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Stratified ejecta boulders as indicators of layered plutons on the Moon

Kickapoo Lunar Research Team [a,1], Georgiana Kramer [b,c,*]

[a] Kickapoo High School, 3710 S. Jefferson Avenue, Springfield, MO 65807, USA
[b] Center for Lunar Science and Exploration, Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston, TX 77058, USA
[c] NASA Lunar Science Institute, USA

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ABSTRACT

High resolution images of stratified ejecta boulders on the lunar nearside reveal layers of alternating low and high albedo material. We measured the thickness and albedo of each alternating light and dark layer from 29 stratified boulders located in Aristarchus Crater and Mare Undarum. The results were used to test hypotheses to explain the origin of the observed strata in these impact ejected boulders. Morphologically, these boulders demonstrate cross-bedding, trough-shaped layering, tapered layering and cumulate enclaves. We interpret these characteristics to be evidence that these layers result from periodic disruption by convection or density currents within a cooling layered igneous intrusion. We demonstrate that the layering observed in these boulders cannot be the result of known processes occurring on the surface, but instead suggests a history of complex intrusive igneous processes within the lunar crust.

1. Introduction

Among the wealth of new observations and amazing imagery captured by the Lunar Reconnaissance Orbiter's high-resolution Narrow Angle Camera (NAC) (Robinson et al., 2010), the stratified ejecta boulders, first reported by Zanetti et al. (2011), provide an unexpected glimpse into the heterogeneity of the lunar crust. Stratigraphic layering has previously been observed on the Moon, for example, Silver Spur at the Apollo 15 landing site (cf. Apollo 15 frame AS15-84-11250; Swann et al., 1972). Individual lava flows that make up the lunar maria have been identified in remote sensing imagery as flow fronts on the horizontal surface (e.g., Pieters, 1993; Staid et al., 1996). More recently, stratigraphic layering of multiple basalt flows has been observed in cross section in the walls of impact craters, rilles, and skylights in high resolution NAC imagery (e.g., Robinson et al., 2012). In these examples the layers have very similar albedos and are distinguished morphologically and/or compositionally. The stratified boulders that are the focus of this study, however, are distinguished by layers of contrasting albedos (Fig. 1) in monochromatic NAC imagery. The width of these layers are on the order of only a couple of meters or less. This is most likely why these types of stratified boulders had not previously been observed. As such, the data set used to observe and measure these boulders is NAC imagery, as this is the only current data set able to resolve these features.

Zanetti et al. (2011) put forward three hypotheses to explain the formation of these fragments of crust with multiple layers of contrasting albedo. The purpose of this research was to deduce the most plausible origin for these boulders by testing these hypotheses as well as a fourth, inspired by an analysis by Pieters (1991) of Bullialdus Crater.

2. Methods

The search for stratified boulders with contrasting albedos began with LRO's Wide Angle Camera (WAC) imagery of the nearside, and was constrained to mare-highland contacts or where crater ejecta exhibited a distinct albedo difference with respect to the target surface. This constraint was imposed simply to restrict the number of NAC images to locations where the occurrence of contrasting lithologies is already demonstrated. Even with this constraint, we searched over 500 NAC images for stratified boulders. From this survey of 500 NAC images we identified only one other location (in addition to Aristarchus), Mare Undarum, where the contrasting albedos on the stratified boulders was unambiguous. The occurrence of these boulders as dislocated fragments in the walls and ejecta of impact craters indicates they were ejected by the impact event. The lack of similar banding in exposed bedrock elsewhere in the vicinity, such as layers in crater walls or volcanic rilles, indicates that these boulders did not originate just beneath the regolith, but from depth within the lunar crust. The paucity of locations on the lunar nearside at which we observed these boulders suggests the origin has a limited lateral extent.

In addition to the boulders in the northeast wall and proximal ejecta of Aristarchus originally discovered by Zanetti et al.

* Corresponding author at: Center for Lunar Science and Exploration, Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston, TX 77058, USA.
E-mail address: kramer@lpi.usra.edu (G. Kramer).
[1] Abby Delawder, Austen Beason, Victoria Wilson, and Richard D. Snyder.

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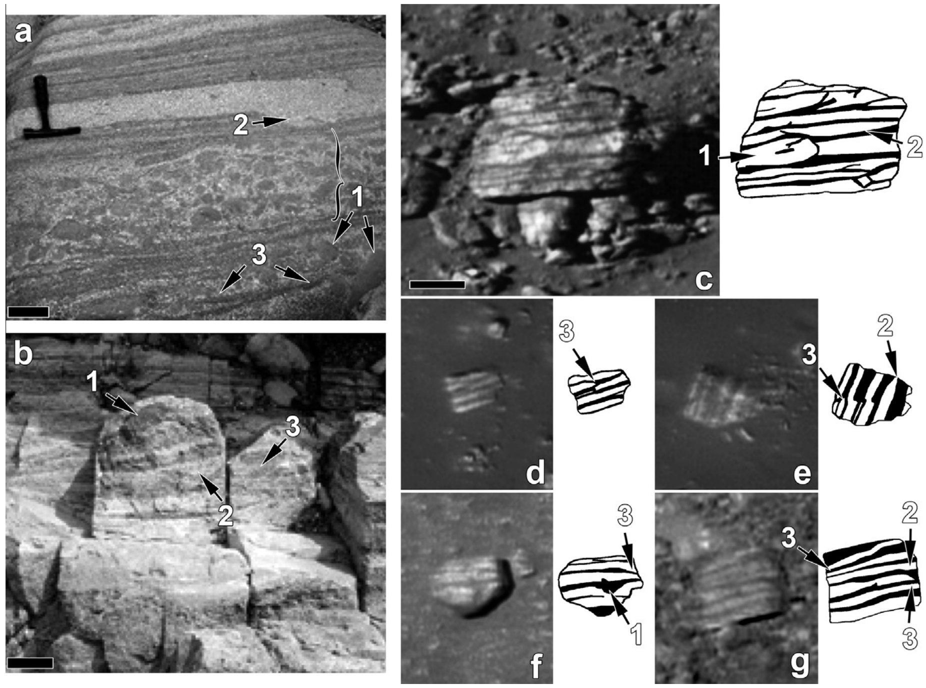

Fig. 1. Bedding features: (a) Analog example showing cross-bedding from Barbey (2009) from the Coastal Batholith, Ilo, southern Peru; Scale bar = 10 cm. (b) Analog example showing layering and mafic enclaves from Barbey (2009) from the Coastal Batholith, Huatiapa, southern Peru; Scale bar = 10 cm. (c–g) Examples of boulders and types of bedding features observed in this study. Each NAC image of a lunar stratified boulder is accompanied by a sketch map to its right to elucidate interpreted bedding features. Shadows and ponded dust are omitted from the sketch maps. Scale bar = 10 m. (c–g) are all at the same scale. (c) is from Aristarchus, NAC frame M120161915L, (d) and (e) are from Aristarchus, NAC frame M173226167R. (f) and (g) are from Undarum, NAC frame M154799629R. Numbered arrows point out bedding morphologies: (1) cumulate enclaves, (2) trough-shaped layering, and (3) tapered layering and cross-bedding.

(2011), we found boulders that are clearly composed of layers of contrasting albedos within the bowls and proximal ejecta of 3 craters between 300 and 1000 m in diameter at Mare Undarum (Fig. 2). We were careful to limit analysis to boulders with banding that is inherent to the rock; not the result of regolith settled into grooves on monolithic boulders. We focused on 29 examples of stratified boulders from both locations, 7 from Mare Undarum and 22 from Aristarchus (Tables 1 and 2). Although more than 29 such boulders can be observed at both regions, several are large exposures of layered boulders having identical characteristics. Such boulders are clearly fragments from a larger piece, so reporting the measurements from each one would be redundant. The measurements reported in Tables 1 and 2 are representative of the range in layer thicknesses and layering morphology in the boulders at both locations.

For each layered boulder we measured the following characteristics (Tables 1 and 2): (1) number of layers, (2) albedo of each light and dark layer, (3) thickness of each light and dark layer, and (4) ratio of the light layer thickness to the sum of the light layer thickness and adjacent dark layer thickness ($T_{lt}/(T_{dk} + T_{lt})$). The topmost and bottommost layer of all boulders were not measured because these layers are unconstrained by an observable contact with an adjacent layer, so we could not be sure how thick these layers actually are.

In order to compare layer albedos within a single region as well as between the two regions, it was necessary to compare the pixel values from each of the measured boulders in the six NAC frames to a reference albedo value. We identified a highland and a mare location in both regions that were used to compare to the stratified boulder layer albedos. Since not every NAC image containing the measured boulders also contained both mare and highland references, we used locations where the NAC frames overlap to adjust the image histogram so that mare and highlands from one NAC image can be compared with layer albedos in an adjacent NAC

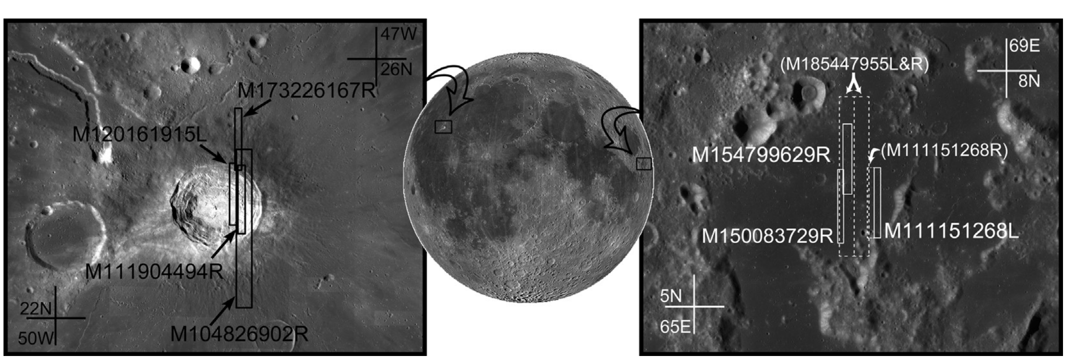

Fig. 2. Locations where stratified boulders were identified and measured in this study: (a) Aristarchus. (b) Mare Undarum. The boundaries of the NAC frames from which the boulders were analyzed are outlined and labeled with the corresponding frame number. In (b), the NAC frames that have dashed outlines do not have identified stratified boulders, but do contain the mare and highland features used to compare with layer albedos (see Fig. 4).