RE-EXAMINING THE IDENTIFICATION OF DARK-HALOED IMPACT CRATERS: NEW CRITERIA FOR MODERN DATA SETS. I. Antonenko, [1]Planetary Institute of Toronto, 197 Fairview Ave. Toronto, ON M6P 3A6, Canada (PlanetaryInstituteofToronto@yahoo.ca).

Introduction: Dark-haloed impact craters (DHC's) are important because they are used to identify and characterize hidden mare deposits, called cryptomaria, thus expanding our understanding of lunar volcanism and the thermal history of the Moon [1]. Historically, DHC's have been identified by the presence of a mature, low albedo halo, symmetrically surrounding a crater of decidedly impact origin, which does not exhibit impact melts (because melts can also form dark halos) [2]. However, multiple new lunar data sets have been obtained since DHC's were originally identified, so it is important to revisit these criteria.

Methods: In order to understand how DHC's behave in the new data sets, a literature survey was conducted to identify all well known DHC's. Only those craters that were either identified specifically by name or clearly identified on good quality images were considered for this study. Many studies [e.g. 2, 3, 4] show their dark-haloed craters mainly in high sun angle images, where it can be very difficult to correlate the observed albedo variations to topography and so ensure that the correct craters are identified (e.g. Fig. 1). Furthermore, the quintessential DHC study [2] presented most of their DHC's only on a global sketch map. Thus, many of these craters could not be used. As a result, only 60 dark-haloed craters were considered in this study, compiled from [2-11].

Each identified crater was accurately located and measured in the Lunar Reconnaissance Orbiter (LRO) coordinate system, using the JMARS for Earth's Moon software package [12]. The craters were then evaluated using a variety of data sets, including Lunar Orbiter photographs [13], Clementine UVVIS multispectral data [14], Clementine-derived FeO composition maps [15], Clementine Optical Maturity Index (OMAT) maps [16], Lunar Reconnaissance Orbiter Camera (LROC) Wide Angle Camera (WAC) and Narrow Angle Camera (NAC) images [17], and Lunar Orbiter Laser Altimeter (LOLA) topography data [18]. Criteria that were assessed included the presence of a low albedo halo, the halo's symmetry, maturity, and iron composition, a distinct impact topography, and the absence of clear impact melt features around the crater.

Results: This study found that many well-established DHC's do not conform to the original criteria laid out by [2]. For example, many DHC's were found to have very non-symmetrical halos. These can include gaps in mostly symmetrical halos, discrete dark patches around the crater, and even one or two directed

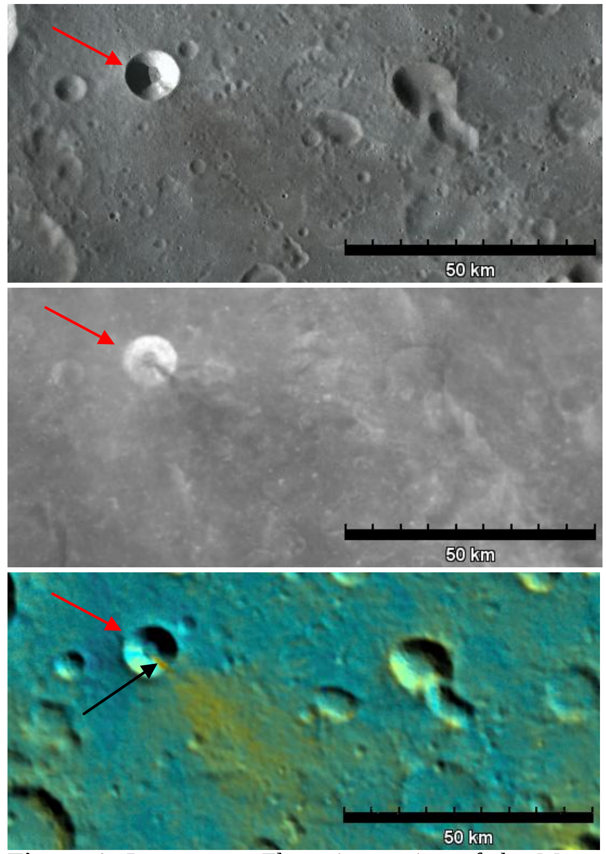

Figure 1: Lomonosov-Flemming region of the Moon centered on 109.6E, 20.7. Top view shows LROC WAC data. Centre view shows Clementine 750 nm data. Bottom shows Clementine-derived FeO data (yellow is high FeO, blue is low) overlain on WAC data. Comparison between the top and centre images illustrates how a lack of topographic information in the high sun angle Clementine data makes orientation difficult. The prominent fresh crater (red arrow in all three images) is one of the DHC's of this study. The directed wedge-shape of this crater's dark halo is well seen in the Clementine 750 nm image. The "wedge" is also seen in the FeO map, where the shape of the iron anomaly matches that of the albedo anomaly, and elevated iron levels (yellow) can even be seen inside the crater (black arrow).

"wedges" of dark material (Fig 1, centre). Roughly 37% of the craters in this study have non-symmetrical halos. In addition, the soils around many DHC's were not found to be mature based on OMAT maps. Only 47% of DHC's were fully mature compared to their surroundings, with 40% being only moderately mature, and 13% being completely immature (Fig 2, top right). Two craters (#14 and 19 from [10]) were found to have no clear dark halo at all, but did have very distinct FeO anomalies, and [10] found basalt-like spectra on the ejecta of their crater #19.

As expected, all of the craters exhibited topography that was indicative of an impact origin. Image data showed predominantly circular features of relatively high symmetry and a classic bowl appearance (Fig. 1, 2). LOLA profiles showed steep sided depressions with curved or flat floors, and occasional slumping. Five small craters (1-2.5 km in diameter) did not register in the LOLA data, having fallen between the sampling grid points (Fig. 2, bottom right). However, such situations could be easily identified by looking at the data contours and examining the high resolution NAC data.

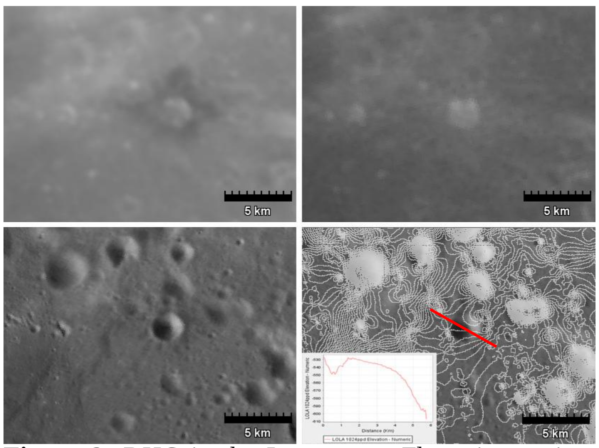

Figure 2: DHC in the Lomonosov-Flemming region, centered at 111.2E, 17.8N. Top left shows Clementine 750 nm data, top right shows Clementine OMAT map, bottom left shows LROC WAC data, and bottom right shows LOLA contour data (overlain on WAC data) with a topographic profile (red line across crater) inset to the bottom left. Comparison between the top images shows that the halo for this DHC is optically immature in comparison to its surroundings. The bottom two images illustrate how this same small crater falls between the LOLA sampling grid, resulting in a topo profile (inset) that lacks an appropriate crater feature, even though WAC data shows a clear impact structure.

No distinct impact melt flow features could be unequivocally identified around any of the study craters. However, when viewed in high resolution NAC images, almost all of the craters exhibited numerous smooth dark patches, which are thought to be indicative of impact melt veneers [e.g. 19], around their crater rims.

Every single crater, for which Clementine FeO data was available, showed a clear iron anomaly around the DHC. These anomalies generally matched the shape of the low albedo halo (Fig. 1). In addition, elevated iron contents were often visible in the crater interior.

For approximately half of the craters identified in this study, their original sources [3, 4, 7, 9-11] had also obtained spectra for the DHC's in question. In all these cases, the craters were shown to be associated with basalt-like spectra.

Discussion: The results of this study suggest that historical criteria for the identification of DHC's may not be optimal. The symmetry of the halo, the maturity of the halo soils, and even the presence of a low albedo halo have been shown to be variable aspects in the range of possible dark halo states. Even the requirement for the absence of melt materials is called into question, since high resolution images are suggesting that many, if not most, fresh craters may be draped with melt veneers along their rims.

The DHC criteria that were found to be most consistent and reliable in this study were the identification of a clear impact topography, together with compositional data supporting the presence of a high iron content or specific mafic minerals (such as high-Ca pyroxenes [e.g. 11]). In fact the usefulness of obtaining and classifying spectra in DHC identification is so promising, that future work will look more closely at both Clementine 5-band UVVIS spectra and Chandraayan-1 Moon Mineralogy Mapper (M^3) hyperspectral data [20] in the analysis of these known DHC's.

The identification of DHC's using predominantly compositional data has significant implications for estimating cryptomaria. For example, basalts exposed on crater walls should be detectable with these compositional techniques. However, such craters may not have excavated basalt material beyond the crater rim. Converesely, such craters may have excavated sufficient substrate highland material to obscure a dark halo (e.g. Dionysis crater [11]). The resulting craters tell us useful, but different information about the depth and thickness of the underlying basalt layers. More work is needed to learn how to distinguish between such craters in order to accurately estimate cryptomare volume.

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