THE RECENT ATMOSPHERIC HISTORY OF MARS DERIVED FROM SMALL CRATERS OBSERVED BY MSL. M. E. Hoffman[1], H. E. Newsom[1], B. M. Adair[1], J. M. Comellas[1], J. M. Williams[1], J. P. Williams[2], F. J. Calef [3], J. A. Grant[4], R. C. Wiens[5], S. Le Mouélic[6], and K. Escarcega[1], [1]Univ. of New Mexico (mehoffman13@unm.edu), [2]Univ. of Los Angeles, [3]JPL/Caltech, [4]Smithsonian Inst., Washington, DC, [5]Los Alamos National Lab, [6]Univ. of Nantes, FR

Introduction: The obliquity of Mars has experienced semi-periodic, quasi-chaotic fluctuations resulting in atmospheric density fluctuations throughout the history of the planet [1], [2]. During periods of high obliquity, the Martian poles are exposed to sunlight for an extended amount of time, which allows for CO_2 ice to sublimate and contribute to the density of the atmosphere. During periods of low obliquity, the reverse happens and more CO_2 is frozen out of the atmosphere reducing the atmospheric density. Evidence of these fluctuations has been recorded in the layered deposits of the Martian poles [3]. Small craters can provide another geologic record of recent atmospheric fluctuations caused by Martian obliquity changes [2]. The frequency of small craters on the Martian surface can determine how the atmosphere has evolved over the lifespan of the small craters. We are reporting here the improvements to the data since the work of Hoffman et al. [4], [5].

Methods: This study was conducted to catalog small craters observed by MSL and to find the smallest observable crater. Most craters were identified with OnSight, an augmented reality tool composed of black and white Navcam images and color Mastcam images from the mission. OnSight can be used as a web version or a 3D HoloLens headset version. The 3D headset was a valuable tool for identifying small circular depressions. Questionable candidates we analyzed with Midnight Mars, a program that provides anaglyphs of Navcam and Mastcam images from the mission. If a candidate appeared to be a circular, bowl-shaped depression in the anaglyph, then it was considered to be a strong crater candidate. If a crater candidate was still hard to distinguish, a topographical profile was drawn with Analyst Notebook, another tool to analyze images from MSL, to determine if there was a circular depression. If a crater candidate remained questionable at this stage, it was not included in the final catalog. Once a crater was identified, it was measured with the ruler tool in OnSight. Each crater candidate was measured rim-to-rim along the short and long axis to obtain a mean diameter and eccentricity. Candidates with an eccentricity below 0.7 were removed as probable secondaries, or impacts formed from ejected material from another impacts.

Crater Mechanics: Objects that interact with an atmosphere experience some degree of deceleration, ablation, and possibly fragmentation as they exchange energy with the atmosphere [6], [7]. The small objects that result in $D < 5$ m primary impact craters are greatly influenced by deceleration and ablation but are less likely to experience fragmentation [7], [8]. Fragmentation could result in primary crater clusters, but the smallest objects that form $D < 5$ m craters are generally more homogenous, contain less fracturing, and have a greater bulk strength, so they are far less likely to fragment [7]. Most small projectiles are decelerated to speeds below hypervelocity or ablate completely before they can impact the surface [7]. There are still projectiles that can survive and impact with enough speed to form a small $D < 5$ m hypervelocity primary impact crater. Atmospheric effects are dependent on the composition of the projectile. For the current atmospheric conditions on Mars, the smallest primary crater predicted to be able to form is $D = 25$ cm [7], [9], [10].

Crater Catalog: Over the first 2300 sols, from the start of the mission through the Vera Rubin ridge, a total of 160 craters were found along the traverse. Of the 160 total craters, 28 were $D < 1$ m and 5 were $D < 0.5$ m. The smallest crater identified was $D = 0.33$ m (figure 1).

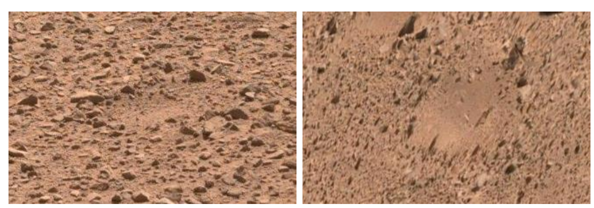

Figure 1. left) Mastcam image of the smallest crater observed along the traverse $D = 0.33$ m, 9.8 meters from the rover at azimuth 288° **right)** vertical projection of the same crater.

There were several areas across the traverse where craters were difficult to confidently identify, usually because they were heavily eroded, there was limited imagery, or the terrain was too rough. The catalog is considered to consist of small primary impact craters as opposed to secondary craters. The craters from this catalog are mostly circular and are assumed to be young enough that evidence of rays, clustering, or other secondary effects could be present if they were secondary impact craters [11], [12]. There is still continuing debate in the literature on how secondary craters influence crater statistics, especially at the crater diameter range of this study [11], [13]. Craters that were suspected of being secondaries were not included, however it is still very difficult to differentiate between distant secondaries and primary impacts.

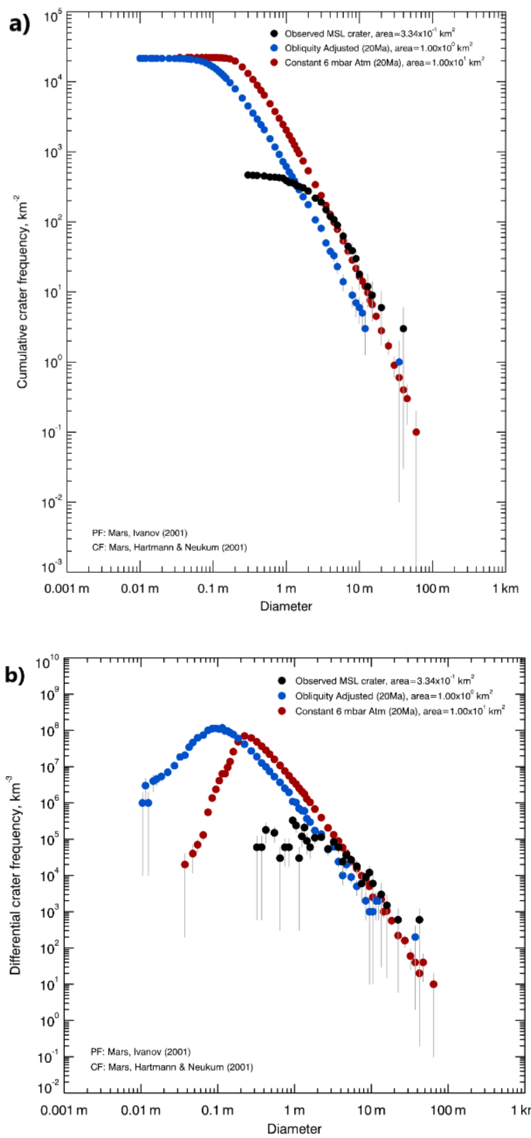

Figure 2. **a)** The cumulative crater frequency of the craters observed by MSL (black) over an area of 334,029 m^2 compared with simulations of a 6 mbar average Martian atmosphere propagated for 20 Ma (red) and of a Martian atmosphere varying in pressure with obliquity over 20 Ma (blue) [Williams et al., (2018)]. **b)** The differential crater frequency of the craters identified along the traverse compared with the same simulations. The turnover of crater frequency occurs at D = 0.93 m and the smallest craters appear to fall off similar to the obliquity adjusted scenario. Plots from Craterstats 2 [15].

Atmospheric Fluctuations: If the atmosphere of Mars has experienced fluctuations over the lifetime of the smallest craters, then it should be reflected in the crater frequency distribution [2], [14]. According to Laskar et al., (2004), the obliquity of Mars reached angles greater than 40 degrees as recently as 5 million years ago, which could result in atmospheric pressures of 100 mbar. The crater statistics of this study were compared to simulated statistics from Williams et al., (2018) which sought to understand how the recent obliquity and atmospheric fluctuations effected the crater size frequency distribution (figure 2).

Erosion Rates: The crater catalog can provide insight into the atmospheric history of Mars only as long as the smallest craters can survive at the surface. Current estimates predict that centimeter-sized craters can survive at the surface for 20 million years [14], [16]. There is still work to be done to understand current erosion rates and how they affect the crater statistics. The more gentle turnover of crater diameter distributions at D = 0.93 m from the differential crater size distribution could be the result of eroded craters not being counted. The texture and roughness of the terrain may also be influencing the amount of small observable craters. The target density encountered is possibly changing as the rover travels to new geologic units. Craters may be harder to identify when there are numerous rock fragments present due to erosion, or when the rocks are comparable or larger than the impactors, the impact energy might contribute to fragmenting the rock rather than forming craters. An increase rock abundance might cause the suppression of small crater formation [17].

Conclusions: There have be 160 craters observed by MSL over the first 2300 sols. The size frequency distribution illustrates that there are fewer than predicted small submeter diameter craters for the current Martian atmospheric conditions. However, the crater catalog maybe influenced by erosion of craters, imaging limitations, and the specific characteristic of the target terrain. It is still plausible that the data support a that Mars had a denser atmosphere over the last 5 to 20 million years.

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