AUTO-SECONDARY CRATERING VS TARGET PROPERTY EFFECTS ON EJECTA BLANKETS OF COPERNICAN CRATERS: WHAT ARE THE IMPLICATIONS FOR AGE DATING USING SMALL-DIAMETER CRATER STATISTICS?

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Introduction: Small diameter crater size-frequency distributions (CSFDs) and corresponding absolute model ages (AMAs) on the ejecta blankets of Copernican-aged lunar craters show considerable variation between the ejecta blankets and impact melt deposits depending on measurement location and material properties of the target rocks [1-7]. Target material properties are known to have an effect on the diameters of craters occurring in the strength regime (>300 m diameter) [e.g., 6-10], where more competent target rocks (e.g., impact melt ponds) produce craters with smaller diameters than those in less-competent material (e.g., ejecta blankets). This effect may explain why impact melt ponds have apparently younger CSFDs and AMAs than same-aged ejecta blankets. Alternatively, auto-secondary cratering (impact craters formed on the continuous ejecta blanket by fragments of ejecta from the parent crater formation [11]) could similarly affect CSFD measurements by producing more craters on the ejecta than on later arriving impact melt, resulting in apparently older ejecta blanket ages [12]. However, auto-secondary cratering is not a well-established aspect of the ejecta emplacement process and lacks a formation mechanism consistent with current theoretical modelling (e.g. high-angle ejecta) [4].

Here, we provide evidence that auto-secondary cratering is a strong candidate for the CSFD disparity using equal-area measurements on a melt pond and adjacent ejecta deposit at Tycho Crater. Additionally, we show examples of putative ghost craters in melt, that suggest some impact craters on near-rim ejecta formed prior to the arrival of melt. Such ghost craters would thus represent observational evidence that auto-secondary cratering occurs.

New Measurements: Our previous investigations, based on CSFD measurements using Kaguya-TC (7 m/pixel) and down-sampled LROC-NAC (~10 m/pixel) images on the continuous ejecta blankets of Tycho and Aristarchus, showed that impact melt ponds are strongly correlated with low crater density regions [4]. The measurements could have been biased by image resolution (craters on melt not included because they were not resolvable), thus leading to the perceived differences. To determine if fewer craters actually occur on melt ponds compared to ejecta, CSFDs were measured to the limit of resolution of 0.5 m/pixel LROC-NAC images (~3 m diameter craters resolved) -

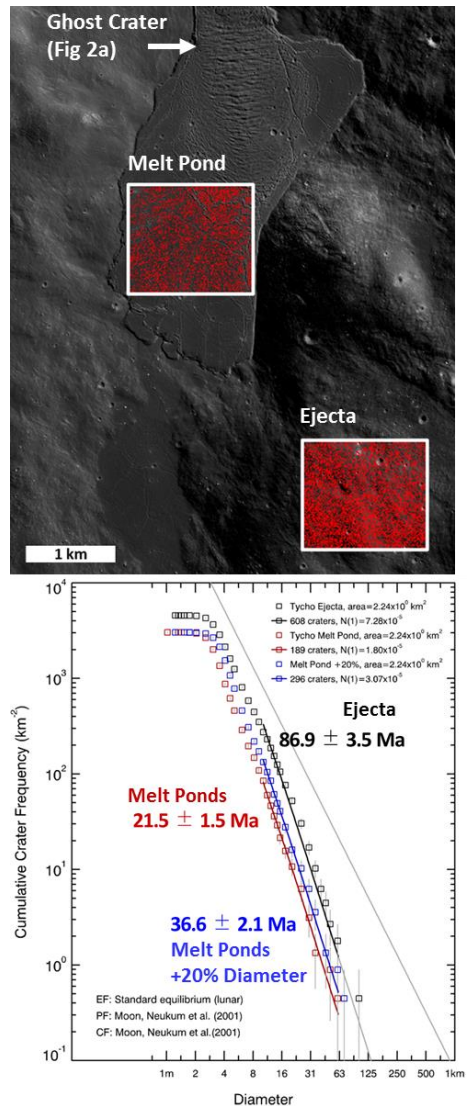

Figure 1: (Top) Equal-sized count-areas at Tycho Crater on a melt pond and adjacent ejecta (LROC-NAC M150578086). (Bottom) CSFD results for Ejecta, Melt Ponds, and Melt Ponds with a 20% diameter increase (to account for target property effects [e.g. 6, 8]).

in equal-sized count areas (2.25 km^2) (Fig. 1) using CraterTools [13]. AMAs were generated using CraterStats [14] and the chronology and production functions (CF/PF) of [15].

Results: 10,220 craters were counted in the ejecta blanket area, resulting in an AMA of ~87 Ma for 608 craters in 10-65 m diameter bins (compared to the cosmic-ray exposure age of Tycho of 109 ± 1.5 Ma [16] and other CSFD-derived AMAs of ~85 Ma for

small count areas and ~124 Ma for large count areas [2]). On the melt pond, 6,795 craters give an AMA of ~22 Ma for 189 craters with 10-65 m diameters. The ejecta count area contains ~33% more craters than the equal-sized melt pond area. The cumulative number of craters (N(1)) is 4x greater on the ejecta blanket [N(1) = 7.28×10^{-5}] compared to the melt [N(1) = 1.8×10^{-5}].

Auto-secondary Cratering vs. Target Property Effects: Ejecta blankets should exhibit the same CSFD as same-aged melt deposits, because they are emplaced nearly simultaneously, with impact melt ponds forming minutes to days after the ejecta blanket [9,17]. Results from Zanetti et al. [4] suggested, based on crater density alone (irrespective of crater diameter, and thus avoiding target property effects), that melt ponds contained ~4x fewer impacts than surrounding ejecta at both Tycho and Aristarchus, a discrepancy confirmed, using the highest resolution counting possible, by the current study. Although crater modeling, experiments, and observational evidence have suggested that target properties of competent materials can result in craters up to 20% smaller in diameter compared to less consolidated targets [6-9], adding 20% to the diameters of melt pond craters in our count areas (Fig. 1, blue isochron) cannot account for the entire AMA disparity between melt and ejecta (but does increase the apparent age of melt). Moreover, changing the crater diameter to account for target properties cannot explain the larger difference in crater populations between melt and ejecta. Thus, auto-secondary cratering may be needed to account for the enhanced production of craters on the ejecta.

Ghost craters found in impact melt ponds at Tycho (Fig. 2) and partially-melt-filled craters on ejecta at other lunar craters (e.g. G. Bruno; [16]), lend strong support to the occurrence of auto-secondary cratering during the very short interval between the emplacement of the ejecta blanket and the formation of melt ponds. Ongoing studies of the abundance and distribution of ghost craters will aid our understanding of the auto-secondary process.

Implications for dating young lunar surfaces: If the goal is to date the formation of small-area units with small-crater statistics, and if auto-secondary craters are abundant in ejecta blankets, then melt ponds (the last arriving units on ejecta blankets) are the most suitable units for recording the primary flux of impact craters on the Moon. This implies that young surfaces containing only small craters (e.g., IMPs [19]) are affected by a cratering rate that is as much as a factor of 4x less than currently estimated, such that the surfaces could be much older. This estimate is also supported by the lower cratering rate currently measured on Mars [20], suggesting that cratering rates of small craters throughout the inner solar system might be less than originally modeled by [15] and measured by [21].

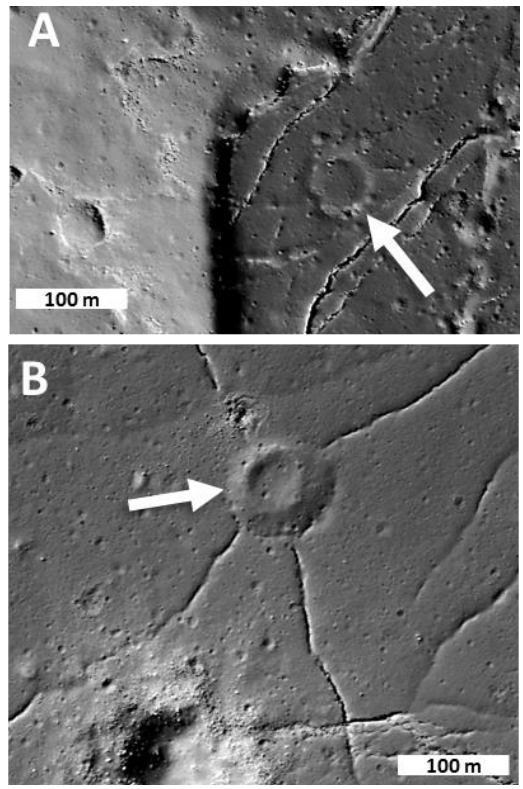

Figure 2: Examples of possible ghost craters in impact melt ponds at Tycho Crater (LROC-NAC M150578086). Crater in (a) is located in same melt pond as count area (Fig 1a).

Conclusions: While target property effects are certainly part of the observed disparity between CSFDs and AMAs on ejecta and melt deposits, they cannot account for the greater population of craters on ejecta, nor for the entire discrepancy between the CSFDs. Auto-secondary cratering could explain these effects, and attention should be focused on a plausible mechanism for auto-secondary formation and the possible contribution of auto-secondary cratering in the current lunar chronology calibration.

References: [1] Plescia et al. 2012 LPSC 43, 1614. [2] Hiesinger et al. 2012 JGR 117, E2. [3] Zanetti et al. 2013 LPSC 44, 1842. [4] Zanetti et al. 2014 LPSC 45, 1528. [5] Xaio et al. 2012 Icarus 220, 254. [6] van der Bogert et al. 2010 LPSC 41, 2165. [7] van der Bogert et al. 2013 LPSC 43, 1962. [8] Dundas et al. 2010 GRL. 37, L12203. [9] Wünnemann et al. 2012 LPSC 43,1805. [10] Melosh 1989 *Impact Cratering*, 245p. [11] Shoemaker et al. 1962 NASA SP184, 19-128. [12] Shoemaker et al. (1969) *in* Surveyor VII Mission Report Part II. *NASA Tech Rept* 32-1265, 9. [13] Kneissl et al. 2010 PSS 59, 1243. [14] Michael and Neukum 2010 EPSL 294, 223. [15] Neukum et al. 2001 Space Sci. Reviews 96, 55. [16] Arvidson et al. 1975 LPSC 7, 25. [17] Bray et al. 2010 GRL 37, L21202. [18] Williams et al. 2014 LPSC 45, 2882. [19] Braden et al. 2014 Nat. Geosci. 7, 787. [20] Dauber et al. 2013 Icarus 225, 506. [21] Oberst et al. 2012 PSS 74, 179.