STRATIFIED EJECTA BOULDERS AS INDICATORS OF LAYERED PLUTONS ON THE LUNAR NEARSIDE. Kickapoo Lunar Research Team[1] and G. Y. Kramer[2], [1](A. Beason, A. Delawder, V. Wilson, and R. D. Snyder) Kickapoo High School, 3710 S. Jefferson Ave, Springfield, MO 65807 rsnyder2@spsmail.org, [2]Lunar and Planetary Institute, 3600 Bay Area Blvd. Houston, TX 77058 kramer@lpi.usra.edu.

Introduction: Among the wealth of amazing imagery and new observations of the lunar landscape captured by the the Lunar Reconnaissance Orbiter's high-resolution Narrow Angle Camera (NAC), the stratified ejecta boulders first reported by [1] offer an unexpected glimpse into igneous processes and heterogeneity of the lunar crust. Several hypotheses have been put forward to explain the formation of these thick sequences of crust with multiple layers of alternating albedo. The purpose of this research was to test these hypotheses to determine the most plausible origin of these boulders.

Methodology: We searched over 500 NAC images near mare-highland contacts for striped boulders including those at Aristarchus discovered by [1]. For each stratified boulder we measured its overall size and the thickness and albedo of each layer. Here we report our observations of twenty-four examples located at Aristarchus Crater and Mare Undarum that best demonstrate the variety of layer thicknesses, albedos, and bedding morphologies (Fig. 1). All analyzed boulders clearly derive from beneath the target crust, excavated by the craters which they surround.

Results: Layer thicknesses can be approximated by a Gaussian distribution having a median between 1 and 2 meters and tails that extend out to 10 meters and below the spatial resolution of NAC imagery (~50 cm). The measured thicknesses of alternating light and dark material 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.

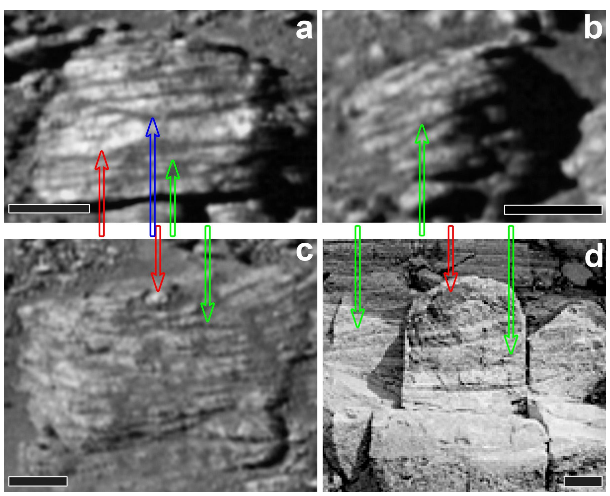

Figure 1: Examples of boulders and bedding features measured in this study. Arrows indicate locations of bedding morphologies: red arrows show cumulate enclaves, blue arrow shows trough-shaped layering, and green arrows show tapered layering and cross-bedding. Figures a, b, and c are from NAC image M120161915L; scale bars = 10 m. Figure d is an analog example from the Coastal Batholith, Ilo, southern Peru; Scale bar = 10 cm (from [2]).

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. In general, 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. 2). Some of the variation in albedos among dark layers as well as light layers may be due to the accumulation of fine coatings of dust, which would reduce albedo contrast. The lack of any layers with albedos that exceed the endmember values demonstrates that the layers have compositions that fall between, if not actually approximated by these two endmembers.

Discussion: We tested the leading formation hypotheses for the stratified boulders (Fig. 3) and assessed their plausibility based on our measurements and observations.

Scenario A: Pyroclastic Deposits: This hypothesis postulates that the dark layers are pyroclastic deposits atop lighter mare basalt layers [1]. The hypothesis predicts that the thicknesses of the pyroclastic dark layers should be between 10 and 30 meters [4]. Our measurements of layers thickness are significantly below 10-30 meters, arguing against this hypothesis, or at least this particular prediction of the hypothesis. Measured albedos of the layers falls roughly midway between those of the highlands and mare, with the lighter layers having a difference from that of the highlands about equal to the difference between the dark layers and mare. If

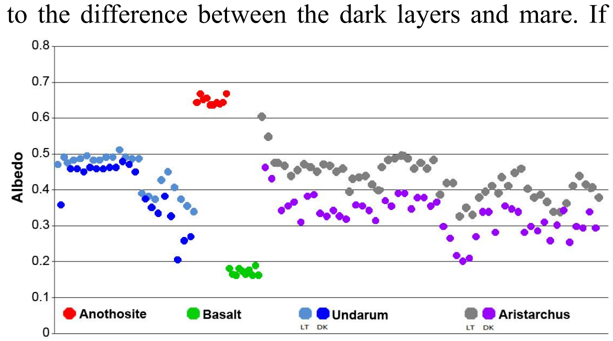

Figure 2: Measured albedos of layers in boulders demonstrate that the layers do not actually have a strong albedo contrast. All layers have albedos lower than that of anorthositic highlands and higher than that of mare basalts.

the layering were the result of alternating dark mare basalt flows and darker pyrocastic deposits we would expect to see the distribution of albedos shifted closer to the basalt endmember in Figure 2.

Scenario B: Impact Gardening: A second hypothesis states that the alternating layer albedos reflect the development of regolith atop periodic mare basalt flows [1]. The rate of regolith production is ~1 cm/10 million years [5]. To build up the number of layers observed in some boulders, the period of time between flows would have to be geologically short, in which case, only a very thin layer of regolith could develop. As a result of this slow rate, the thicknesses of dark lava flow layers would always greatly exceed the thicknesses of the lighter regolith layer. However, the lighter layers are not consistently thinner than the darker ones, and both have thicknesses ranging from 1-5.5 meters - too great to be regolith build-up.

Scenario C: Vesiculated Crust: Upon exposure to the cooler, ambient surface temperature, the surface of a lava flow quenches, forming a thin, glassy rind [1]. This rind acts as an insulator to the remaining melt, allowing time for some of the gases to exsolve. Trapped beneath the glassy rind, the gases inflate the upper surface, forming a vesiculated crust, ~10% of the height of the

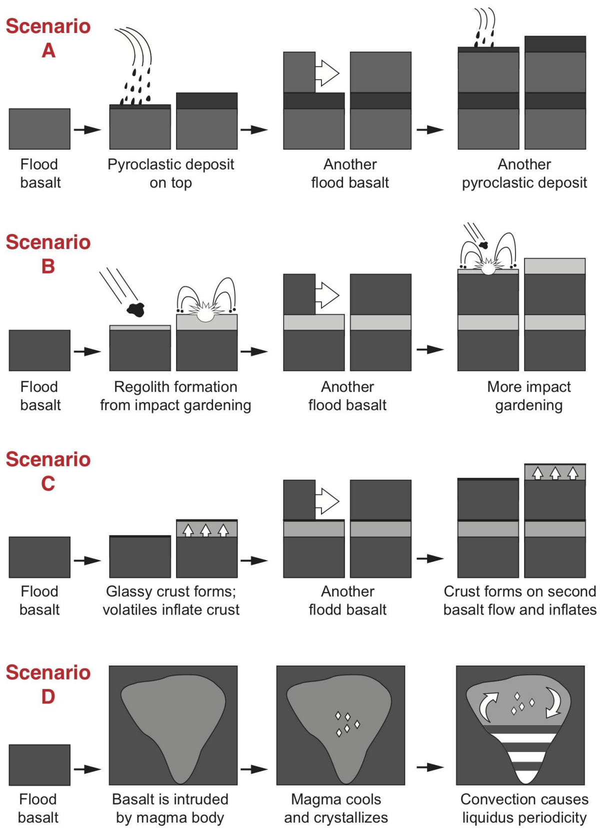

Figure 3: Summary of the four hypotheses for the origin of the stratified boulders. See text for details. Figure after [3].

flow [6]. None of the measured boulders exhibit a ratio between the light and dark layer thicknesses consistent with this hypothesis.

Scenario D: Layered Pluton: Alternating sequences of felsic (light) and mafic (dark) mono-mineralic layers are common enough on Earth, and are interpreted to be the result of periodic changes in the composition of the liquidus due to convection or magma recharge in a cooling intrusive body [7,8,9]. Layer thicknesses are a function of the magma composition and thermal gradient, so have no prescribed ratio between light and dark layers. Crystallization on the walls of the pluton can lead to cross-bedding features, and cumulate fragments broken off of the chamber walls and entrained by the convecting magma can manifest as cumulate enclaves in the cooled, layered intrusion [2].

Our observations support the hypothesis that the stratified boulders derive from layered igneous intrusions in the lunar crust [10]. Measurements of light and dark layers have albedos that lie between anorthositic highlands and mare basalts, respectively (Fig. 2). In the absence of fluvial or aeolian forces, observed bedding morphology, such as cross-bedding, cumulate enclaves, and tapered layering can be explained by convection or magma recharge in a cooling intrusive body.

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. We observed bedding morphology (crossbeds, trough-shaped layers, tapered layers, and enclaves) often attributed to sedimentary deposits involving the movement of water or air. The only plausible means of generating such bedding features and alternating layers of mafic and felsic lithologies on the Moon is crystallization in a convecting igneous intrusion. We conclude that these layers are the result of periodic changes in the composition of the liquidus due to convection or magma recharge in a cooling intrusive body. Fragments of these plutons were excavated by large impacts that penetrated overlying mare basalts and, in some cases, anorthositic crust.

References: [1] Zanetti M. et al. (2011) *LPS XLII,* Abst. #2262; [2] Barbey, P. (2009) *Geologica Belgica*, **12**; [3] Malaska, M. (2011, 3/29). [Figure in web blog message]. Retrieved from http://planetary.org/blog/article/00002980/; [4] Weitz, C. M. et al. (1998) *JGR*, **22**; [5] Quaide, W. & Oberbeck, V. (1975) *The Moon*, **13**; [6] Self, S. et al. (1997) *Geophys. Monograph*, **100**; [7] Poldervaart, A. & Taubeneck, W. H. (1969) *Bull. Geol. Soc. Am.*, **70**; [8] Maaloe, S. (1978) *Mineralogical Magazine*, 337-347; [9] Conrad, M. E., & Naslund, H. R. (1984) *J.Pet.*; [10] Pieters, C. M. (1991) *GRL*, **18**