THE SERENITATIS WE NEVER KNEW: 70-CM RADAR REVEALS RUGGED MARE DEPOSITS.

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Introduction: Recent Earth-based radar data reveal the surviving signature of rugged morphology, beneath the regolith, for extensive mare-forming basalt deposits [1]. While such roughness was expected, based on terrestrial analogues, for steep-sided domes and other localized constructs such as those in the Marius Hills [2], the formation of blocky, platy, or ridged terrain was not predicted for the low-viscosity, typically thin flow units mapped from orbit and sampled by Apollo and Luna [3, 4]. We present new 70-cm data for Mare Serenitatis that greatly improves our capability to map variations in morphology beneath the regolith, and discuss the implications of these results for possible flow emplacement conditions.

Mare Flow Morphology and Thickness: Analysis of returned samples suggests that mare-forming lavas had very low viscosity (1-10 Pa s), and flow lobes mapped from orbital photos have a typical thickness of 10-25 m. These observations, combined with the obvious low relief of the regolith-mantled mare surface, are consistent with lava flows that traveled, probably in the laminar regime, beneath an intact cooled crust that was minimally disrupted during the emplacement process. Such an emplacement regime allows thin flow units to travel long distances by limiting heat loss from the mobile interior.

Given the age of the mare-forming flows from prior to Orientale (3.85 b.y.) to about 2 b.y., a significant depth of regolith will exist on any deposit. The formation of the regolith by impact erosion must alter the roughness of a terrain, and one model is to assume the creation of an essentially similar transition zone regardless of the morphology of the initial surface. Radar studies of rugged sub-regolith features suggest that the process is more complex [1, 2], though how an original blocky or platy surface layer persists as an excess of rocks near the base of the comminuted debris is unclear.

Data for Mare Serenitatis: The Arecibo 70-cm radar system can transmit pulses as narrow as 1 μs, allowing for an effective horizontal spatial resolution along the "range" direction of about 200 m per pixel. A comparable resolution in azimuth is realized by a coherent integration period of about 33 minutes. The radar echoes from the Moon are received in both senses of circular polarization at the Green Bank Telescope. We obtained two full Arecibo-GBT observing runs (about 4 hours total integration) on a region centered on Mare Serenitatis in September 2009. These new data provide seven looks to reduce speckle, relative to the single-look 2006 data used in [1], and improve upon the signal-to-noise performance by 2-3 dB in the use of a narrower low-pass filter bandwidth.

We co-registered the 70-cm radar data with Lunar Orbiter mosaicked images, FeO and TiO_2 abundance maps based on Clementine UV-VIS data, and Kaguya laser-altimeter data. The topography data were particularly useful in identifying subtle wrinkle ridges across the basin.

New Views of the Flows: The improved 70-cm dataset provides a more detailed view of the sub-regolith rough terrain in central Mare Serenitatis. The northern extension of this material is particularly striking in its narrow finger-like or lobate distal margins (Fig. 1).

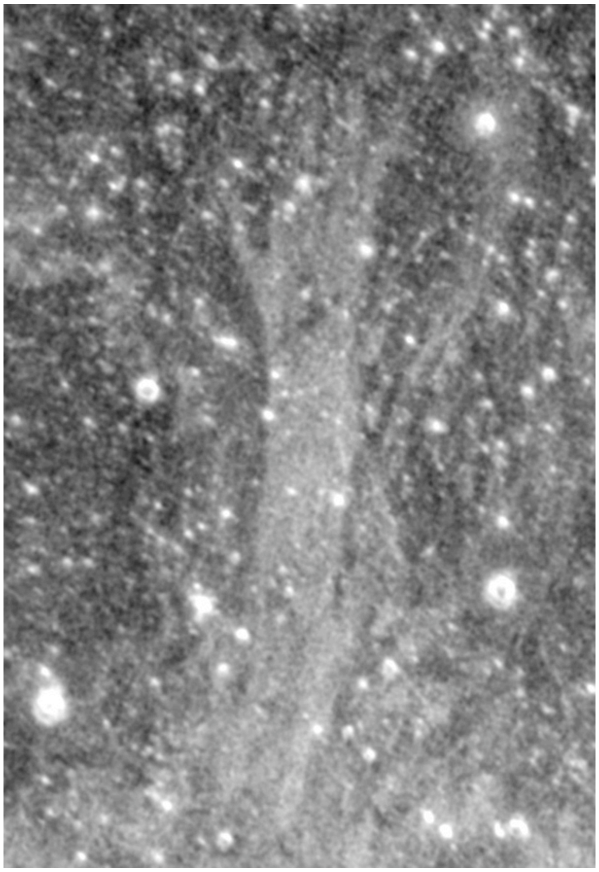

Fig. 1. 70-cm same-sense circular (SC) radar view of the northern reaches of rugged sub-regolith deposits in central Serenitatis. Image width about 120 km.

Also visible with the improved data are apparent outliers of high-backscatter terrain surrounded by lower-return deposits. The stratigraphy of the flows is evidently complex, and blurred in part by lateral mixing in the formation of the regolith, but the radar view suggests emplacement of alternating rough and smooth units during the course of the eruptions.

Age of the Rugged Deposits: It was proposed in [1] that the area of high radar backscatter and circular polarization ratio (CPR) that extends up to about 250 km from the central part of Serenitatis formed over a relatively short span of time. To check this conclusion, we selected two adjacent large regions in the eastern "lobe" of the deposit, and determined their cumulative crater density functions. Based on the intercepts for 1-km crater diameter, the estimated absolute ages of these sample boxes are 3.43 b.y. and 3.45 b.y., where the difference is within the margin of error. We conclude that this region of high backscatter is of essentially uniform age, and consistent with dating of areas of similar TiO_2 content (but lower backscatter) to the north at 3.44 b.y. [5]. This supports the notion that the rough deposits represent morphologic variations within a flow field of generally uniform composition. Age dates for higher-TiO_2 units along the east, west and south margins of the central-Serenitatis flow field are 2.94-3.28 b.y. [5], suggesting that the central complex is an older feature embayed at its edges by younger flows.

Possible Flow Emplacement Scenarios: The low viscosity of lunar basaltic magma allows for the possibility of turbulent flow (Reynolds numbers >2000) for relatively thin layers moving at modest velocity [6]. In contrast, terrestrial flows must be thicker and/or moving much faster to sustain turbulence, and laminar flow is probably much more common [7]. Turbulent flow has been proposed as a mechanism for more efficient thermal erosion of the substrate to form lunar sinuous rilles, but only for the case of a stable, cooled crust much thinner than the flow depth [8]. If the flow core drags and fragments the crust, which is the most likely mechanism to form rugged surface morphology, then core heat loss occurs too quickly [9] to allow a thin flow to travel 100-200 km.

The formation of a several-meter layer of platy or blocky debris atop a mare deposit, with no apparent variation with distance away from any putative vent region, therefore suggests a flow thickness at the upper end of those mapped from orbital photos (50 m or more) [10]. All else being equal, a thicker flow will result from increased viscosity or volume eruption rate [11]. Lunar basalt viscosity, however, shows relatively modest variability due to alkalinity or other factors across the sample collection, and the rapid rise rates for mare-forming flows [12] argue against large, arbitrarily cooler batches. The simplest explanation may be that the rugged flows reflect occasional very high-rate eruptions amid more common sheet-like, lower-rate deposits.

There is one instance in southwestern Serenitatis of an apparently discrete flow lobe with high radar backscatter and width from about 10 to 26 km, comparable to the young "Phase II" and "Phase III" Mare Imbrium flows but smaller than their maximum width [13]. Flow thicknesses average 30-35 m for the Imbrium flows. The degree to which flow width may reflect thickness depends, at minimum, upon the relative importance of regional slope and effusion rate differences among various lobes [14], so we do not yet have a strong constraint on the Serenitatis deposit. Thick lobes in Mare Serenitatis might be distinguished in low-Sun photos, depending on the degree to which they are embayed at their margins by younger deposits.

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