Stratified Ejecta Boulders as Indicators of Layered Plutons on the Lunar Nearside

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Introduction

Layers are like pages in a book with each layer telling the story of how material was deposited on the surface. Interpreting these layers are important in that they provide clues to the geologic history of a planet's surface. Stratified ejecta boulders found in Aristarchus and Mare Undarum (Fig. 1) demonstrate alternating layers of dark and light albedo material. Multiple hypotheses have been proposed to explain the origin of these alternating layers[7,11] (Fig. 8). The purpose of this research was to test these hypotheses to determine which is most probable. Understanding the origin of these layered boulders can provide a more accurate description of the heterogeneity of the lunar crust and insight into the evolution of the lunar magma ocean.

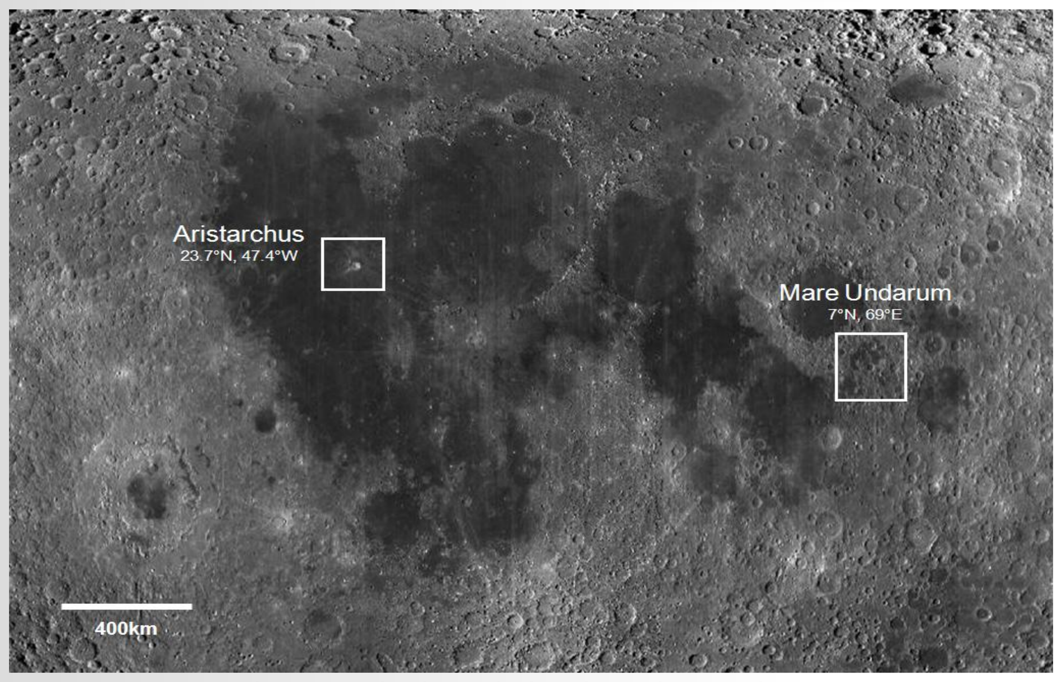


Figure 1: Regional Map of Aristarchus and Mare Undarum

Methods

In high resolution Lunar Reconnaissance Orbiter (LRO) Narrow Angle Camera (NAC) images, we found twenty four examples of stratified ejecta boulders located in Artistarchus and northwest Mare Undarum. For each stratified boulder we measured the thickness of each layer and looked for patterns in the ratio of adjacent layers. We then measured the albedo of these dark and light materials and compared them to the albedo values of the anorthositic highlands as well as the basaltic mare. Additionally, we analyzed these boulders to describe morphological characteristics occurring within the alternating dark and light material.

Data

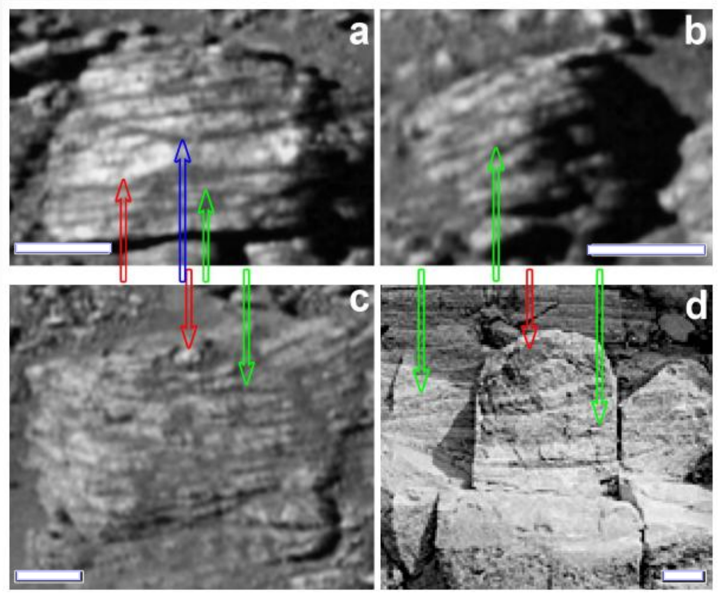


Fig. 2: Examples of boulders and bedding features. Arrows indicate locations of bedding morphologies: red arrows show cumulate enclaves, blue arrow shows trough-shaped layering, and green arrows show tapered layering and cross-bedding. Figures a, b, and c are from NAC image M120161915L; scale bars = 10 m. Figure d is an analog example from the Coastal Batholith, Ilo, southern Peru; Scale bar = 10 cm (from [2]).

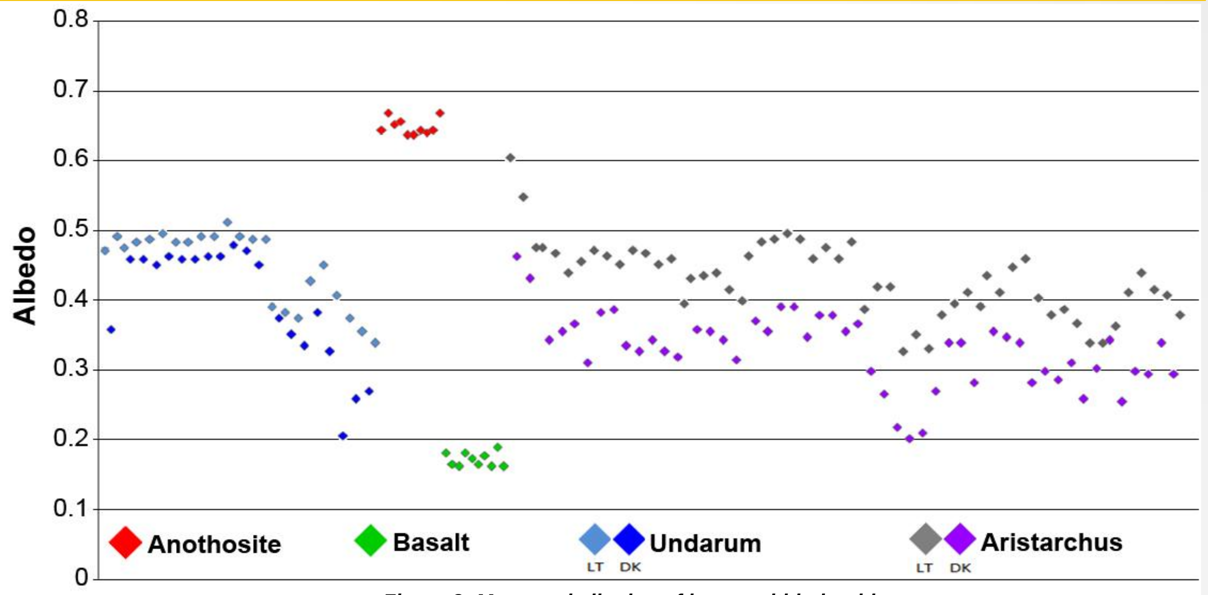
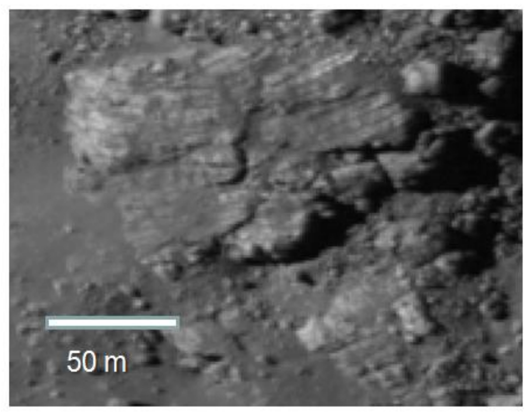
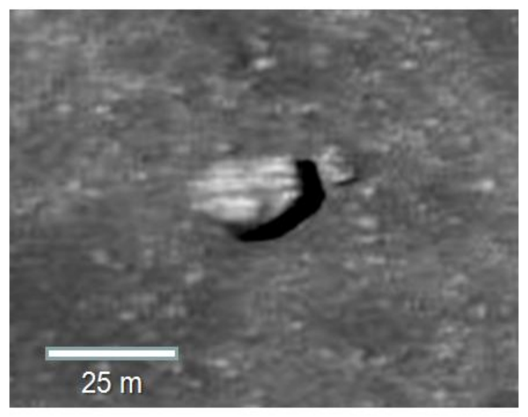


Figure 3: Measured albedos of layers within boulders.



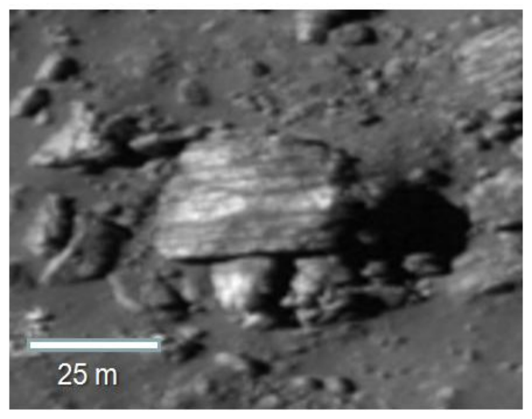
	Layer Thickness (m)	Albedo Value	Ratio DK:DK+LT
LT	1.14	0.40	
DK	1.14	0.30	0.35
LT	2.10	0.38	
DK	1.14	0.28	0.50
LT	1.14	0.38	
DK	1.02	0.31	

Figure 4: Measured layer thickness and albedo values of stratified boulder from Aristarchus Crater (M120161915LE)



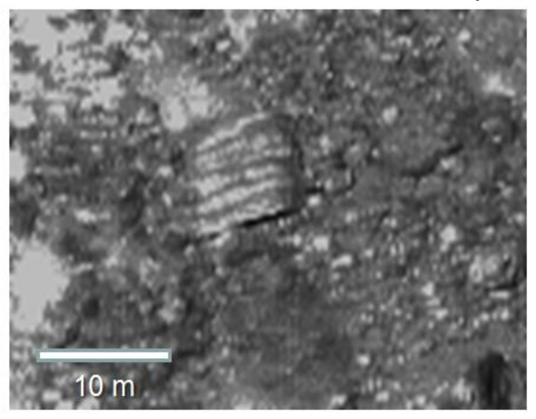
	Layer Thickness (m)	Albedo Value	Ratio DK:DK+LT
LT	2.05	0.47	
DK	1.14	0.46	0.35
LT	2.05	0.48	
DK	1.53	0.45	0.57
LT	1.14	0.48	
DK	1.53	0.45	

Figure 6: Measured layer thickness and albedo values of stratified boulder from Mare Undarum (M154799629RE)



	Layer Thickness (m)	Albedo Value	Ratio DK:DK+LT
LT	3.1	0.43	
DK	1.5	0.35	0.41
LT	2.1	0.41	
DK	1.0	0.34	0.32
LT	2.1	0.44	
DK	1.5	0.34	

Figure 5: Measured layer thickness and albedo values of stratified boulder from Aristarchus Crater (M120161915LE)

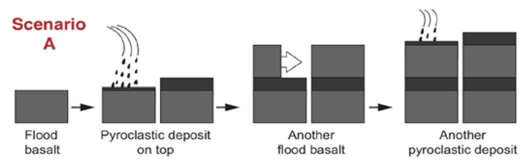


	Layer Thickness (m)	Albedo Value	Ratio DK:DK+LT
LT	1.02	0.49	
DK	1.62	0.46	0.50
LT	1.62	0.48	
DK	0.51	0.45	0.33
LT	1.02	0.48	
DK	1.02	0.45	

Figure 7:Measured layer thickness and albedo values of stratified boulder from Mare Undarum (M154799629RE)

Results

Pyroclastic Deposits (Weitz, Zanetti)

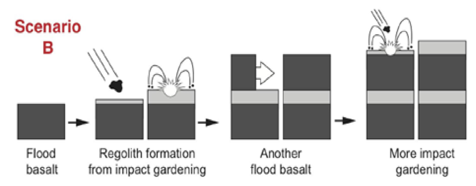


Postulate: The dark layers are pyroclastic deposits atop lighter mare basalt layers.

Prediction: The thicknesses of the pyroclastic dark layers should be between 10 and 30 meters (Weitz).

Observations: Thickness of dark layers varies significantly below 10-30 meters. Mare Undarum is not in close proximity to a region of pyroclastic deposits.

Impact Gardening (Zanetti, Campbell, Crawford)

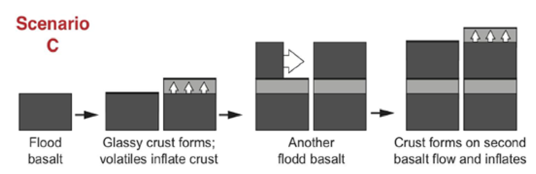


Postulate: Lava flows every 200 million years cut normal rate of regolith formation from 1 meter/billion years to 20 cm/200million years (Crawford).

Prediction: Dark layers should exhibit thicknesses that can not exceed 20 cm.

Observations: Dark layers demonstrate thicknesses ranging from 1 meter to 5.5 meters, too great to be regolith build-up.

Glassy, Vesiculated Crust (Zanetti, Self)



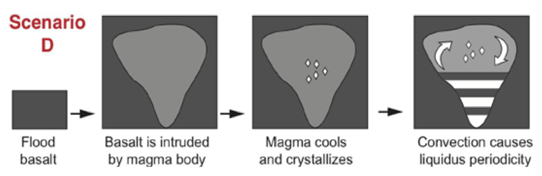
Postulate: As lava cools, a thin, glassy crust forms on top of lava. Glassy crust acts as insulator to the remaining melt, resulting in distinguished layering (Zanetti).

Prediction: Glassy crust should be 10% of entire flow and should be centimeters in thickness. Albedo values should not vary throughout the layer itself due to the consistent composition (Self).

Observations: Stratified boulders in both Aristarchus and Mare Undarum demonstrate thicknesses of dark strata that range between 1 meter and 5.5 meters and not centimeters in range.

Images modified from http://planetary.org/blog/article/00002980[7]

Layered Pluton (Pieters)



Postulate: Alternating layers are compositions of cumulates crystallizing in a magmatic intrusion. The alternating cumulate composition reflects periodic changes in the composition of liquidus due to convection or magma recharge in the cooling intrusive body.

Prediction: Layers are mineral cumulates, likely alternating felsic (plagioclase-rich) light layers and mafic (pyroxene-rich) dark layers.

Observations: Measurements of light/ dark strata demonstrate albedo values that lie between anorthositic highlands and basaltic mare values (>60 but < 150). Morphological characteristics such as troughing, cross-bedding, cumulate enclaves and tapered layering within the layers indicate convection or magma recharge.

Figure 8: Summaries of the four hypotheses for the origins of the stratified boulders.

The measured thicknesses of alternating light and dark material (Figs. 4-7) showed no consistent patterns compared between boulders from a single nor from geographically distinct regions. In addition, the ratio between adjacent light and dark layer thicknesses demonstrated no observable relationship even within a single boulder. This last point reflects the fact that several of the boulders demonstrate cross-bedding, trough-shaped layering, tapered layering and cumulate enclaves.

Albedo variations between the layers did demonstrate a more consistent relationship between different layers within a single boulder and, at least for Undarum, between different boulders. Measurements of light and dark strata in both regions have albedo values between that of anorthositic highlands and mare basalts measured from the same respective NAC image (Fig. 3)

Several stratified boulders demonstrate cross-bedding, troughing, tapered layering, and cumulate enclaves (Fig. 3 a,b,c), indicating gravitational settling within a convecting volcanic intrusion (layered pluton).

Kickapoo High School Lunar Research Team

"We choose to go to the 'Poo not because it is easy..... but because it is hard"

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Conclusions

Our results, in many cases, are at odds with the multiple hypotheses[2,7,11] proposed for the origin of these stratified boulders. Measurements of light and dark layers have albedos that lie between anorthositic highlands and mare basalts, respectively.

The relative thicknesses of dark and light layers show no relationship consistent with recurrent episodes of mare volcanism separated by episodes of pyroclastic deposits, regolith gardening, or formation of a vesiculated crust. We observed bedding morphology (crossbeds, trough-shaped layers, tapered layers, and enclaves)

Based upon our analysis, we propose that these layers result from periodic change in the composition of the liquidus by convection or density currents within a cooling igneous intrusion.

Our results from this research are consistent with the previous work of Pieters[8] and Hawke[5] and their studies on the distribution and modes of anorthosite and lunar plutons. Fragments of these plutons were excavated by large impacts that penetrated overlying mare basalts and, in some cases, anorthositic crust.

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