LINNE: SIMPLE LUNAR MARE CRATER GEOMETRY FROM LRO OBSERVATIONS:

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Introduction: Simple, non-degraded lunar impact craters offer unprecedented insights into the physics of the hypervelocity impact cratering process, as well as on the shallow structure of the lunar lithosphere [1,2]. As such, their preserved geometric properties provide essential boundary conditions for investigating the cratering process in crystalline target rocks (mare basalts) as a function of gravitational acceleration and mechanical properties. The Lunar Reconnaissance Orbiter (LRO) permits first-of-a-kind analysis of the detailed geometric and related geologic properties of such landforms at scales previously available only for Earth. In an effort to assess whether there exists a canonical lunar mare "simple" crater and related "main sequence" of simple crater morphologies, we have developed and analyzed an ensemble of high spatial and vertical resolution topographic datasets from LRO, including best-available LOLA laser altimeter transects and a 2m horizontal scale digital elevation model (DEM) derived from LROC NAC stereo images, controlled by LOLA ground control points [3]. Experience with ultra-high resolution DEM data for terrestrial features, including *Barringer* (Meteor) Crater and features within the Nevada Test Site (nuclear explosion craters) enables a basis of comparison [4]. The feature selected for detailed analysis is the ***Linne*** simple crater located in NW Mare Serenetatis, which has long been suspected to represent an archetypical fresh mare crater [1]. Excellent coverage of *Linne* from LROC NAC images, LOLA topographic transects, as well as by the MiniRF hybrid polarity SAR and Kaguya Terrain Mapping Camera allows for comprehensive analysis. Here we test the hypothesis that *Linne* represents a canonical fresh lunar mare crater suitable as a benchmark for investigating similar features across the Moon as the basis for evaluating crater degradation sequences and target property variations.

LRO Datasets: During the primary LRO mission, excellent coverage of *Linne* was acquired (Fig. 1). *Linne* was targeted for LROC NAC stereo coverage with supporting NAC imaging observations at differing solar illumination conditions between March 2010 and October 2010. Near center-line topographic transects of the feature were acquired by LOLA between June 2010 and Sept. 2010, permitting generation of a 60m scale DEM. These data form the basis of the analysis presented herein.

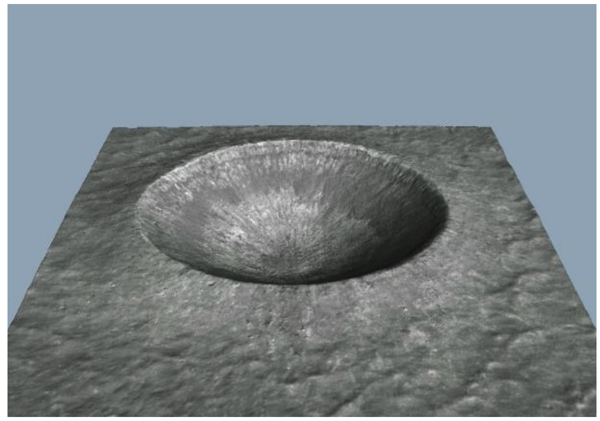

Figure 1: LROC-based DEM of *Linne*, combined with LROC NAC images [m046 and m161] at 2m resolution.

Linne is a 2.22 km diameter simple impact crater often described as "bowl-shaped" [1,2] with a well-preserved continuous ejecta blanket (CEB) that displays classical morphologic features, including a herringbone pattern of swales and an observable distribution of large ejecta blocks. Prior to LRO measurements, *Linne* was often cited as the typical lunar fresh crater with a depth-to-diameter (d/D) ratio of ~ 0.25. Analysis by Pike [2] and Wilhelms [1] supported the use of *Linne* as a representative example of a pristine mare crater. *Linne* is located in NW Mare Serenitatis within target materials that have been interpreted by Wilhelms [1] and others as Fe-Ti-rich basalts that filled the impact basin subsequent to its formation and modification. Other investigators have treated it as a model of a minimally-degraded mare impact crater, likely as young as features such as Cone crater [1].

Geometric Analysis: Preliminary analysis of Linne was undertaken on the basis of a 60m (x,y) DEM constructed via circular-gridding of 3 LOLA transects, using codes developed (and validated) on MGS MOLA data [4], as well as terrestrial laser altimetry of Meteor Crater. The results of these preliminary analyses suggested that *Linne* is far from being "bowl-shaped", but rather is a flattened, inverted cone, with a continuous ejecta blanket thickness that decays more rapidly than the typical values estimated by Moore and summarized in [1,2]. With the availability of the LROC NAC-derived 2m (x,y) DEM (Fig.1), more detailed analysis of the geometric properties of *Linne* in comparison with other features has been possible. Figure 2 illustrates a first-order comparison with the *Barringer* Meteor Crater. While *Barringer* is a modified simple crater in a sedimentary target, it illustrates how cavity infill modifies the pre-erosional topology of such features under terrestrial gravity and with the role of water. The *Linne* crater cavity is best fit by a truncated cone with a power law exponent *n* of 1.4-1.5, where 1.0 represents a perfect inverted cone. Its ejecta thickness function (ETF) decays with a power-law exponent of -3.84 (+/- 0.04), which differs from classical ETF behavior where a power-law of -2.75 is typical. The mean inner cavity wall slope at *Linne* is ~ 33 degrees (on a baseline of 4m), which is as large as that at fresh terrestrial and martian craters. The normalized cavity volume to surface area divived by total crater depth (V/SA/d) for *Linne* (0.368 +/- 0.010) is lower than most other craters on the Moon, Mars, and Earth for which measurements are available, but very similar to the *Danny Boy* nuclear explosion crater (in basalt) in Nevada (V/SA/d for Danny Boy is 0.372). This comparison suggests that the *Linne* cavity is largely unmodified, and LROC NAC imaging of the crater floor indicates only limited infill by slumped blocks from late modification stage adjustments (Fig. 1).

Comparative Analysis: In order to more fully understand what the topology of the *Linne* crater indicates, we have developed a set of quantitative comparisons with other craterforms on Mars and Earth. Using a 2m (x,y) scale DEM developed by the MRO/HiRISE PI A. McEwen for a lunar-like 2.48 km crater on Mars (Amazonis Planitia) first identified in MGS MOC images by M. Malin, we observe that minimally-modified simple craters on the Moon and Mars display similar geometric properties, in spite of differences in gravity. The Mars Amazonis crater (16.4N, 209.65E) has the following characteristics when compared with *Linne*:

- Cavity shape n = 1.4; ETF exponent of -2.75 (*Linne* is steeper); V/SA/d of 0.344 +/- 0.010 (*Linne* is similar); d/D of 0.26 (*Linne* is 0.245).

Using cylindrical harmonic analysis methods we developed for analysis of martian impact craters [4], we compared *Linne* to the Mars analogue and found general similarity to degree and order 10. Thus, we believe we have discovered a simple set of geometric properties that can be used on the Moon and Mars to recognize and quantify pristine simple craters in mare-like target rocks, as the basis of a "main sequence".

Summary: On the basis of detailed analysis of the LRO topographic data for the simple mare crater *Linne*, it is evident that the feature represents a canonical landform with characteristics that can be used as a point of reference for comparisions with other pristine impact landforms on the Moon, Mars, and Earth. Our analysis demonstrates that the *Linne* cavity is best approximated by a truncated cone and is not "bowl-shaped" as previously described. Further, the continuous ejecta blanket for *Linne* displays a radial thickness decay with an exponent of -3.84, which is steeper than that typical of many classical terrestrial impact craters [4]. We suggest this is because of the mare basalt target rock properties in which *Linne* formed. Our normalized impact crater shape parameter (V/SA/d) illustrates how *Linne* differs from less pristine craters. Thus, we suggest that *Linne* is a suitable archetype for a pristine mare simple crater that can be used effectively to investigate crater degradation pathways and target property variations across the Moon, and via similar data (from MRO/HiRISE with MOLA) for Mars.

References: [1] Wilhelms D. (1987) *USGS Prof. Paper 1348*. [2] Pike R. (1980) *USGS Prof. Paper 1046-C*. [3] Robinson M. et al. (2010) *Space Sci. Rev. 150*, p. 84-121. [4] Garvin J. et al. (2000) *Icarus 144*, pp. 329-352 (see also *Icarus 145*, p. 648-652) .

Figure 2 : ***Linne*** **(from 2m LROC DEM) at Left versus 2m lidar (ATM) results for** ***Barringer*** **Crater (Right).**