AN AGE FOR HELL Q FROM SMALL DIAMETER CRATERS.

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Introduction: A study field in the northern continuous ejecta blanket of 4km diameter Hell Q (S33.0°, W4.4°) is used as a case study for detecting secondary impact contamination using statistical analysis of spatial randomness of very small craters (dia. 5m-41m) [Fig 1]. Crater spatial randomness is a pre-condition to using Neukum's lunar production function (NPF) [1-3]. Based on F and G statistical tests for spatial randomness, one crater diameter bin was excluded from absolute modeling age (AMA) estimation. Applying AMA methods of Neukum et al [4-6] to the remaining sample, the age of Hell Q is estimated to be less than 10Ma. This conclusion is consistent with gross visual comparison of Lunar Reconnaissance Orbiter Narrow Angle Camera (NAC) images of Hell Q's blanket and a Tycho melt pond [7-8]; there are fewer impacts in the Hell Q blanket than in the Tycho melt pond. This Hell Q age estimate refines McEwen et al.'s previous estimate of less than 110Ma based on superposition of Hell Q rays over Tycho's rays [9].

Methods: *Data collection.* Small 4-km lunar crater Hell Q and its associated Cassini's Bright Spot feature are the result of an oblique impact evidenced by shape of Hell Q's bright rays. Hell Q's distal rays superpose over the older ejecta blanket of Tycho, *e.g.* – distal ray north of Walter E at S33.0213°, W1.3334°. NAC image M126961088LE provided a high resolution photograph (0.49m) of the 2.2 km by 7.5 km (16.3 km^2) study region in Hell Q's northern continuous ejecta blanket [Fig 1, above the white bar] illuminated by 43.4° incident sunlight [7]. The image was registered and calibrated using U.S. Geol. Serv. Integrated Software for Imagers and Spectrometers (ISIS) utilities (lronac2isis, spiceinit, lronaccal) [10]. A 0.11km^2 zone was excluded based on boulder and ray ejecta contamination. Blanket thickness was estimated at 4.5m-6m from two dark halo craters. 890 craters were measured, and after excluding craters based on secondary impact characteristics of overlapping impact and elliptical shape, 852 candidate primary craters remained [11]. The assumed count error was the square root of the count in each dia. bin [12]. Table 1 shows the cumulative spatial frequency data for those 852 craters. The $5m<D\le7m$ dia. bin was interpreted as the resolution rollover bin, and that bin was excluded from AMA.

Table 1 – Cumulative crater size frequency data by crater diameter (m).

dia>	≤ dia	N	N_{cum}	log(N_{cum}/A km^2)
5	7	117	852	1.720
7	9	476	735	1.650
9	13	190	259	1.200
13	21	57	69	0.627
21	37	10	12	-0.133
37	69	2	2	-0.911

Spatial randomness analysis. Michael et al recommends analyzing craters in each diameter bin for spatial randomness in order to assure that AMA assumptions of the uniformity and independence of crater distributions are satisfied [1-3]. Non-random bins should be excluded from counting, unless geologic reasoning explains the anomaly [1],[13]. Geospatial randomness analysis methods developed by Michael et al [1-3] in *Craterstats* [14] were not used, and instead the less sensitive F and G statistical spatial analysis methods were applied. F and G-statistics on second nearest neighbor ("k2nn") distances, that respectively measure the degree that points in the study field are uniformly dispersed or contain non-random clustering, were computed for random simulated fields within each bin for dia. 5m to 21m and for all 852 craters. Empirical cumulative distribution functions for D_{max} critical value statistics used in a Kolmogorov–Smirnov (KS) test of randomness were determined by simulation. Table 2 summarizes the result of that analysis. By the KS test method, the p-value of the D_{max} test statistic of crater bins in the study field must be ≥ 0.95 in order accept the alternative hypothesis that craters in a diameter bin are spatially distributed non-randomly.

Per Table 2, one testable crater dia. bin ($13m<D\le21m$) was non-random, and the remaining sample of 678 craters were considered reasonable for inclusion in AMA estimation.

Table 2 – Results of Kolmogorov-Smirnov F and G spatial randomness tests - p-values of D_{max} by crater dia. (m).

dia>	≤dia	N	F	G
5	7	117	0.72	0.77
7	9	476	0.36	0.52
9	13	190	0.29	0.66
13	21	57	0.96	0.48
21	37	10	n/a	n/a
37	69	2	n/a	n/a
5	69	852	0.64	0.28

Notes: "n/a" - sample size ≤ 50.

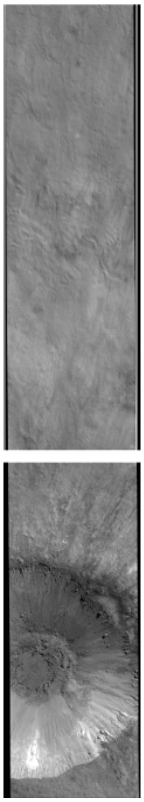

Fig. 1 - Study region north of Hell Q [7].

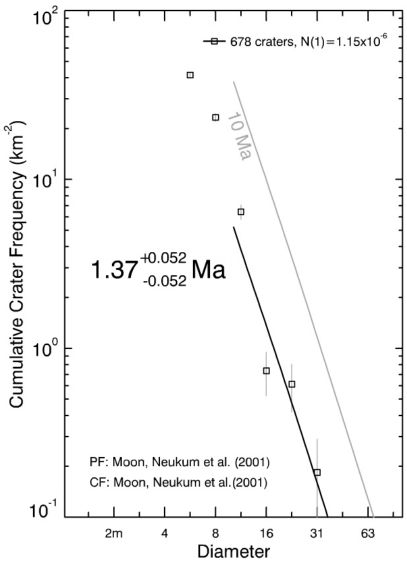

Fig. 2 – AMA for Hell Q per *Craterstats*.

Absolute modeling age. AMA analysis was performed using *Craterstats* on 678 craters with diameters between 7 and 41m, and a cumulative spatial frequency diagram (CSFD) of the results are shown in Fig. 2 [14]. The lower doman limit of NPF is 10m, and curving fitting in Fig. 2 relies extending the domain below < 10m in dia. Extension is justified because the logarithmic best fit line of the data points in Fig. 2 has an R^2 of 0.96. All data points fall below a 10 Ma isochron.

Results: Spatial statistical analysis implies that craters with small diameters between 7m<D≤13m in Hell Q's continuous ejecta blanket are spatially distributed randomly. A non-random bin was detected and excluded. The AMA estimate for Hell Q is less than 10Ma. The *Craterstats* derived point estimate of 1.37 ± 0.05 Ma is considered only a sign that supports an estimated Hell Q age that is less than Tycho's melt ponds. The estimated age of crater Tycho's melt ponds are ~32Ma [15-16], but the accuracy of those estimates and the method of CSFD-NPF age dating are disputed by Xiao and Strom [17].

Discussion: There is a division in the planetary sciences community concerning the viability of the AMA method. Xiao and Strom conclude, using McEwen & Bierhaus's rollover point method on lunar mare, DHC, and melt pond fields, that the wide variation in secondary contamination in those physical settings invalidates application of AMA estimation [17] for small diameter craters. In recent absolute age studies by practitioners of and opponents of the AMA method, researchers did not report spatial statistical analysis results [16, 18-21], [17]. AMA researchers typically used the *Craterstats* analysis package developed at the Instit. for Geosciences of the Freie Univ. of Berlin by Michael et al [1-3, 14]; however, studies do not report applying the spatial randomness utility incorporated in that software [16, 18-21]. Given the lack of current knowledge about secondary impact processes, consistent reporting of crater spatial statistical analysis as demonstrated in this Hell Q case study may help to resolve the "forty-year old lunar controversy" concerning secondary impact contamination and AMA from samples of small diameter craters <100m [22].

Conclusion: In a future article in progress, these findings, the statistical tests applied, current issues surrounding AMA based on craters <100m in diameter, and extension of the NPF below its 10m dia. domain will be discussed in more detail. A second planned article will propose a procedure for estimating the minimum study field size needed for NPF-AMA estimation.

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