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

Tori Wilson, Abby Delawder, and Austen Beason
Kickapoo High School, Springfield, Missouri
April 25th, 2012

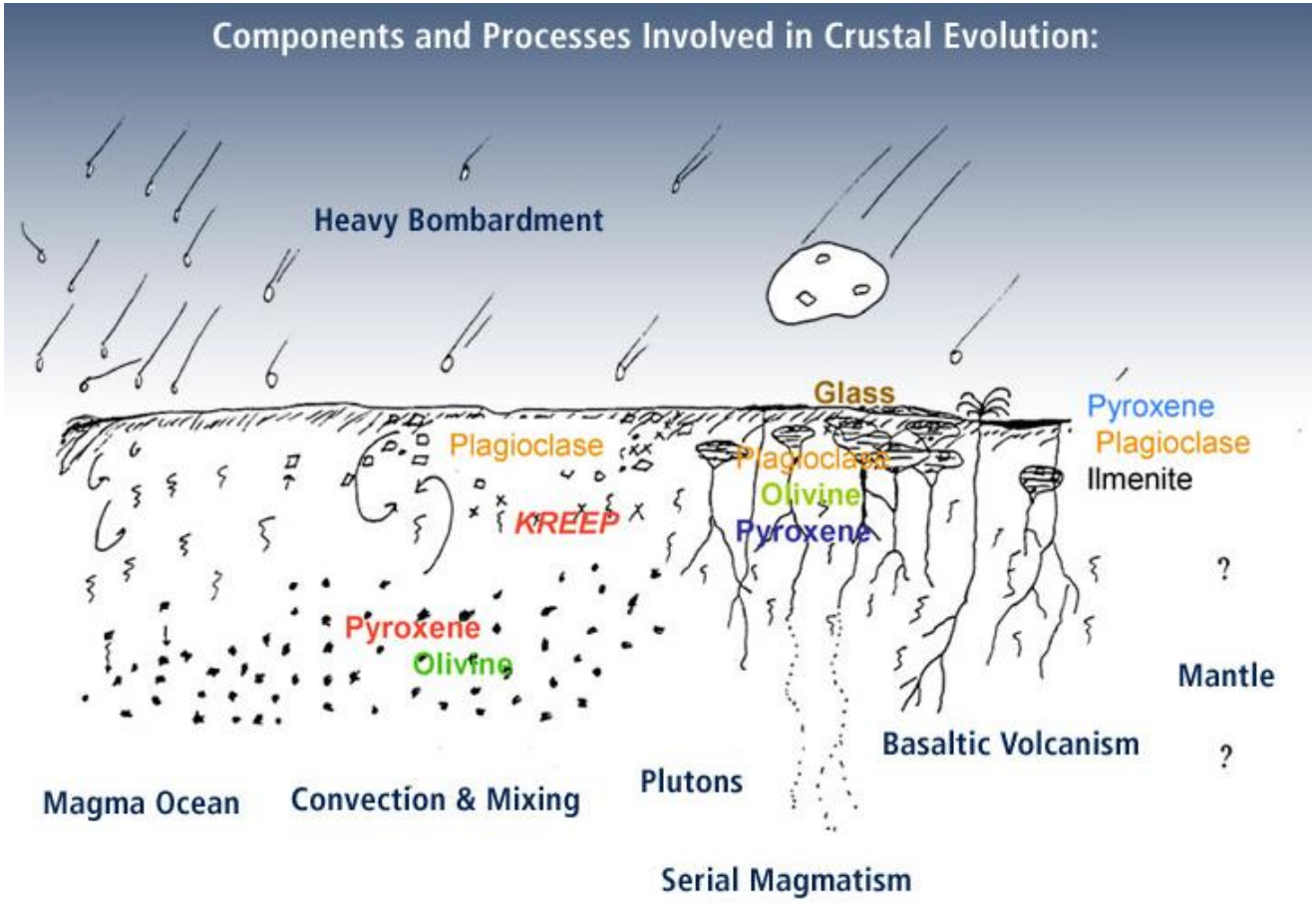
"We choose to go to the 'Poo not because it is easy…. but because it is hard"

Purpose of Research

To test multiple hypotheses in an attempt to explain the origins of the alternating light and dark layers in stratified ejecta boulders on the lunar nearside

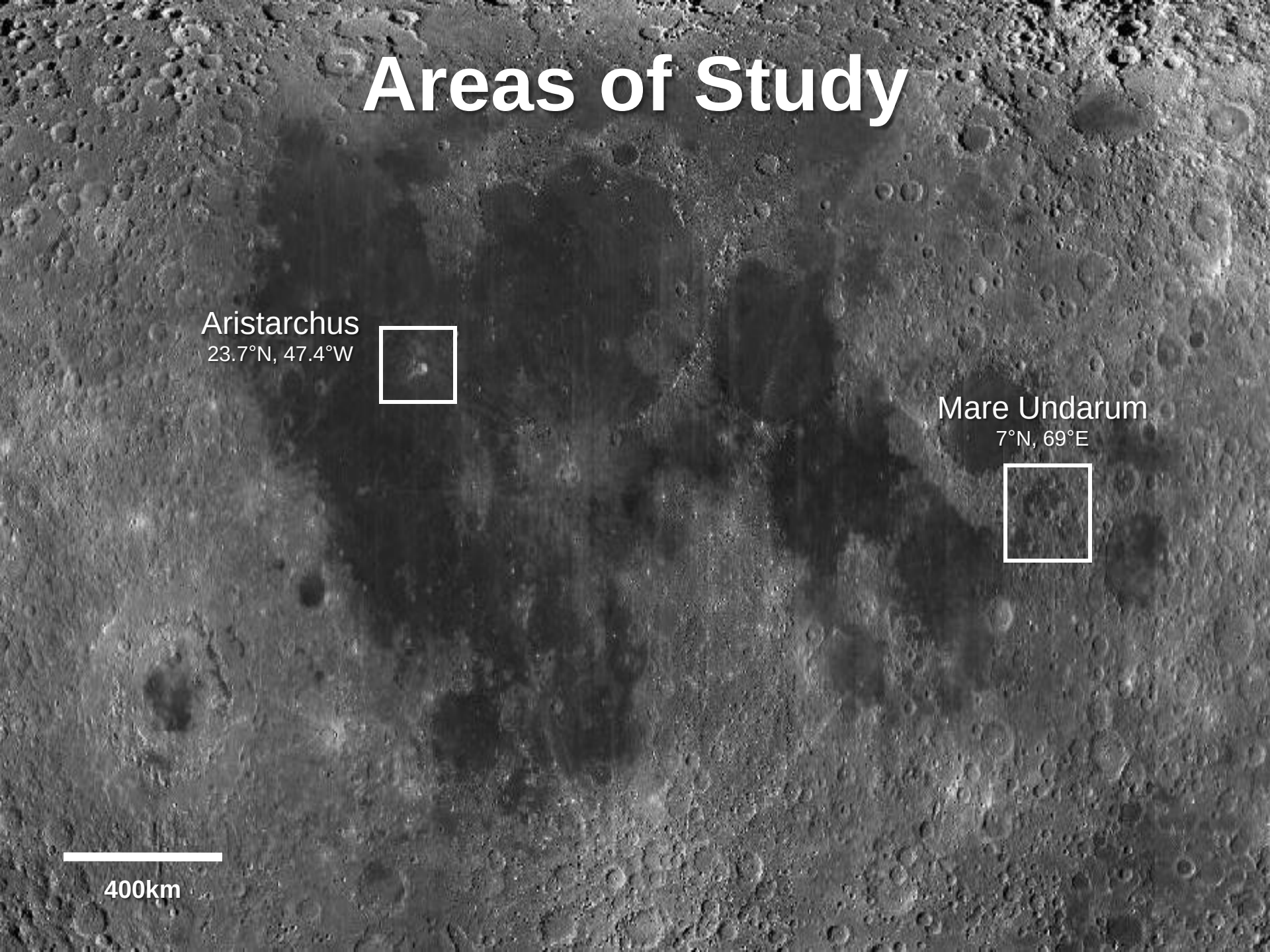
Significance of Study

To provide a better understanding of the heterogeneity of the lunar crust and insight in the evolution of the lunar magma ocean by explaining the origins of stratified boulders



The above image has been obtained and modified from the following website: M3 - **Moon** Mineralogy Mapper - Science - **Lunar Crust** m3.jpl.nasa.gov

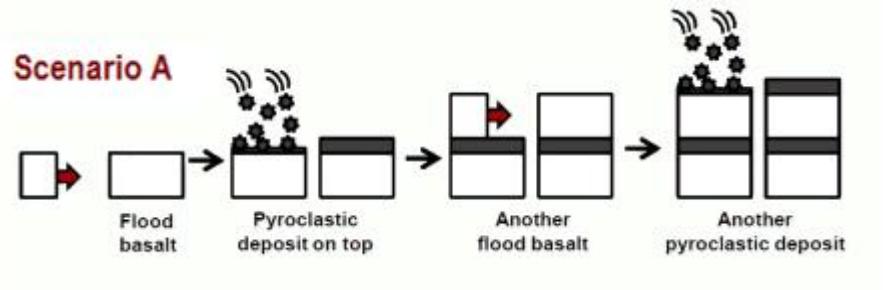
Areas of Study



Background: Multiple Hypotheses of Formation

A. Pyroclastic Deposits

(Weitz, Zanetti)

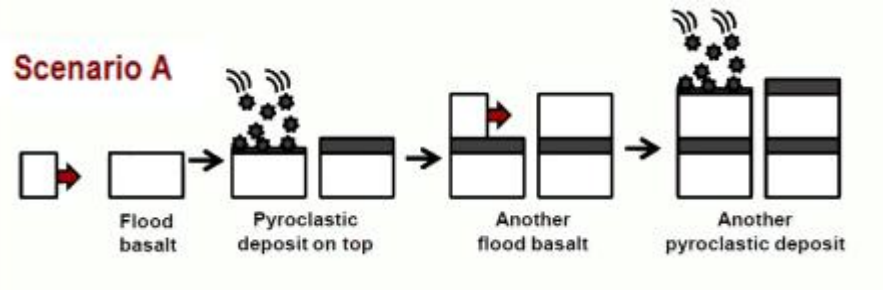


Figures modified from:
http://planetary.org/blog/article/00002980/

Background: Multiple Hypotheses of Formation

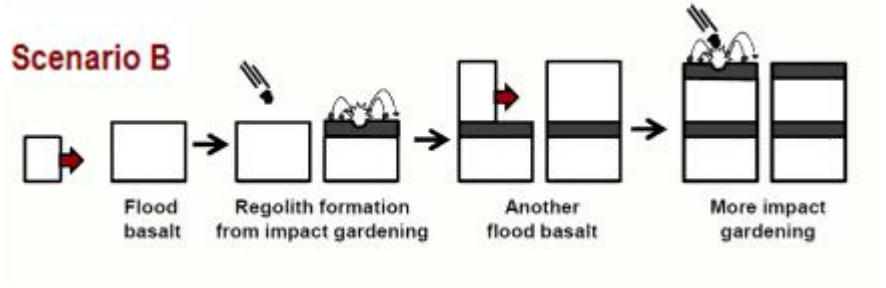
A. Pyroclastic Deposits

(Weitz, Zanetti)



B. Impact Gardening

(Zanetti, Campbell, Crawford)

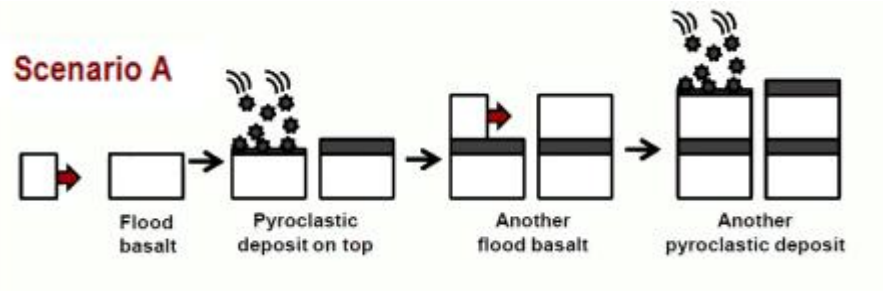


Figures modified from:
http://planetary.org/blog/article/00002980/

Background: Multiple Hypotheses of Formation

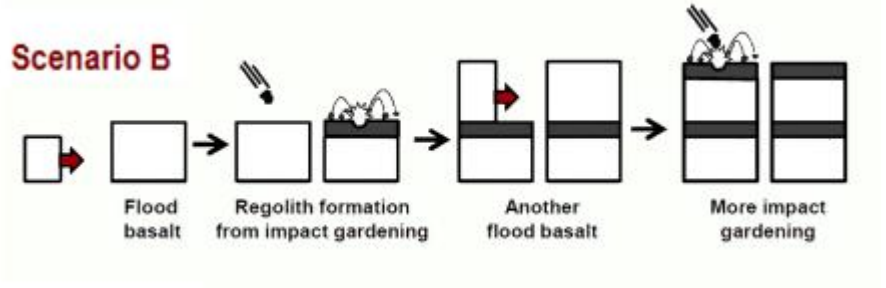
A. Pyroclastic Deposits

(Weitz, Zanetti)



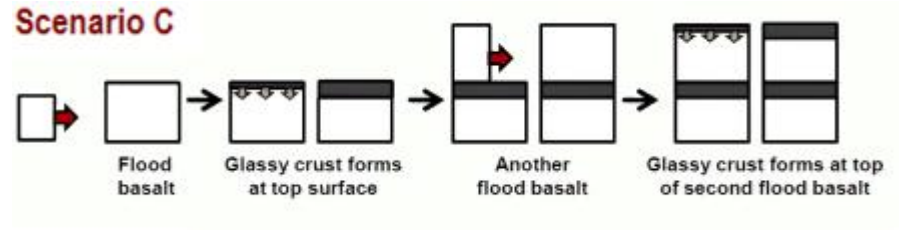
B. Impact Gardening

(Zanetti, Campbell, Crawford)



C. Glassy, Vesiculated Crust

(Zanetti, Self)

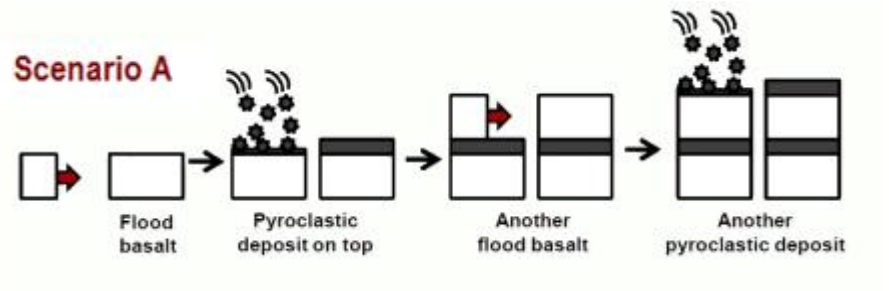


Figures modified from:
http://planetary.org/blog/article/00002980/

Background: Multiple Hypotheses of Formation

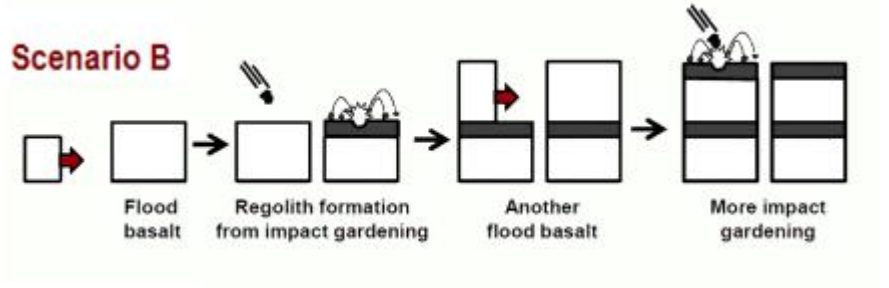
A. Pyroclastic Deposits

(Weitz, Zanetti)



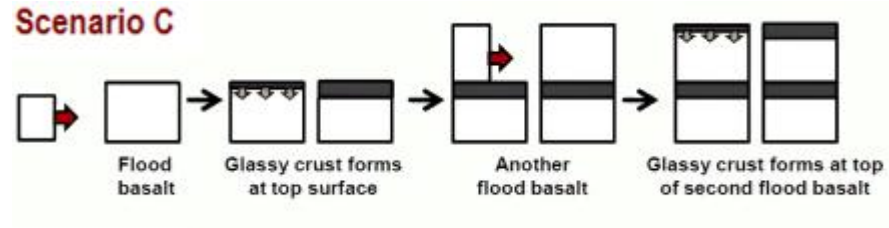
B. Impact Gardening

(Zanetti, Campbell, Crawford)

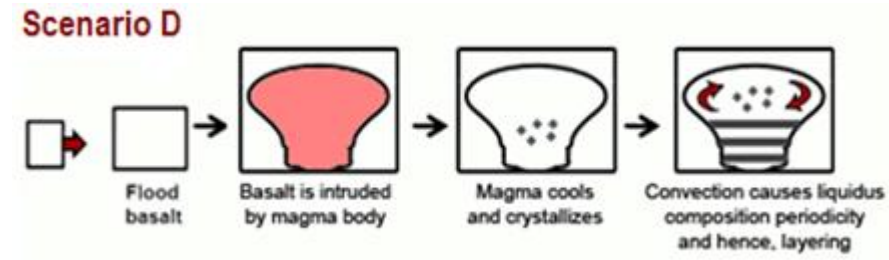


C. Glassy, Vesiculated Crust

(Zanetti, Self)



D. Layered Pluton (Pieters)



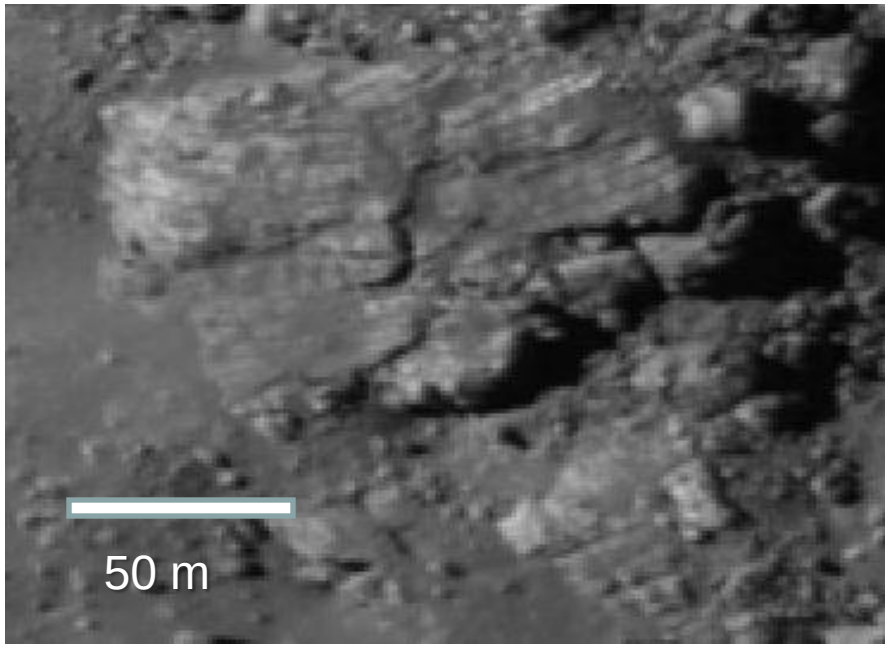
Figures modified from:
http://planetary.org/blog/article/00002980/

Methodology

- Analyzed high resolution EDR images containing 24 stratified ejecta boulders obtained by the Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC) using Adobe Photoshop
- Only observed EDR images with incidence angles between 20° and 60°
- Measured boulder size and each individual light and dark layer (in meters)
- Determined Albedo value
- Analyzed the following qualitative and quantitative characteristics of each stratified boulder:
  - Overall size (meters) of boulder measured at its widest part discordant to layer orientation
  - Orientation (linearity) of each alternating strata in relation to boulder orientation (qualitative)
  - Thickness (meters) of each alternating light and dark layer within a specified boulder
  - Ratio of dark layer width to total layer width (Light +Dark) Ld / Ld + LL

Quantitative Data

Aristarchus
M120161915LE

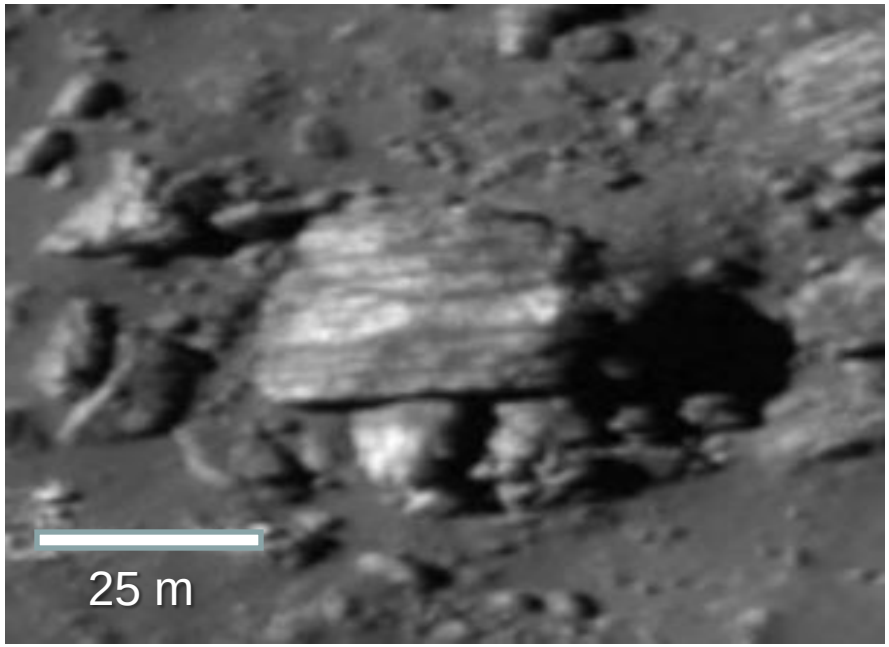


	Layer Thickness (m)	Albedo Value	Ratio DK:DK+LT
LT	1.14	0.40	
DK	1.14	0.30	0.35
LT	2.10	0.38	
DK	1.14	0.28	0.50
LT	1.14	0.38	
DK	1.02	0.31	

-Cross Bedding,
Tapered Layers,
Troughing

Quantitative Data

Aristarchus
M120161915LE

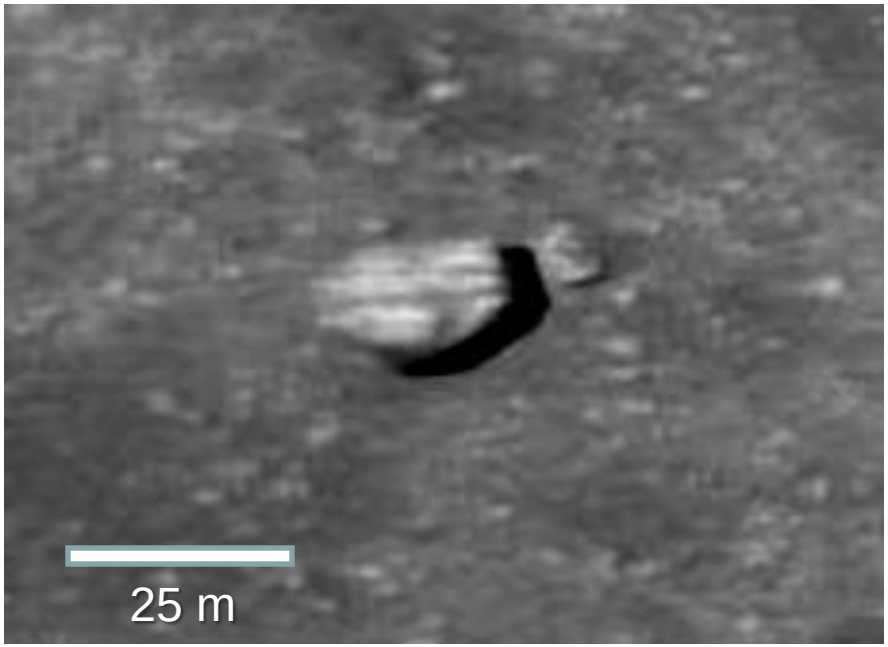


-Cross Bedding, Troughing, Tapered Layers, Enclaves

	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	

Quantitative Data

Mare Undarum
M154799629RE

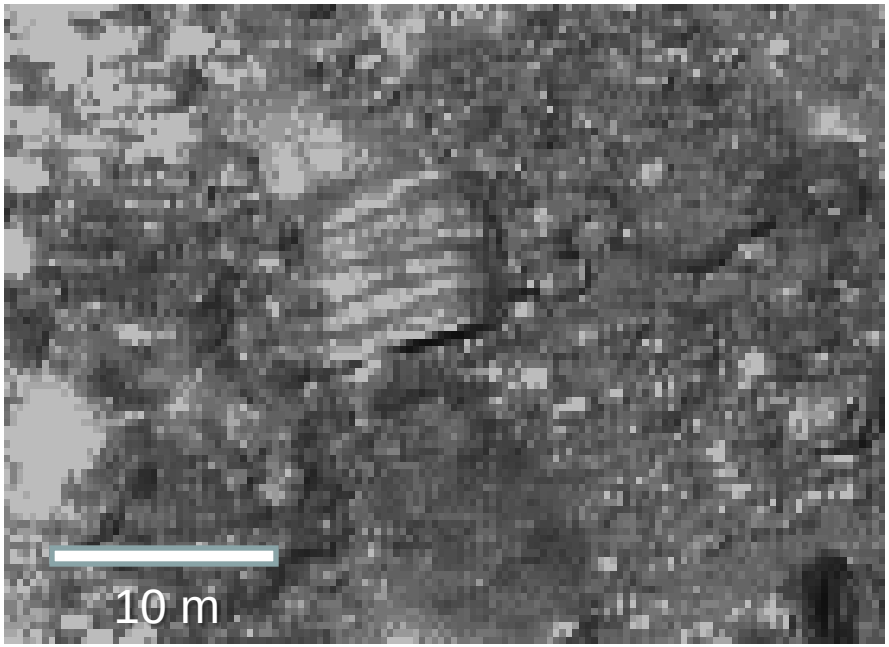


	Layer Thickness (m)	Albedo Value	Ratio DK:DK+LT
LT	2.05	0.47	
DK	1.14	0.46	0.35
LT	2.05	0.48	
DK	1.53	0.45	0.57
LT	1.14	0.48	
DK	1.53	0.45	

-Tapered Layers,
Enclaves

Quantitative Data

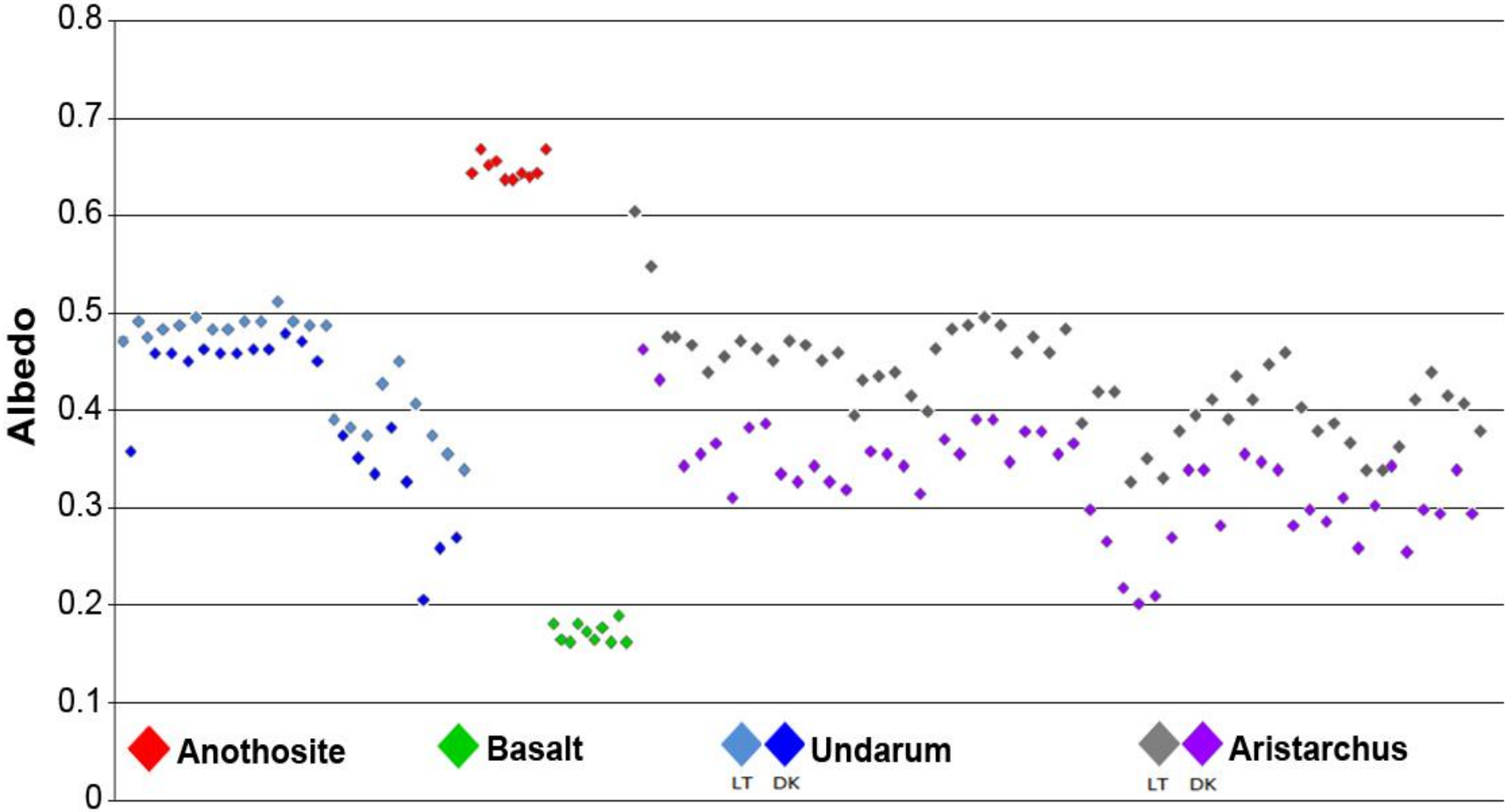
Mare Undarum
M154799629RE



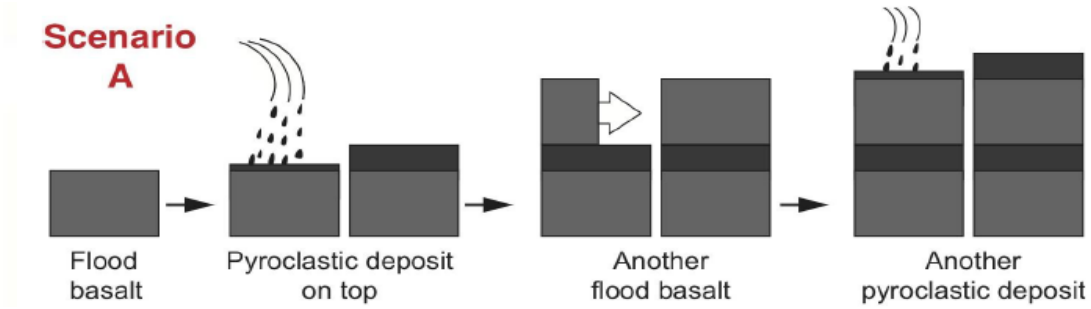
	Layer Thickness (m)	Albedo Value	Ratio DK:DK+LT
LT	1.02	0.49	
DK	1.62	0.46	0.50
LT	1.62	0.48	
DK	0.51	0.45	0.33
LT	1.02	0.48	
DK	1.02	0.45	

-Tapered Layers,
Crossbedding

Albedo Values



Testing the Formation Hypotheses:
Pyroclastic Deposits (Weitz, Zanetti)

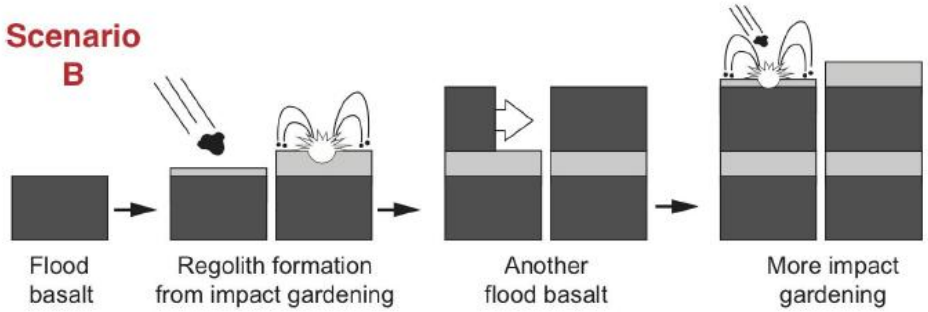


Postulate: The dark layers are pyroclastic deposits atop lighter mare basalt layers.

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.

Testing the Formation Hypotheses:
Impact Gardening (Zanetti, Campbell, Crawford)

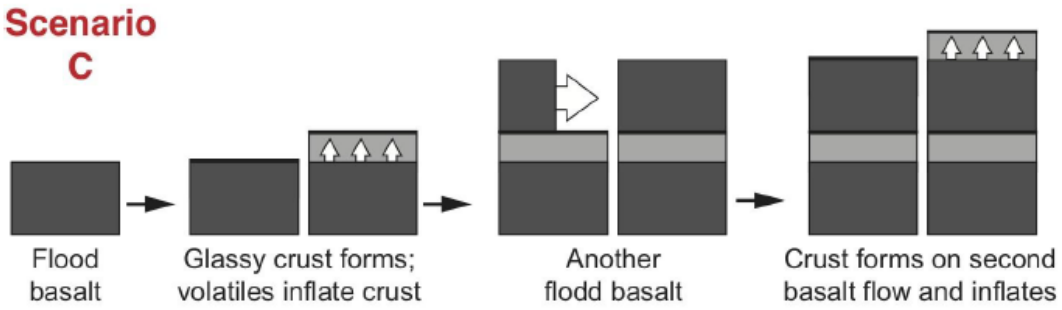


Postulate: Lava flows every 200 million years cut normal rate of regolith formation from 1 meter/billion years to 20 cm/200million years (Crawford).

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.

Testing the Formation Hypotheses:
Glassy, Vesiculated Crust (Zanetti, Self)

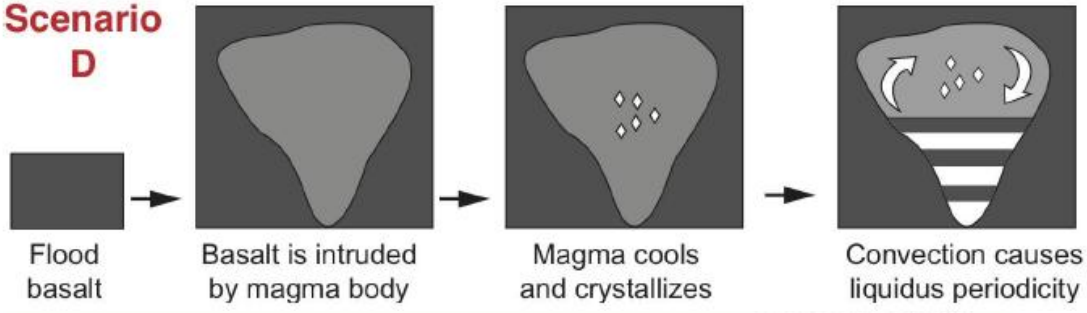


Postulate: As lava cools, a thin, glassy crust forms on top of lava. Glassy crust acts as insulator to the remaining melt, resulting in distinguished layering (Zanetti).

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.

Testing the Formation Hypotheses:
Layered Pluton (Pieters)



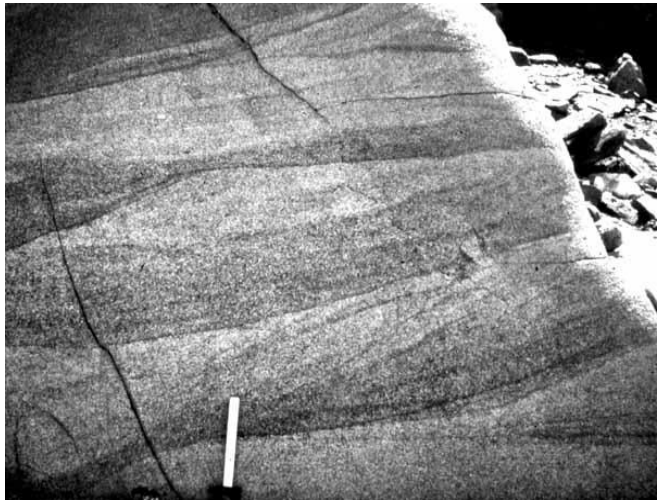
Postulate: Alternating layers are compositions of cumulates crystallizing in a magmatic intrusion. The alternating cumulate composition reflects periodic changes in the composition of liquidus due to convection or magma recharge in the cooling intrusive body.

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.

Conclusions

- 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.
- Measurements of light and dark strata in both regions demonstrate albedo values between that of the anorthositic highlands and basaltic mare.
- Several stratified boulders in Aristarchus and Mare Undarum demonstrate cross-bedding, troughing, tapered layering, and cumulate enclaves, supporting the hypothesis that these stratified boulders originated from a layered pluton.



Cross-bedding in cumulate layers. Skaergård Intrusion, E. Greenland. Layering caused by different proportions of mafics and plagioclase.

Cross-bedding in cumulate layers. Stratified boulder in Aristarchus Crater

Acknowledgements

- **Dr. Georgianna Kramer**
  - for her student mentoring on scientific analysis and critique of the methods of science. (“she is the bomb!”)
- **Kickapoo High School Art Department**
  - for their providing of the Adobe Photoshop C5S program used for analysis of stratified ejecta boulders and their technical expertise on using this program
- **Mr. Mike Zanetti**
  - for his student mentoring and direction in analysis of the Aristarchus stratified boulders
- **Dr. Brent Garry**
  - for his student mentoring on the formation and processes of lava flows

References

[1] Barbey, P. (2008, March 10). *Layering and Schlieren in Granitoids: A record of interactions between magma emplacement, crystallization and deformation in growing plutons*. Retrieved from http://popups.ulg.ac.be/Geol/docannexe.php?id=2714

[2] Campbell, B. A., Carter , L. M., Hawke, B. R., Campbell, D. B., & Ghent, R. R. (2008). *Volcanic and impact deposits of the moon's Aristarchus plateau: A new view from earth-based radar images*. Retrieved from http://www.geology.gsapubs.org

[3] Conrad, M. E., & Naslund, H. R. (1984). Modally-Graded Rhythmic Layering in the Skaergaard Intrusion. *Journal of Petrology* , 251-269.

[4] Crawford, I., Fagents, S., & Joy, K. (2007). Exploring the basaltic lava flows of oceanus procellarum: Valuable (non-polar) lunar science facilitated by a return to the moon. *Astronomy and Geophysics.*

[5] Hawke, B. R., Peterson, C. A., Blewett, D. T., Bussey, D. B. J., Lucey, P. G., Taylor, G. J., & Spudis, P. D. (2003). Distribution and Modes of Occurrence of Lunar Anorthosite. *Journal of Geophysical Research*, *108*(E6), Retrieved from http://www.spudislunarresources.com/Bibliography/p/77.pdf

[6] Maaloe, S. (1978). The Origin of Rhythmic Layering. *Mineralogical Magazine* , 337-347.

[7] Malaska, M. (2011, March 29). [Web log message]. Retrieved from http://planetary.org/blog/article/00002980/

[8] Pieters, C. M. (1991). Bullialdus: Strengthening the Case for Lunar Plutons. *Geophysical Research Letters* , 2129-2132.

[9] Self, S., Thordarson, T., & Keszthelyi, L. (1997). *Emplacement of Continental Flood Basalt Lava flows*. Informally published manuscript, Geology and Geophysics and Hawaii Center for Volcanology, University of Hawaii , Manoa, Honolulu, Hawaii. Retrieved from http://cat.inist.fr/?aModele=afficheN&cpsidt=1623040

[10] Weitz, C. M., Head, J. M., & Pieters, C. M. (1998). Lunar regional dark mantle deposits: Geologic, multispectral, and modeling studies. *Journal of Geophysical Research*, 22, 725-22, 759. Retrieved from http://www.planetary.brown.edu/pdfs/2053.pdf

[11] Zanetti, M., Hiesinger, H., van der Bogert, C. H., & Jolliff, B. L. (2011, March). *Observation of stratified ejecta blocks at aristarchus crater*. 42nd lunar and planetary science conference, The Woodlands, TX. Retrieved from http://www.lpi.usra.edu/meetings/lpsc2011/pdf/2262.pdf

Possible Sources of Error

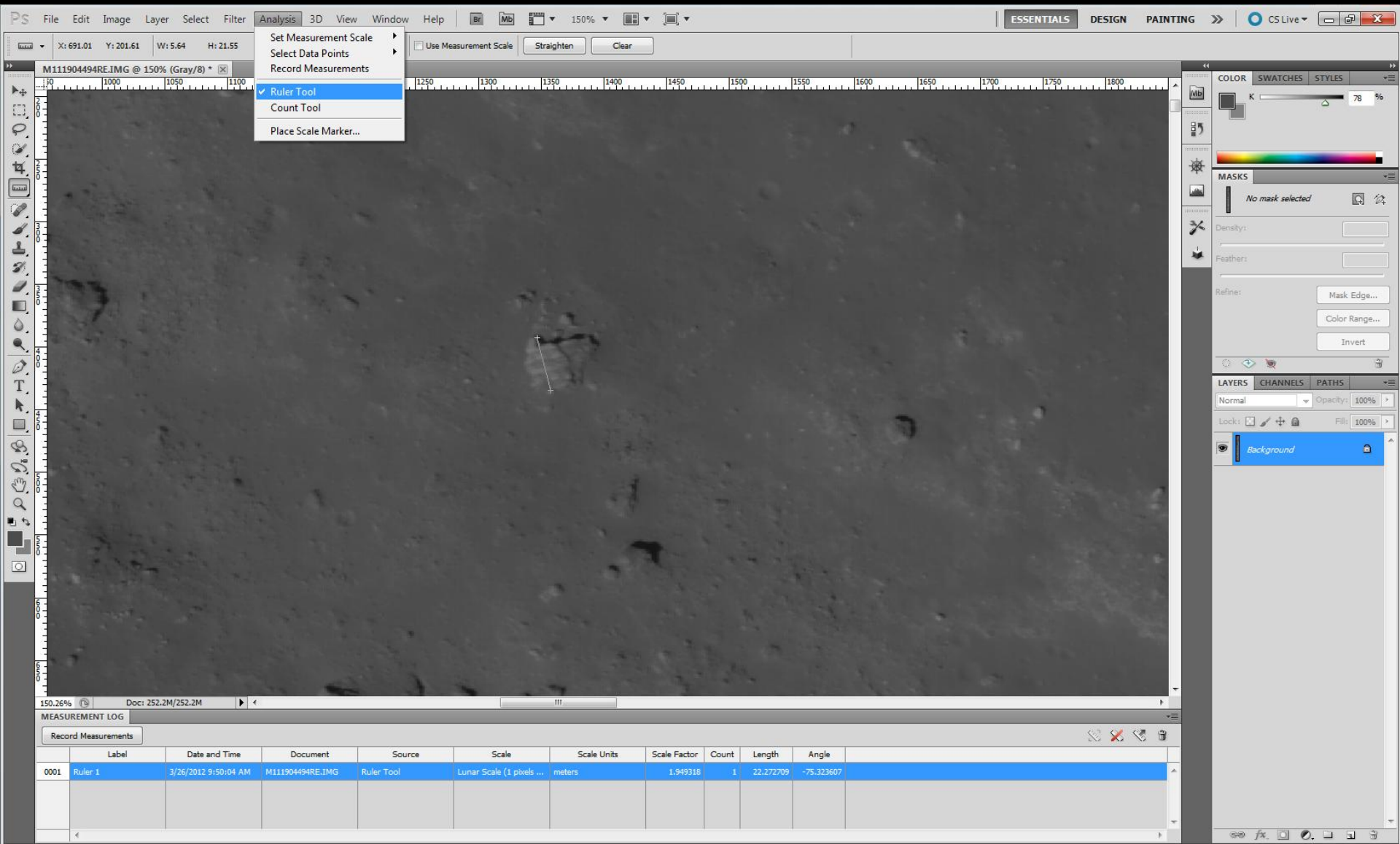
-Distinguishing “exact” boundaries between the dark and light layers was not always evident on all downloaded EDR images

-Resolution of EDR imagery did not provide 100% clarity for analysis of boulders 15-20 meters in size.

-Downloaded imagery of boulders in Mare Undarum were of lower incidence angles (20°) which may have influenced accuracy of albedo measurements of light strata.

Methods of Measurement

Measuring Size of Boulders and Individual Layers



Methods of Measurement

Measuring Albedo Values