Lunar Surface Model Age Derivation: Comparing Automatic and Human Crater Counting Across LRO-NAC and Kaguya TC Images.
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Introduction: The ability to derive a formation age for planetary surfaces is made possible by crater counting and the application of crater chronologies calibrated for the Moon [e.g., 1, 2]. Understanding the chronological order of young Copernican geological events, (typically <1Ga) that shaped the lunar surface, is very valuable in understanding the outside and inside processes responsible for the surface's evolution. This method is currently limited by the ability to manually count all the needed small craters to generate a reliable model age for a young event. Here we present the use of a Crater Detection Algorithm (CDA), to automatically extract the Crater Size-Frequency Distributions (CSFD) required to date geological events [3]. CDAs have had great success in deriving model ages for planetary bodies such as Mars [e.g., 4, 5], but to our knowledge, a CDA has not been specifically used to generate model ages for the Moon. We present here a study, comparing the model ages and cratering densities produced by our CDA to that of published manual counts. The analysis looked at four Copernican impact craters (North Ray, Tycho, Copernicus [6], and Lalande [7]) and four young mare sites (Chang'e-5 #05, #21 [8], P60, and I30 [9]) (Fig 1.a). To depict each site, we used two global high-resolution image datasets: the Lunar Reconnaissance Orbiter - Narrow Angle Camera (LRO-NAC) [10] and Kaguya Terrain Camera (TC) images [11].

The CDAs: The CDA is a Convolutional Neural Network (CNN) image-based object detection algorithm which has been developed to identify impact craters at multiple pixel-scales across image datasets [4, 5]. Two different CNN versions were utilized by our team within this analysis. The first variation was trained for crater detection across NAC images with intermediate incidence angles (50°-70°) using the YOLOv3 (You Only Look Once version 3) architecture [12]. This CDA boasts a high overall detection accuracy of ~96% for craters <500m [4]. The second CDA was developed and optimized for crater detection across Kaguya TC images. This CDA runs on an updated version, YOLO(v5) [13], which has been trained on both evening and morning Kaguya TC versions [11]. This algorithm was evaluated over both Kaguya image versions, which resulted in an overall detection accuracy of ~96% for craters between 100m-1km.

Method: Our CDA was run across the needed NAC and Kaguya images for each of the 7 regions (Fig 1.b). The detections were compiled and only the craters that coincided within the published crater count areas were used for model age derivation. As our CDA is insensitive to secondary and/or overlain craters, we employed two techniques to remove such craters from our datasets. The first was to edit the published count areas, removing any additional secondary clusters we identified. The second, mathematically flagged craters that were overlain by crater ejecta, based on radial ejecta models [14, 15] and crater depth to diameter ratios [16]. To keep the analysis as transparent as possible, we split the results into two. The first reports the raw detections within the originally published count areas, and the second reports the adjusted dataset values. To derive comparable model ages using the CDA, the CSFD fitting methods and chronology models were kept the same as the cited published studies. All the CSFD plotting and isochron drawing was conducted in the CraterStats II software [17].

Results and Discussion: Across all 8 sites, where only the raw datasets were used, the crater densities/model ages were systematically overestimated by up to ~50% when compared to the published values. This is indicative of the additional secondary and overlain craters still being included in the crater count datasets, artificially increasing the values for the events we were dating. Filtering out the secondary and pre-existing craters significantly reduced the gap between crater density/model ages inferred from CDA detections and published data from manual counts. Of the 8 sites analyzed, 6 sites (North ray, Lalande, Copernicus, #21, P60, I30) show an overall difference of <30%, and of these all the ages were within the error ranges reported in the cited publications (Fig 1.c). These are within the acceptable error ranges observed for manually derived model ages [18]. However, two major deviations from published ages are observed for Tycho and the Chang'e-5 #05 sites. The CDA underestimated the model ages for Tycho by 32% (Fig 1.c). After careful investigations, we could not determine the definitive direct cause for this difference. The Discrepancy for CE-5 #05 arises from the significant difference in recorded cratering densities between the CDA and the published dataset. When

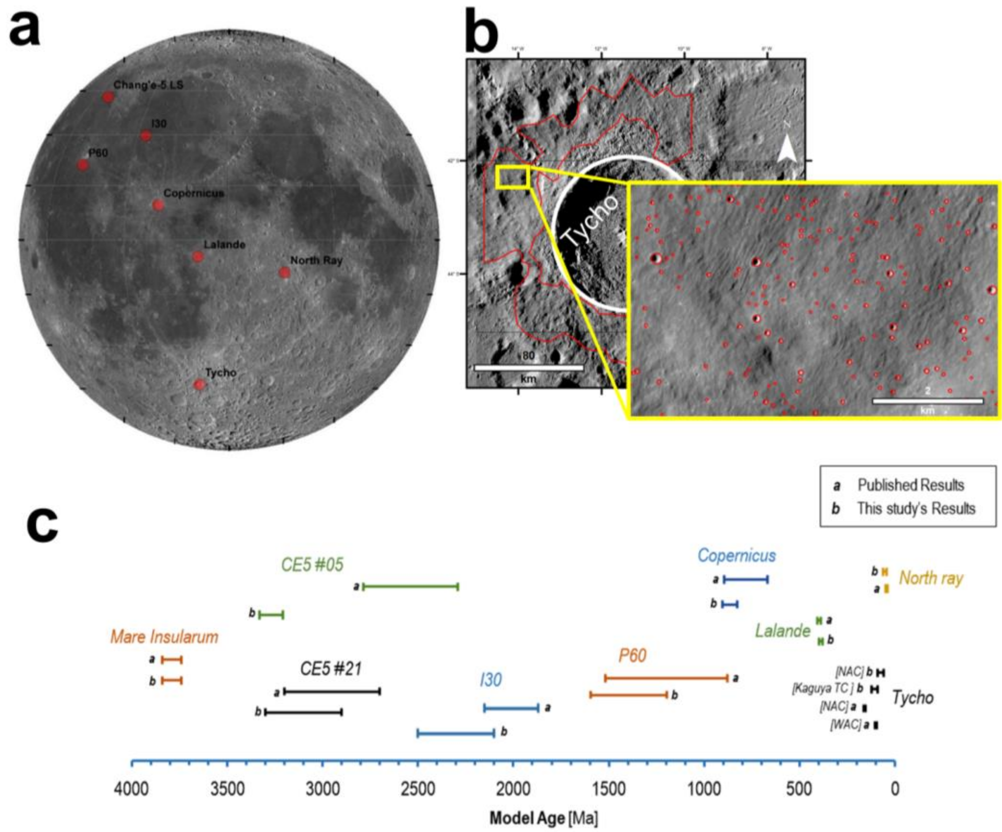

Fig 1: (a) Locations of each of the Regions of Interest analyzed in this study, background is a stereographic projection of the LRO-WAC mosaic [9]; (b) Our CDA detections over Kaguya image Tiles for Tycho Crater within the published Tycho crater count areas [5]; (c) Summarized timeline of the calculated model age results from the for each of the analyzed count areas, subdivided by dataset type, refer to figure key.

specifically looking at craters >200m in diameter, the CDA detected twice as many as the manual dataset. The difference was found to be constrained to degraded craters between ~200m and ~400m. The difference in lighting conditions will influence the ability to detect degraded craters [7], which is what has resulted in the differences we have observed. Where we used a single Kaguya TC image tile with consistent lighting, whereas Giguere et al. (2022) used a series of NAC images with varying lighting conditions, which resulted in different levels of accuracy.

Conclusion: We show that a CDA can produce comparable cratering densities and model ages for young lunar surfaces with proper procedures and interpretations. The reported values from the adjusted datasets are acceptable and within the error margins for manual counts. When investigating the discrepancies, we highlight the importance of a consistent crater detection method with a known levels of accuracy and reproducibility. Finally, our semi-automatic approach could be extended routinely to other sites of interest to derive crater retention and or formation model ages of multiple lunar geological units.

References: [1] Opik, E. J. (1960). Monthly Notices of the Royal Astronomical Society, 120(5). [2] Hartmann, W. K. (1965). Icarus, 4(2), 157–165. [3] Fairweather, J. H., et al. (2022). Earth and Space Science, 9(7). [4] Lagain, A., et al. (2021). Earth and Space Science, 8(2). [5] Benedix, G. K., et al. (2020). Earth and Space Science, 7(3)[6] Hiesinger, H., et al. (2012). Journal of Geophysical Research: Planets, 117(2).[7] Xu, L., et al. (2022). Icarus, 386, 115166. [8] Giguere, T. A., et al. (2022). Icarus, 375, 114838. [9] Hiesinger, H., et al. (2011). Geological Society of America. [10] Robinson, M. S., et al. (2010). Space Science Reviews, 150(1–4), 81–124. [11] Isbell, C., et al. (2014). LPSC abstract #2268. [12] Redmon, J., et al. (2018). ArXiv Preprint ArXiv. [13] Jocher, G. (2022). Ultralytics.[14] Pike, R. J. (1974). Earth and Planetary Science Letters, 23(3), 265–271. [15] Sharpton, V. L. (2014). Journal of Geophysical Research: Planets, 119(1), 154–168. [16] Stopar, J. D., et al. (2017). Icarus, 298, 34–48.[17] Michael, G. G., et al. (2010). Earth and Planetary Science Letters, 294(3–4), 223–229.[18] Robbins, S. J., et al. (2014). Icarus, 234, 109–131.