EVIDENCE OF OBLIQUITY DRVEN CLIMATE FLUCTUATIONS ON MARS FROM SMALL CRATER SURVEYS

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Introduction: The obliquity, or axial tilt of Mars has been theorized to fluctuate quasi-chaotically over semi-periodic timescales [1]. Modeling the obliquity history of Mars for the most recent 20 Ma is supported by measurements of the layered deposits at the Martian poles [2]. For timescales beyond 20 Ma, the obliquity fluctuations become increasingly chaotic and impossible to predict without additional constraints.

Fluctuations in the Martian obliquity result in changes in the atmosphere as the CO_2 ice reservoir at the poles (largely concentrated at the south pole) is coupled with the predominantly CO_2 Martian atmosphere [2] (Figure 1). At higher angles of obliquity, >40 degrees, the Martian poles experience higher amounts of solar insolation. This results in greater sublimation of the CO_2 ice at the poles, which increases the amount of atmospheric CO_2 and causes an increase in the atmospheric pressure and density. At lower obliquities, <40 degrees, the poles experience less solar insolation and are able to accumulate CO_2 ice at the poles. This scenario results in more CO_2 being removed from the atmosphere, which will cause a decrease in the overall atmospheric pressure and density. At more extreme angles >65 degrees, ice begins to be deposited at the mid latitudes; however, the obliquity is thought to be <45 degrees for the last 20 Ma, so this scenario will not be considered here.

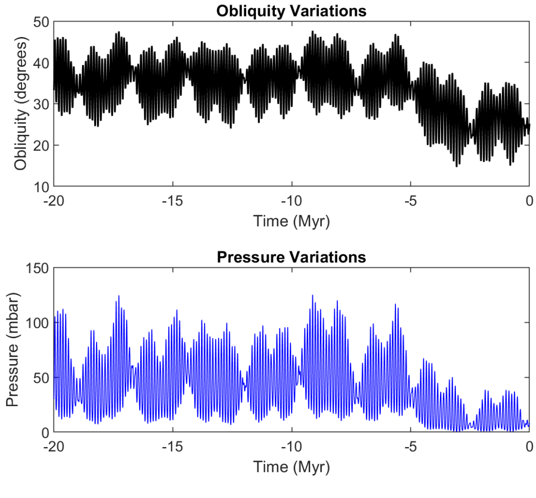

Figure 1. Obliquity angle (degrees) vs. time (Myr) as determined by Laskar et al., (2004) for the last 20 Myr (top) and the corresponding pressure (mbar) for obliquity from Williams et al., (2018).

The changes in obliquity and resulting changes in atmospheric pressure can be seen indirectly through geologic features such as small impact craters. For the present-day Martian atmosphere, the limit for the diameter of the smallest crater that can form at the surface is theorized to be $D \approx 0.25$ m [3,4,5]. Understanding the population of small decimeter- to decameter-diameter craters will lead to improved interpretations of the recent Martian atmospheric pressure.

Cratering Mechanics: Incoming projectiles from space that encounter a planetary atmosphere endure some degree of ablation, where material from the projectile is vaporized and removed, and deceleration, where the projectile is slowed by the atmosphere [5]. Additionally, some projectiles experience fragmentation, where one projectile may break apart into several separate projectiles, often resulting in multiple, or clustered, impact craters forming at the surface [5,6].

The atmospheric pressure of Mars is less than 1 percent of the Earth's, but it is still able to filter out and remove small projectiles intersecting the orbital path of Mars. Smaller projectiles are more susceptible to ablation and deceleration as these projectiles have a larger surface area to volume ratio [5]. Smaller projectiles are also less likely to experience fragmentation, but possible fragmentation events will still need to be considered [6,7].

Crater Catalog: The best resolution of HiRISE orbital imagery is approximately 25cm/pixel. This resolution is not sufficient to accurately resolve the smallest craters at the surface. Using imagery taken from rovers at the surface provides detailed context of possible small crater candidates (Figure 2). An extensive survey of the Mars Science Laboratory (MSL) Curiosity rover traverse through the first 2300 sols of the mission (through the completion of the Vera Rubin ridge campaign) was conducted to compile a catalog of small craters [8,9]. Additionally, a survey of the first 500 sols of the Mars Exploration Rover (MER) Spirit rover traverse was conducted to compile a crater catalog of the Gusev Plains and the start of the Columbia Hills region [10].

The MSL Curiosity survey found 198 craters throughout the first 2300 sols of the traverse. There were fewer than expected $D < 1.0$ m craters, and the smallest crater found was $D = 0.33$ m [8,9]. Vasavada et al., (1993) predicted an abundance of small cm-

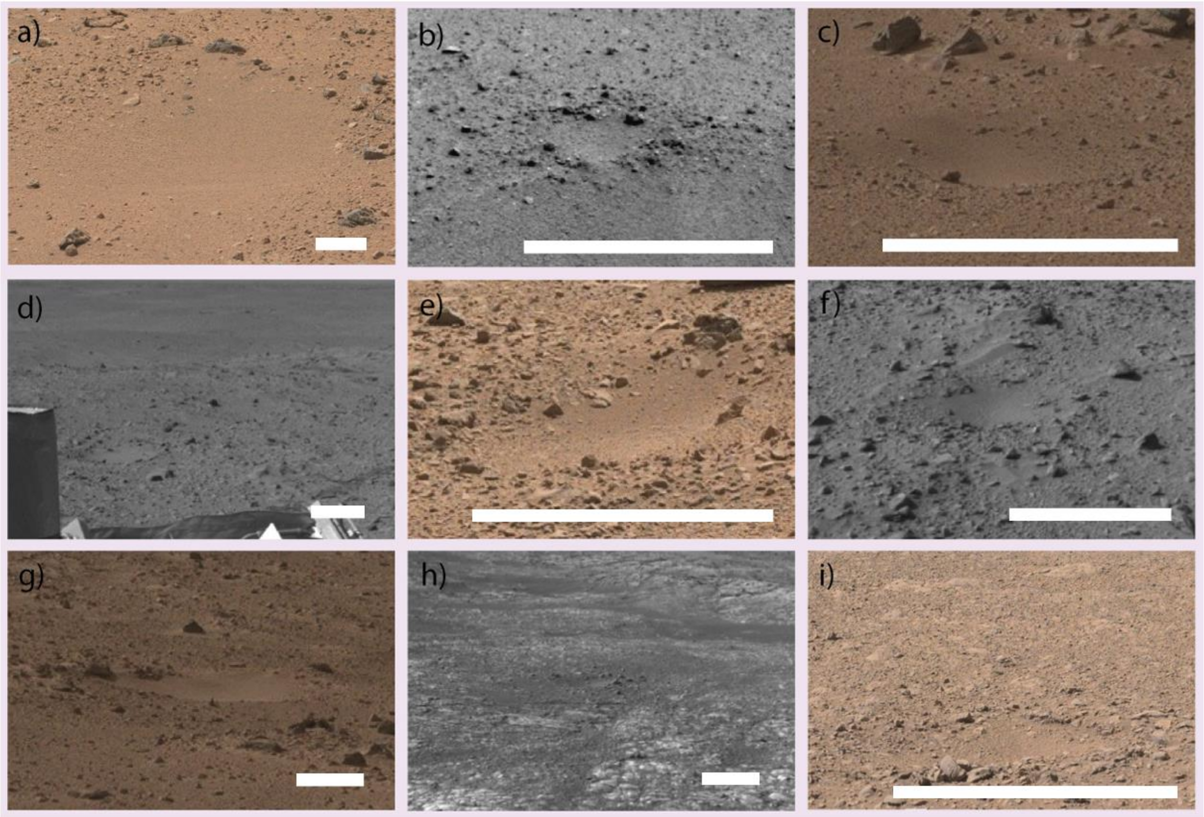

Figure 2. Nine examples of small craters seen throughout the MSL mission. Images are from the Navcam (black and white) and Mastcam (color) instruments. Each white bar corresponds to an approximate length of 1.0 meter.

size craters across the Martian surface [11]. Over the first ~20 km of the Curiosity traverse, there were only five $D < 0.50$ m craters discovered. There is an overall lack of cm-sized craters found at the surface at Gale crater.

The MER Spirit rover survey found and documented a total of 267 small craters [10]. The smallest crater measured was $D = 0.23$ m, making it the smallest crater observed from the combined MER and MSL catalogs thus far. Almost 80 percent of the total small craters in this Spirit survey were found within the first 155 sols of the traverse [10]. This portion of the traverse was noticeably flatter and smoother, allowing the Spirit rover to traverse greater distances in less time. Additionally, the flat terrain allows for unobstructed crater formation and for such craters to be identified more easily.

Erosion Rates: The small crater populations gathered from each of the rover traverses can only provide insight into the behavior of the recent Martian atmosphere for the lifetime of the craters. Erosion rates on Mars can be orders of magnitude slower than on Earth. Eventually, the small craters will be removed by aeolian processes eroding down the rims or infilling the central depression with fine material.

Bridges et al., (2012) estimated rates on the order of 10-50 m/Myr for saltation processes eroding bedrock from analyzing the active dune field from Nili Patera [12]. Golombek et al., (2014) determined erosion rates from studying small craters along the Opportunity rover traverse in Merdiani Planum to be ~1m/Myr for recently formed craters <1 Ma and ~ <0.1m/Myr for older craters 10–20 Ma [13]. Grant et al., (2022) used measurements from the 27 m-diameter Homestead hollow, where the InSight lander is located, to find degradation rates within the hollow to be 10^{-4} m/Myr for regolith-covered lava plains [14]. The InSight lander is located in Elysuim Planitia, just 600 km to the north of Gale crater. Newsom et al., (2015) analyzed small craters and blocks within the first 360 sols of the Curiosity traverse and estimated aeolian erosion rates on the order of ~0.01m/Myr from crater counts [15]. Golombek et al., (2006) estimated average erosion rates for the Columbia Hills portion of the Spirit traverse to be $\sim 3*10^{-5}$ m/Myr by analyzing small craters [16].

There are a wide range of erosion and degradation rates across Mars that reflect different erosional processes on regional environments (Table 1). The slower rates at Gale and Gusev reflect a slow deflation by aeolian processes that have likely persisted in these locations for over a billion years [14,15,16].

Using these rates and known cratering mechanics

	Rate of Erosion (m/Myr)	Location	Associated Rover/Lander
Bridges et al., (2012)	10 - 50	Nili Patera	
Golombek et al., (2014)	1.0	Merdiani Planum	Opportunity rover (MER-B)
Grant et al., (2022)	10^{-4}	Elysium Planitia	InSight lander
Newsom et al., (2015)	0.01	Gale crater	Curiosity rover (MSL)
Golombek et al., (2006)	$3x10^{-5}$ - 10	Gusev cratered plains	Spirit rover (MER-A)

Table 1. Erosion/degradation rates (m/Myr) for various locations across Mars along with the corresponding studies and the rover/lander associated with each location, if applicable.

for approximate depth to diameter ratios [17], it would take approximately 20 Myr to fill a 1.0 m diameter crater along the Bradbury Group at Gale crater and approximately 600 Myr to fill a 1.0 m diameter crater along the Gusev plains. The slower erosion rates at the Gusev plains could be contributing to the increase in the number of small craters identified along the Spirit traverse as the craters would have longer lifespans before being infilled and removed from the crater record (Figure 3).

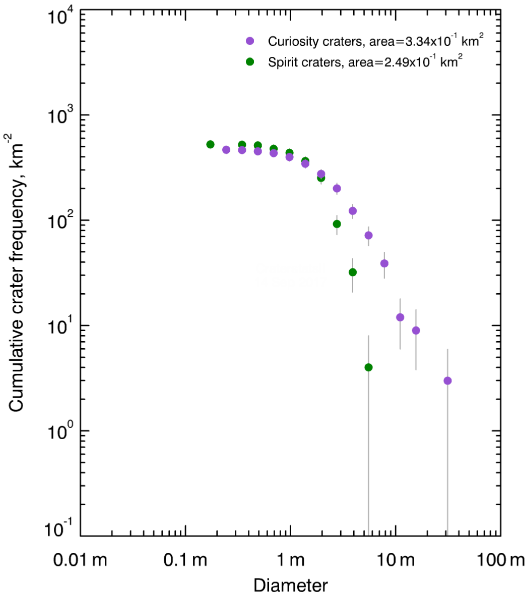

Figure 3. A cumulative crater frequency distribution for the Curiosity and Spirit rover traverse surveys. The Spirit craters (green) show a higher accumulation of $D < 1.0$ m craters, likely the result of slower degradation rates at the Gusev Plains. All cratering plots were made in CraterStats 2.0 [19].

Under present conditions on Mars, the smallest crater at Gale crater could survive for at least 5 Myr, meaning that the decimeter- to decameter-scale crater catalog from the Curiosity and Spirit traverses are likely to be reflective of the last 20 Myr of the atmospheric history or longer. These small crater populations could provide additional evidence to support an atmospheric pressure increase corresponding to increased obliquity angles as illustrated by Laskar et al., (2004).

Atmospheric Modeling: A previous study of small crater production at the surface of Mars was conducted by Williams et al., (2018) to find a noticeable shift in cratering for possible obliquity induced atmospheric pressure changes [7]. Williams et al., (2018) used insolation and temperature equations from Ward et al., (1974) to estimate the atmospheric pressure increase from sublimating CO_2 at the poles experiencing higher solar insolation at higher past obliquities [7,18]. For present conditions, Mars has an average global pressure of ~6mbar, which allows for greater production and retention of small craters at the surface [7,11]. For an obliquity adjusted scenario, the atmospheric pressure increases, which allows for a greater degree of filtering by the atmosphere and reduces the number of small impactors that make it to the surface with enough speed to form an impact crater [7].

For generalized Martian conditions and cratering production rates, Williams et al., (2018) modeled the cumulative crater frequency distributions for a constant 6 mbar atmosphere and an obliquity adjusted atmosphere modeled for 20 Ma over 1.0 km^2 as seen in figure 4 [7].

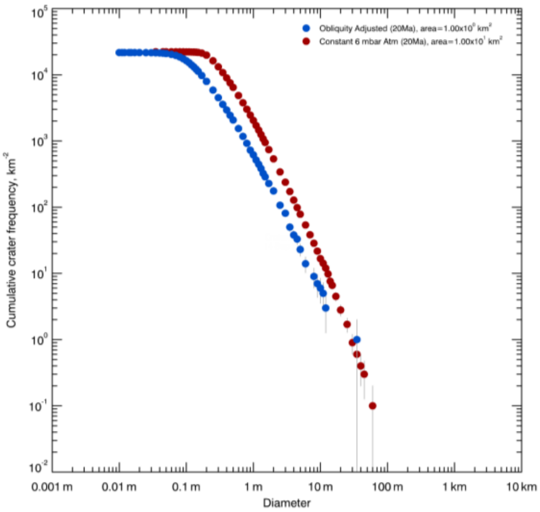

Figure 4. A cumulative crater frequency distribution from Williams et al., (2018) demonstrating a shift in small crater production for a hypothetical atmospheric scenario where atmospheric pressure is aloud to vary with obliquity. The obliquity adjusted craters (blue) show decreased production than the scenario of a constant 6 mbar Martian atmosphere (red) for 20 Ma.

The obliquity adjusted model illustrates a decreased crater production when compared to a constant 6 mbar Martian atmosphere.

The small crater catalogs from the two rover traverses can be compared to modern cratering rates as measured by Daubar et al., (2013). Using erosion rate estimates and approximate crater resurfacing calculations of ~50 Ma for the Curiosity craters and ~500 Ma for the Spirit craters, both catalogs can be compared to the empirical global Martian production function [6,17]. The resulting cumulative size-frequency plot is shown in figure 5.

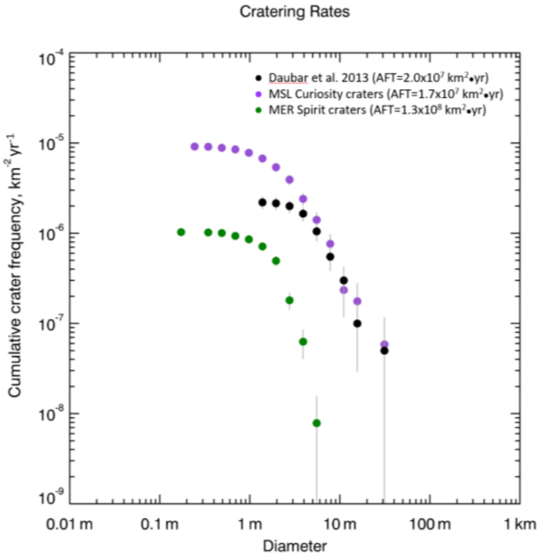

Figure 5. Cumulative size–frequency diagram of the current empirical global Martian production rate (black) from Daubar et al., (2013) scaled to the area-time function discussed in [6] and the Curiosity (purple) and Spirit (green) crater production functions estimated from multiplying the survey areas by the small crater lifespans determined from local degradation rates. Craters are in √2 diameter bins.

The current production rate calculated by Daubar et al., (2013) was determined by observing new impacts in before and after CTX imagery and is therefore unable to resolve craters smaller than $D \geq 2.0$ m [6]. The Curiosity craters indicate a cratering rate at Gale crater that is similar to modern estimates, but the Spirit craters indicate a much slower cratering rate at Gusev. These results illustrate the regional dependance of crater formation and retention across Mars. The increased erosion rates at Gale crater may be removing information about past atmospheric properties, while Gusev may show evidence of slowed crater production due to an increase in atmospheric pressure resulting from a prolonged increase in the Martian obliquity starting ~5 Ma (Figure 1). It is still important to use caution when comparing datasets of small craters from across Mars as there are many variables involved in crater formation and retention [6].

Conclusions: Observational, small crater surveys from the surface of Martian rover traverses can be used to compare with modern cratering rates and theoretical models for cratering productions to determine constraints on recent Martian atmospheric fluctuations driven by changes in obliquity. Small crater frequency distributions serve as an indirect geologic proxy for changes in the Martian atmosphere. Future work will be conducted to refine the theoretical crater production and retention rates for Gale crater and the Gusev Plains, accounting for their respective elevations and rates of degradation.

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