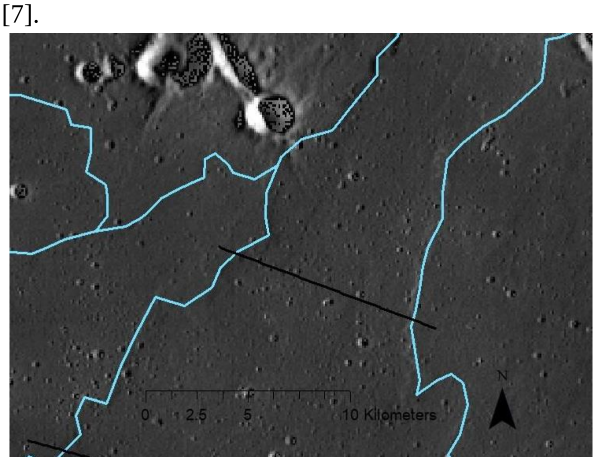

Figure 2: Detail of a single flow at location F2. Flow margins are marked in blue, the cross section taken along the black transecting line.

Where possible, the effusion rate was estimated by:

(4) $F = 300\, \kappa\, w\, L/H$ [8]

where κ is taken to be equal to 7 x 10^{-7} $m^2\, s^{-1}$, the thermal diffusivity for mafic lavas [9], and L is the total length of the flow, estimated in ArcGIS by taking the point

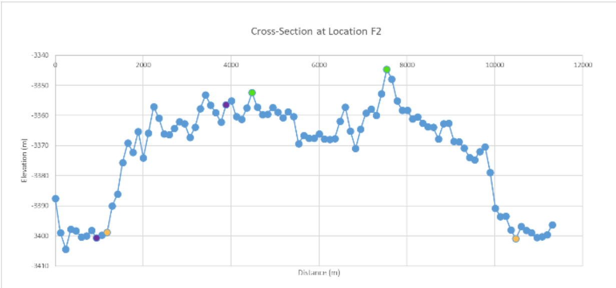

Figure 3: Cross sectional profile at location F2. Points used for measurements are shown in color, with purple for thickness, H, orange for flow width, W, and green for channel width, w.

23°N and 31°W to be the approximate origin of the flows [2].

Findings: 42 cross sections representing 13 distinct lobate flows and several tributary flows were taken and measured between 24.9°N – 38.3°N and 12.9°W – 32.0°W. These flows had measured thicknesses between 19 m and 106 m, with a mean of 48 m, and horizontal widths ranging from 5089 m to 43910 m, mean 17854 m. In all cases, the regional slope was less than 1 degree, with the mean slope being 0.25 degrees. Table 1 lists calculated yield strength values for flow F using each of the three equations above, as well as mean values and standard deviations for the yield strength of the flow. Formula 3, where utilized, consistently gave the highest yield strength values, while formula 2 gave significantly lower values than either of the others, more similar to the 1.5±0.5 x 10^2 calculated previously [10]. The formula 2 values are significantly lower than those known for terrestrial basaltic rocks, but not unreasonable.

Yield strength varies along the length of each flow regardless of the method of calculation used, and without any apparent trend in these variations related to location along the flows, indicating that the distance from the origin of the flow is not a primary factor in determining the rheologic properties of the lava. Additionally, the standard deviation of these values, even within a single flow, is quite high, suggesting variations in the lava and surface properties within a flow.

The mean effusion rate onto the surface of the moon is calculated to be 8660 m^3s^{-1}. This rate implies a mean velocity of 0.01 ms^{-1} for the cross-sectional area obtained using the mean width and height of the flows given above, a rate which is consistent with pahoehoe-style basalt flows, where a chilled crust allows for significant flow inflation [11].

Further analysis of these and other, similar flows using LROC images would be possible with further examination of other images and areas, and may be aided by examining images taken at different sun angles and the use of other forms of data, such as compositional variations between flow generations. An improved understanding of the Mare Imbrium flows should prove useful in any future landings in this or other mare regions.

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			Height	Width	Channel Width	Slope	Flow Length	Yield Strength			Effusion Rate
Flow	Location	Profile Number	H (m)	W (m)	w (m)	θ (degrees)	L (m)	Y1 (Pa)	Y2 (Pa)	Y3 (Pa)	F (m^3/s^-1)
F	1	33	56.7	21112.8	12502.5	0.193	306000	5.57E+04	7.79E+02	1.62E+06	1.42E+04
	2	2	44.1	9304.8	3058.3	0.105		2.36E+04	1.07E+03	3.48E+05	4.45E+03
	3	34	46.0	8812.4	-	0.352		8.12E+04	1.23E+03	-	-
	4	18	31.3	5088.5	1301.7	0.352		5.52E+04	9.86E+02	2.30E+06	2.67E+03
	5	16	91.1	21771.9	-	0.305		1.40E+05	1.95E+03	-	-
Avg.								7.11E+04	1.20E+03	1.43E+06	7.10E+03
st. dev.								4.36E+04	4.49E+02	9.93E+05	6.19E+03

Table 1: Measurements and estimated rheologic properties of lava flow F in mare Imbrium. Lower location numbers are closer to flow origin.