THICKNESSES OF LUNAR MARE FLOW FRONTS

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Abstract. Lunar near-terminator and high-resolution panoramic camera photographs were searched for flow fronts, the edges of flow units in mare areas. Data for twenty areas, including fifteen previously unmeasured areas, are summarized. Height measurements of flow scarps present on the Moon range from 1 to 96 m. More than half (57%) of all flow fronts measured are less than 15 m thick. These observations agree well with other photogeological and experimental observations of flow unit thicknesses on the Moon.

1. Introduction

Although the idea of multiple flow units filling lunar basins has been widely accepted, morphometric characteristics of these units have not been extensively studied. The filling of circular basins and other lowlands by basaltic lavas is significant in deciphering the thermal history of the Moon. Where experimental or observational data are lacking, photogeological measurements of flow height, width and length can be used as clues to eruption style and physical properties of the magma. For example, the ratio of flow thickness to width is the aspect ratio; this is a standard means of comparing flows, and can help in determining physical parameters such as yield stress of the lava (Fielder and Wilson, 1975).

The purpose of this study is to present a summary of measured lunar flow front thicknesses. In addition to measurements previously reported in the literature, a thorough search was made of Lunar Orbiter and near-terminator Apollo orbital photographs to document occurrences of flow fronts in mare units and to establish photogeologically the observable range of basalt flow thicknesses in the various maria.

2. Previous Studies

The best documented flows on the Moon are the Eratosthenian flows in Mare Imbrium. These were first mapped by Strom (1965) from Earth-based photographs. Refinements in mapping, determination of source areas, and thickness measurements for the Mare Imbrium flows were carried out after Apollo 15 and 17 photographs made shadow measurements possible. Schaber's 1973 measurements of scarp heights in Mare Imbrium range from 10 to 63 m, with average heights of 30 to 35 m. Detailed studies of fine structures, especially small crater studies on these particular flows, have been done by Fielder and Fielder (1968).

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The unusually long flows in Mare Imbrium have also been used extensively in theoretical studies of rheological properties and extrusion rates. Without actual samples this is the only area on the Moon where lava properties can be determined based on photographic evidence of flow thickness, width, levees, channels, and slopes (Hulme, 1974; Moore and Schaber, 1975). Experimentally determined viscosities of lunar lavas from returned samples show that the viscosity is low enough to account for movement on the very small slopes in Mare Imbrium (Murase and McBirney, 1970). Walker (1973) has suggested that rate of extrusion is the principle factor influencing length of lava flows; therefore, the lunar flows have extremely high discharge rates (Schaber, 1973). A theoretical formula expressing flow dimensions in terms of fluid properties, flow rates, and slopes has been derived based on experimental models and data from terrestrial lava flows. This has been used in conjunction with photogrammetric data from lunar lava flows to demonstrate high flow rates and low yield stresses for the Mare Imbrium flows (Hulme and Fielder, 1977).

Other photogeologic investigations of lunar lava flow units have been accompanied by only a few actual thickness measurements. An investigation of flow lobes in Oceanus Procellarum (near the Surveyor 1 landing site), Mare Cognitum, and Sinus Medii shows scarp heights of 5 to 10 m (Schaber *et al.*, 1976). Lloyd and Head (1972) measured a flow front 3 to 5 m high in a mare unit southeast of Kunowsky crater. Photogeologic evidence of layering in Hadley Rille suggests that most flow units there average 10–20 m thick; others are thinner (Howard *et al.*, 1972). The latter are possibly compound units of the type discussed by Nichols (1936) or they may be separate flows.

Experimental studies to determine petrologic characteristics of returned samples have also placed bounds on flow unit thickness. Chemical kinetic data of Apollo 11, 12 and 15 basalts have provided evidence that sampled mare basalts originated from cooling units which are no thicker than 8 to 10 m (Brett, 1975). Schaber *et al.* (1976) present a short summary of several experiments on natural and synthetic lunar basalts, all of which suggest that average lunar lava flow thicknesses are less than 10 m.

3. Methods and Observations

Lunar Orbiter, Apollo metric, Hasselblad, and panoramic camera near-terminator photographs were studied in detail for evidence of mare lava flows. Several terminator-crossing sequences using very high speed black-and-white film on Apollo missions 14 through 17 were valuable for locating some of these features (Head and Lloyd, 1971, 1972a,b, 1973), while near-terminator metric photographs made possible the most accurate measurements. Scarp heights were determined by shadow measurements on enlargements of Apollo metric photographs.

Criteria used for identification of flow fronts were the presence of a low scarp with lobate or irregular trend in a mare unit. Often differences in crater density and other associated surface features can be seen on opposite sides of the scarp. Only those scarps identified as flow fronts in this manner were measured even though flow unit thickness can also be estimated from ghost craters and ring moat structures (Cruikshank *et al.*, 1973; Schultz *et al.*, 1976). Obvious flows of impact melt origin near crater rims were also excluded.

3.1. Flow front morphometry and age

Flow scarps were identified at fifteen new sites concentrated on the northwestern near side of the Moon (Figure 1). These new sites are located in Oceanus Procellarum, Mare Insularum, Mare Vaporum, Mare Nubium and Sinus Amoris. The flows in Mare Imbrium and four areas mentioned by Schaber *et al.* (1976) are also shown in Figure 1.

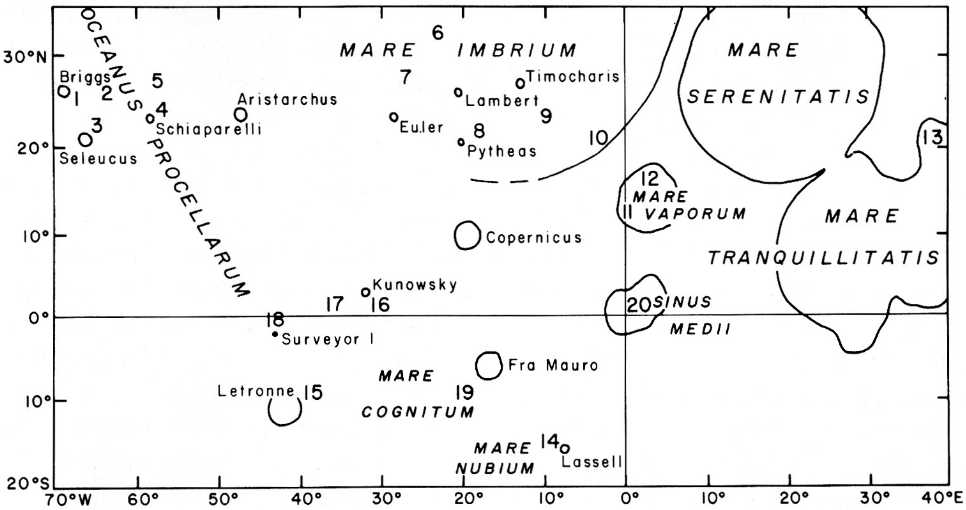

Fig. 1. Sketch map showing locations of lunar mare flow fronts. Numbered scarp locations are keyed to Table I.

Measured heights of flows range from 1 to 96 m; the average is 21 m (Table I). Fifty-seven percent of the scarps measured are under 15 m thick and 28% are less than 10 m high. The only scarps greater than 50 m thick (12% of those measured) are in Mare Imbrium. Excepting only these thick flows, there is no difference in the average size of scarps in irregularly shaped Oceanus Procellarum versus the circular maria. It is probable that true scarp heights are actually greater since only the shadowed portions of the scarps were measured. High resolution Lunar Orbiter images show less steep, unshadowed slopes at the base of the steepest scarps in Mare Imbrium (Fielder and Fielder, 1968). This fact along with some assumed erosion of scarps indicate that original heights of a few flows were over 100 m.

Based on U.S. Geological Survey 1:1 million scale geologic maps, nine of the areas included in Table I occur in mapped Imbrian age units and five are mapped as Eratosthenian, while six are borderline between these two systems. The thickest flow front scarps measured are Eratosthenian in age while the thinnest, according to Wilhelms and

TABLE I

Scarp heights for measured flows

Area (see Figure 1)	Frame	Height (m)	No. of measurements	Age[a]
1. E of Briggs	AS15-M-2750	1–8	12	I
2. E of Briggs	AS15-M-2491	3.5	1	I/E
3. N. of Seleucus	AS15-M-2620	13–27	2	I
4. NE of Schiaparelli	AS15-98-13348	3–6	2	I/E
5. NE of Schiaparelli	AS15-M-2349	1–15	6	I/E
6. N of Prom LaHire	LOV-M-160	17–96	24	E
7. N of Euler	AS15-M-1157	5–40	13	E
8. NE of Pytheas	AS17-M-2122	4–12	4	I/E
9. SE of Timocharis	AS15-M-0596	12–20	2	I
10. NW of Mons Huygens	AS17-M-1829	5–31	6	I
11. W Mare Vaporum	AS15-98-13302	5.0	1	I
12. N Mare Vaporum	AS17-M-1236	10–14	2	I
13. Sinus Amoris	AS18-M-302	48	1	I
14. NW of Lassell	AS16-16-19860	6	1	I/E
15. E of Letronne	AS16-M-2839	15–33	3	E
16. S of Kunowsky	AS14-78-10376	1–6	6	I/E
17. SW of Kunowsky[b]	AS12-54-8105	5–7	?	E
18. Near Surveyor 1 site[b]				
500 m NW	LO III M192	5–7	?	I/E
11.2 km SE	LO III M195	not measured	–	I
19. W of Bonpland[b]	AS16-M-1984	not measured	–	I
20. Sinus Medii[b]	AS10-27-3907	< 10	?	I

[a] Ages of overlying flow units are assigned from Wilhelms and McCauley (1971) and from the U.S.G.S. 1:1 000 000 Geologic Maps of the Moon.

[b] Data from Schaber *et al.* (1976)

McCauley, 1971, are in 'Imbrian possibly Eratosthenian' units (Figure 2). Thus, while the relationship of increasing age equals greater degradation holds well for the smaller size classes, the trend is not smooth and the correlation breaks down at several points on the graph.

Flow scarps are generally located in mare areas which display numerous other flow features. Leveed channels, small rilles, and rimless depressions are common features on flows in Mare Imbrium and are also seen near flow fronts in Mare Cognitum and Oceanus Procellarum. Flow scarps are found in association with mare ridges in Mare Imbrium, Oceanus Procellarum, and Sinus Medii (Figure 3a, b, and c). A 30 km long scarp surrounds several Eratosthenian age mare domes in eastern Mare Imbrium (Figure 3b). A breached lava-filled ghost crater is just north of the flow fronts in Figure 3c.

3.2. CORRELATIONS WITH REMOTE SENSING DATA

Attempts were made to correlate the scarp locations with other remote sensing data. Color differences in the maria have been noted at a few points that coincide with scarp locations, specifically in the area of the Mare Imbrium flows where bluer material overlies

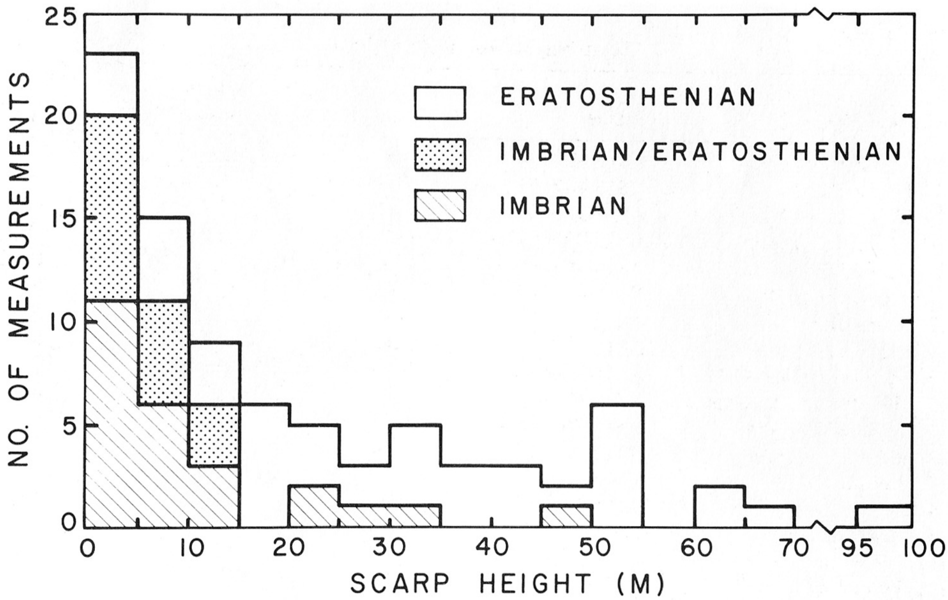

Fig. 2. Age and height distribution of measured flow scarps. Ages of mare units are based on U.S. Geological Survey 1:1 000 000 scale geologic maps of the Moon, and Wilhelms and McCauley (1971).

redder mare (Strom, 1965; Whitaker, 1972). Color differences are probably not more common elsewhere in Mare Imbrium because several episodes of younger mare basalt filling overlap each other, forming well-developed scarps that are indistinguishable on color composites because they all display the same color. Most of the scarps are difficult to locate accurately at the resolution of the available color composite photographs (Whitaker, personal communication). Many color contrasts exist in the maria where scarps are absent or have not been documented.

The same problems arise with other types of remote sensing data. Although spectral reflectance studies have delineated diverse basalt types on the surface of the Moon (Pieters, 1978) the resolution of such data is not high enough to correlate with observed flow front scarps. Compositional variations imply separate flows even where no scarps are observed between units. However, at present there is not enough data to correlate scarp height or flow thickness with composition.

4. Discussion

The fact that flow scarps are not more commonly seen on the Moon can be attributed either to failure to form or to surface degradation. One factor contributing to this paucity is the mode of formation including properties of the lava. In the Imbrium case there are elongate flows that emanate from a distinct source area (Schaber, 1973). However, this characteristic style is not observed in other lunar maria. In conjunction with studies of

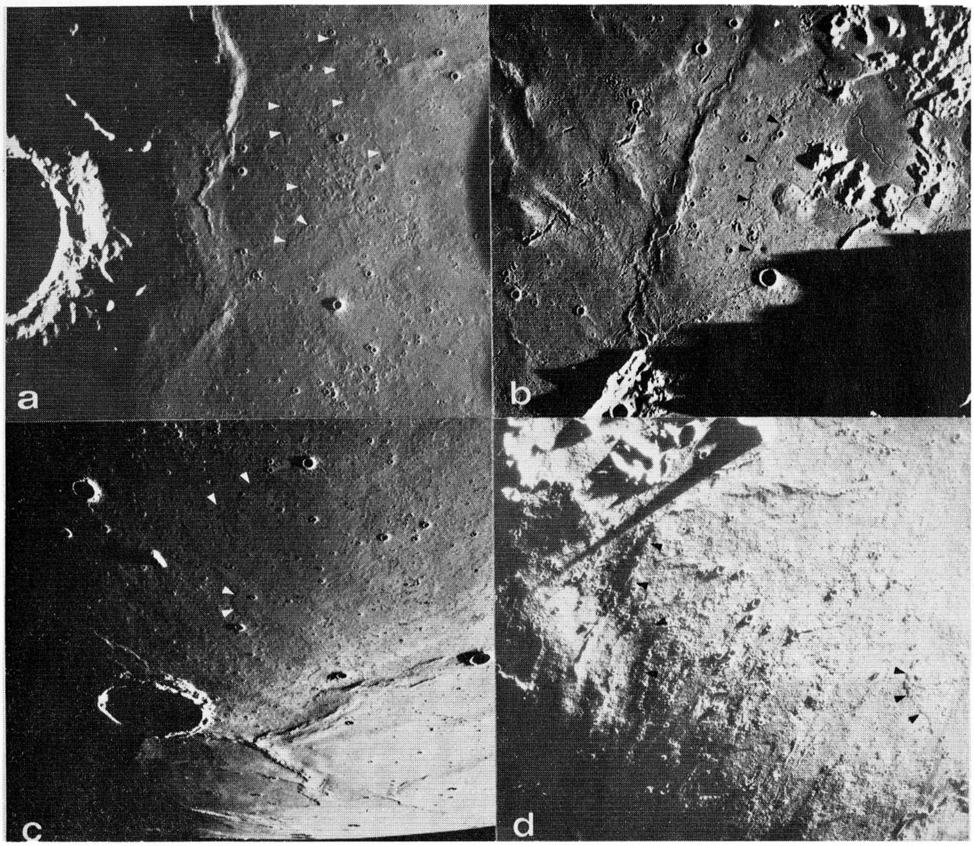

Fig. 3. Examples of the flow fronts discussed in this paper. Arrows point to scarps. (a) Fronts associated with channels and mare ridges east of Briggs, 37 km diameter (AS15-M-2751). (b) Scarps near mare domes and ridges in eastern Mare Imbrium (AS17-M-1829). (c) Small scarps northeast of Seleucus which is 43 km diameter (AS15-M-2620). (d) Oblique near-terminator view of flow features in Mare Vaporum (AS15-98-13302).

the Snake River basaltic province, Greeley (1975) has suggested the presence of two types of volcanism both on Earth and in the lunar maria. One is flood basalt filling, characterized by large volumes and high rates of extrusion, lacking large scale surface features. The other is basaltic plains type volcanism, which is characterized by numerous coalescing low shields formed by multiple thin flow units. Small vents, lava tubes and channels are common features in this second type of flow. Greeley suggests that these two types of volcanism may represent a sequence of basin filling on the Moon. Early continuous flooding may have caused mare flows to merge producing broad, relatively flat, uniform deposits. Emplacement of discrete flows with preserved flow structure may be a stage that all mare areas did not undergo. Head (1976) also points out the importance of topographic effects on flow morphology; for example, there may be areas where topographic obstacles have caused ponding to occur instead of allowing flows to run downhill to low areas of the basin as in the Imbrium example.

The rarity of flow front scarps on the Moon is only partly due to the modification of surface topography. The preservation of occasional very small scarps is inconsistent with the absence of flow features in similar aged mare units elsewhere. Head (1976) suggests that regolith formation can probably account for obliteration of scarps 5 to 15 m high; however, the observational (Howard *et al.*, 1972) and experimental (Brett, 1975) data suggest that most flow units are only this thick to begin with. Therefore the ~ 10 m average of measured scarps does not mean that these flows were originally closer to the ~ 30 m average for the flows in Mare Imbrium. The lack of good age/height correlation also supports this. Figure 4 shows obliteration by cratering of portions of a lava flow in Mare Imbrium; yet, these scarps remain the highest flow fronts known on the Moon. These observations suggest that eruptive style and lava composition rather than surface destruction are more responsible for the sparseness of mare flow features (Schultz *et al.*, 1976).

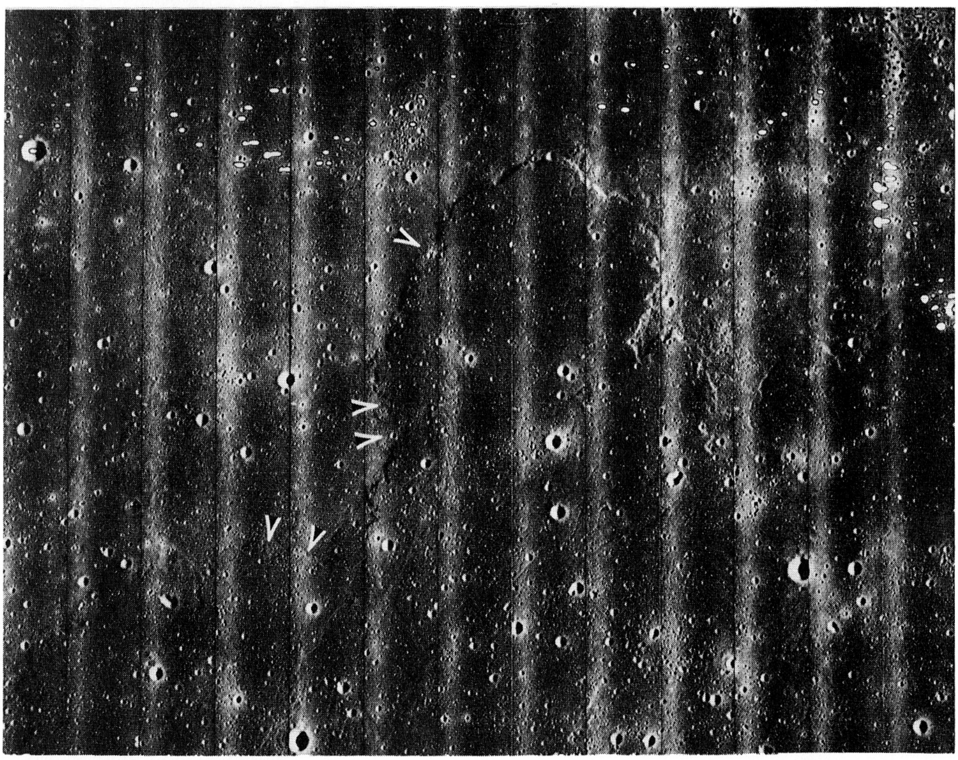

Fig. 4. Eratosthenian flow in Mare Imbrium. Arrows point to places where cratering has degraded or destroyed the scarp (LOV-M-159).

The measurements of scarps reported in this paper agree well with other published data. A summary shows that: (1) flow units from both photo and sample data average 10 to 20 m high; (2) the only flow scarps higher than 50 m found on the Moon are Eratosthenian basaltic units in Mare Imbrium; (3) although the presence of other flow fronts could be shown by near-terminator imagery (with low Sun elevations and high enough resolution to discern fine textural details) of other mare areas, our photogeological studies suggest that the physical factors of lava extrusion and eruptive style are the primary factors accounting for the rarity of mare flow scarps.

Acknowledgements

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