LROC IMAGING OF THIN LAYERING IN LUNAR MARE DEPOSITS.

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Introduction: Typical flow (and flow lobe) thicknesses of lunar mare basalts were not well constrained in the past. Downslope movement of loose material tends to mix and bury stratigraphy originally exposed in the walls of craters and rilles, obscuring the three dimensional nature of the mare deposits over time. New Lunar Reconnaissance Orbiter Camera (LROC) high-resolution Narrow Angle Camera (NAC) images unambiguously reveal thicknesses of mare basalt layers exposed in impact craters, rilles, and steep-walled pits [1].

At least 53 young impact craters [see 2; this conference], and three pits with near-vertical walls up to one hundred meters deep, expose relatively unmodified sections of mare. Oblique views of each pit and nadir to oblique views of many of these craters reveal a series of layers 3 to 14 m thick, indicating that eruptions typically produced a series of ~10 m thick flows (or flow lobes) rather than flows many tens to hundreds of meters in thickness.

Background: Understanding the types and expressions of lunar volcanism is a fundamental topic of lunar research [2]. Establishing the presence and character of layering within mare deposits has significance for investigating basalt flow effusion mechanisms, cooling history, and regolith development between flows. Chief among the questions relating to mare emplacement are 1) how many separate flows occurred at given locations in the mare basins, 2) how voluminous they were, and 3) over what time scale they were emplaced [3-7]. Thickness and volume estimates for basin deposits were originally based on assumptions that basin filling occurred either during massive events with a small number of more-or-less contemporaneous flows, or as fractionated lava lake deposits [8, 9].

Evidence for multiple, relatively thin mare flows was documented by the Apollo 15 reconnaissance of Hadley rille in 1971 with the observation of layers 10 to 20 m thick in the western rille wall [10, 11]. Inspection of a complete cross-section was made difficult, however, by talus covering most of the rille wall visible near the landing site; thus a precise number of individual layers and their thicknesses could not be accurately measured. Other workers [10] speculated that the thinner of these layers 1) were each the result of separate eruption events, 2) were the result of multiple flows from a single eruption, or 3) represent eroded vesicle-rich zones.

Because Hadley rille runs along the western Apennine Mountain front, skirting the margins of Palus Putredinis/Mare Imbrium, it is also possible that the thin units result from a margin thinning effect, and are not representative of actual flow thicknesses in the basin interior [10].

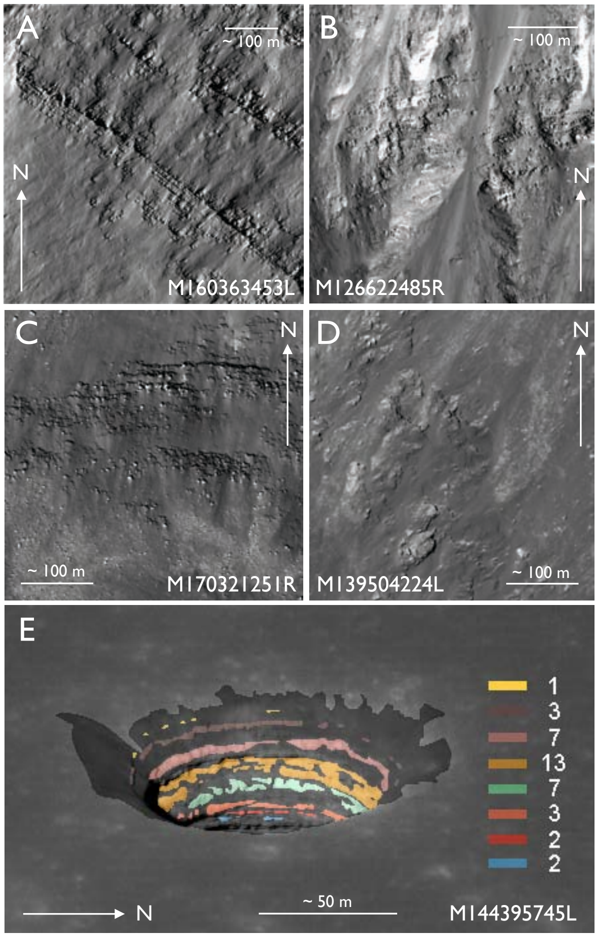

Figure 1. Examples of thin layering in mare deposits. **A:** Galilei crater wall, Oceanus Procellarum; 10.5ºN, 279.3ºW. Down is toward the southwest; incidence angle = 54º, emission angle = 2º. **B:** Messier A crater, Mare Fecunditatis; 2.2ºS, 46.9ºE. Down is toward the south; incidence angle = 25º, emission angle = 1º. **C:** Lucian crater, Mare Tranquillitatis; 14.3ºN, 36.7ºE. Down is toward the north; incidence angle = 21º, emission angle = 1º. **D:** Langrenus crater, central peak summit, Mare Fecunditatis; 8.8ºS, 61.2ºE. Down is to the southwest; incidence angle = 13º, emission angle = 2º. **E:** Mare Tranquillitatis pit; incidence angle = 48º, emission angle = 51º. Detailed layering is visible at the limits of resolution. Outcropping bedrock layer thickness estimates are presented in meters, ± 1 m. Image from [1].

Subsequently, the concept of multiple flow events was proposed for Mare Imbrium [12, 13], Mare Serenitatis [14, 15], Oceanus Procellarum [15], and other mare basins [16]. Other workers [6] suggested that compound flow units are the result of multiple (but temporally related), low-rate effusion events close (within 120 km) to their source vent. They [6] further suggested that compound units were the most common form of basalt emplacement in lunar maria. Evidence for thin flows (<10 m) is provided by flow front shadow measurements for late-stage *surface* units [17, 18], and also inferred from chemical kinetic studies of Apollo samples [19]. Distinctive kinks in crater size-frequency distributions measured for several mare basins were used to estimate the thickness of individual flows to be on the order of 30 to 60 m on average [20].

Compositional studies based on impact excavations into mare stratigraphy (using ejecta and/or crater wall interiors) yield thicker flow estimates (100 to 300 m for the Marius Hills region of Oceanus Procellarum, 80 to 600 m for Mare Serenitatis [15]. This method relies on differences in composition from flow-to-flow to mark flow thickness, and thus is insensitive to flow layering that is compositionally homogeneous. Indeed, these estimates likely represent thicknesses of multiple individual flows (or flow lobes) of the same composition rather than single massive flows. Thick (> 50 m) surface flows are rare but not unexpected on the Moon (e.g., those detected within the Mare Imbrium flow field [e.g., 18, 21]). Such flows are easily explained as 'last gasp' effusions from a nearly expended magma source.

Observations: Thin layering (3 to 14 m thick) revealed in NAC images of steep-walled pits located in the Marius Hills region of Oceanus Procellarium, Mare Tranquillitatis (Figure 1), and Mare Ingenii, provide evidence in cross-section for flow thicknesses in mare deposits at well-separated locations across the Moon. Each pit location is also well removed from its respective mare margin, making the deposits representative of true mare flow thicknesses, and not the product of any marginal thinning effects. Thin layering in each of the three pits could mean either that 1) there is a genetic relationship between pit occurrence and layering, or that 2) thin flows were widespread on the Moon. The occurrence of thin surface flow units seen elsewhere on the Moon [18], and the significant number of thin layers visible in the pit walls, are consistent with the second hypothesis. In addition, NAC imagery has revealed thin layers in the walls (and a central peak) of at least 53 impact craters in the mare [2]; (Figure 1).

While it is possible that processes that formed the pits somehow resulted in anomalously thin layering at each pit, we note that at Hadley rille and in many of these mare crater walls, horizontal layering is exposed for hundreds of meters horizontally and vertically (Figure 2). Thus it is probable that the layers exposed in the pits and crater walls are representative of the average thickness of flows (or flow lobes) across broad areas of all mare.

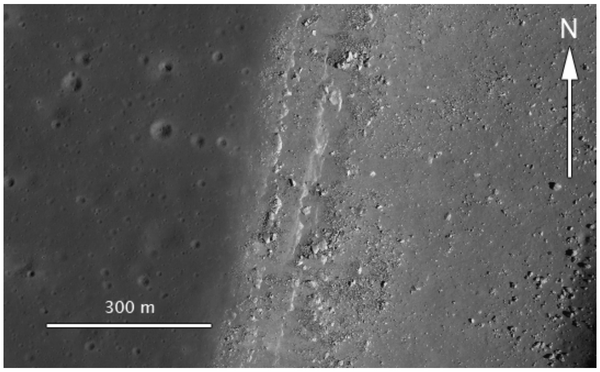

Figure 2. Layered bedrock outcrops are clearly visible in the western Hadley rille wall approximately 50 km southwest of the Apollo 15 landing site. The outcrops can be traced for approximately 2.5 km. LROC NAC image M113941548L; incidence angle = 59º, emission angle = 2º.

Future NAC imagery will facilitate tighter vertical control of these and other layered targets through stereogrammetry (digital terrain modeling) techniques. Used together with LRO Laser Altimeter (LOLA) measurements, the observations should further constrain the character and extent of mare layering.

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