CONSTRAINTS ON RIPPLE MIGRATION AT MERIDIANI PLANUM FROM OBSERVATIONS OF FRESH CRATERS BY OPPORTUNITY AND HiRISE.

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Introduction: The plains surface that Opportunity has explored is dominated by granule ripples composed of a surface lag of 1-2 mm diameter hematite spherules (called blueberries) underlain by a poorly sorted mix of fine to very fine basaltic sand [1, 2]. The granule ripples vary from small (cm size) near the landing site to much larger (m sized) to the south. The largest granule ripples are found in terrain with frequent pavement outcrop 3-4 km north and south of Victoria crater and its smooth annulus. In these regions, the largest and best developed ripples trend mostly north and appear older and more cohesive than younger cohesionless ripples that trend northeast [2]. In this paper, we constrain the age of the most recent phase of migration by the older north-trending granule ripples from Opportunity observations of a fresh crater cluster and High Resolution Imaging Science Experiment (HiRISE) observations of two fresh-rayed impact craters on Meridiani Planum.

Fresh Crater Cluster: On sols 1818-1854 Opportunity explored a cluster of very fresh craters, informally named the Resolution crater cluster (after the first crater explored about 2.5 km southwest of Victoria crater. The cluster consists of about 50 craters, of which the 4 largest are about 5 m diameter (informally named Resolution, Adventure, Discovery and Granbee), that are scattered across a 140 by 100 m area. Based on their morphology in the HiRISE images, the craters appear to be the freshest visited up to that time by the rover.

Observations by Opportunity confirm that the craters are younger than the ripples. Pristine ejecta blocks are superposed on the ripples with minimal eolian modification. Depth/diameter measurements in stereo Navcam images of 29 craters 0.2-6 m diameter observed by Opportunity show depth/diameter ratios of around 0.1, which is about half that observed for other fresh crater clusters [3].

The spatial distribution of this cluster appears similar to others that have formed in the past 20 years from repeat imaging [4]. Modeling by Ivanov [5] shows these clusters form when weak projectiles fragment in the atmosphere, with the dispersion of the cluster being related to its density and strength. Analysis of the dispersion of the Resolution cluster suggests the impactor had a density of about 2 g/cm^3. Many of the larger craters have small dark pebbles scattered across their surfaces, which because of the youth of the craters are most likely fragments of the impactor. This observation suggests that the dark pebbles and cobbles observed by Opportunity are a lag of impactor derived material that is either meteoritic (exogenic) or from elsewhere on Mars (i.e, ejecta, Bounce Rock, Marquette Island [6]).

Two Fresh Rayed Craters (with distinct rays in thermal images [7, 8]) near Opportunity also have clear age relationships with the granule ripples of Meridiani Planum. One 2.25 km diameter rayed crater, Ada, is about 150 km east-southeast of Opportunity. About 6 km to the south-southwest of Ada, its secondaries are clearly superposed on granule ripples similar to those Opportunity has traversed (Fig. 1). Therefore, Ada is younger than the latest phase of granule ripple migration at Meridiani Planum.

An unnamed 0.85 km diameter rayed crater about 40 km west of Opportunity also appears fresh, except that about 9 km to the south, its secondaries have non-circular shapes with ripples that merge with and overprint the crater rims (Fig. 1). Secondaries from this crater clearly have been modified and deformed by the ripples, so this 0.85 km diameter crater is older than the latest phase of ripple migration at Meridiani Planum.

Age of Ripple Migration: Three methods were used to estimate when the latest phase of ripple migration occurred at Meridiani Planum as bracketed by younger small craters, like the Resolution cluster and by the two fresh rayed craters. The first method is a

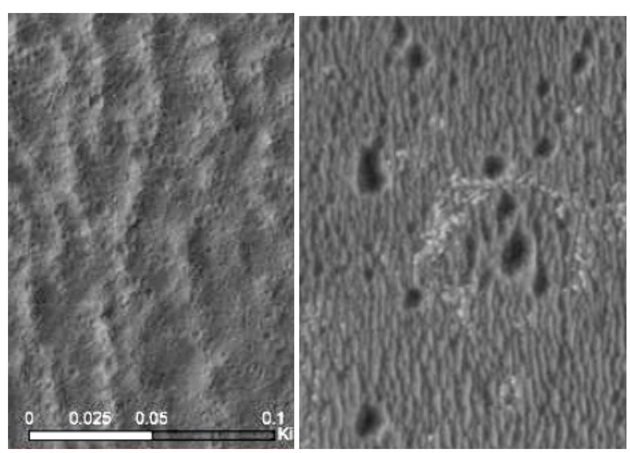

Figure 1: HiRISE images (at about the same scale) of Ada secondaries that are superposed on Meridiani ripples (left) and 0.85 km diameter crater secondaries that have been modified by Meridian ripples.

count of all craters superposed on the ripples in a 23 km^2 area of the southern portion of HiRISE image PSP_1414_1780. We identified craters with rims that are circular, unbroken and superposed on ripple crests, with ejecta blocks on top of the ripples, with crater rims unaffected by nearby ripples (undeformed), and without eolian deposits. We measured the diameter of 8 craters (1.5-12 m diameter), two of which were clusters, for which we calculated an effective diameter using $D_{eff}=(\Sigma D_i^3)^{1/3}$ [5], which defined an age of ~100 ka [9]. Because these craters are superposed on the ripples, the ripples were last active prior to 100 ka.

The second method measured the craters superposed on the continuous ejecta blankets of the two fresh rayed craters that bracket the latest phase of ripple migration. We surveyed the continuous ejecta (within 1 crater radii of the rims) of both craters to distinguish only the freshest craters that formed after the continuous ejecta blanket was deposited [e.g., 10]. We found 3 craters (4-6 m diameter) and 5 craters (2-7 m diameter) on the continuous ejecta blankets of Ada and the 0.85 km diameter craters, respectively. These counts yielded ages of ~100 ka for Ada and ~300 ka for the 0.85 km diameter crater. Because these two craters bracket the latest ripple migration, their ages indicate the latest phase of ripple migration occurred between 100 ka and 300 ka.

The third method estimated the recurrence intervals for the freshest 0.5-5 km diameter craters in the equatorial region of Mars of which Ada and the 0.85 km diameter Meridiani craters are members. We classified the relative age of the 32 freshest 0.5-5 km diameter craters that have been identified in THEMIS thermal and HiRISE images of Mars within 30° of the equator based on the amount of eolian modification. In this classification, Ada is the youngest 2.2-4 km and the 0.85 km diameter crater is the 5^{th}-13^{th} youngest 0.85-4 km diameter crater in the equatorial region of Mars. Because rayed craters are found preferentially on thermal inertia and albedo Unit C [8], we classified the thermal inertia and albedo of the 32 craters and found 17 in Unit C, 11 in Unit B and 4 in Unit A (50-320 of [11] and 70-330 J m^{-2} K^{-1} $s^{-½}$ of [12], with an albedo of 0.1-0.27, which corresponds to about 60% of equatorial Mars. We then took the Hartmann production function as reported in Ivanov [13], multiplied times 60% of the equatorial area of Mars, divided by 3.4 Ga, and inverted to get the recurrence interval.

The calculated recurrence interval for 2.2-4 km diameter craters is ~400 ka and because Ada is the youngest crater of this size range, it formed in the past ~400 ka, which is consistent with the ~100 ka age for Ada derived from craters on its continuous ejecta. The calculated recurrence interval for 0.8-4 km craters is ~30 ka, indicating that the 0.85 diameter rayed crater in Meridiani formed before ~120 ka and after ~400 ka, which is also consistent with the age determined from craters on its continuous ejecta.

Summary/Conclusions: All three methods indicate the latest phase of ripple migration at Meridiani Planum occurred between ~100 ka and ~300 ka. This also suggests that the ripples have been inactive for the past ~100 ka. The apparent bedding in the large north-south oriented ripples and the observation that ejecta around craters is planed off along the ripple bedform are also consistent with the relative stability of the ripples [2]. Finally, Zimbelman [14] measured granule ripple migration at Great Sand Dunes National Park after a wind storm and scaled that motion to Mars based on the frequency of high wind speeds at the Viking landers. Results suggest that migrating a 25 cm high ripple about 1 cm on Mars should take roughly hundreds to thousands of years. In this extrapolation, migrating Meridiani ripples of order 1 m to overprint secondary crater rims would take tens to hundreds ka, which is also consistent with our estimates for the relative antiquity of Meridiani ripple migration.

The inactivity of the ripples over the past ~100 ka at Meridiani is also consistent with the lack of observed eolian bedforms in craters that formed in the past 20 yr, the dearth of evidence for the motion of dunes and other bedforms in the past 30 yr [e.g., 15], and the exceeding low long-term erosion rates determined for the Amazonian and Late Amazonian at the landing sites [e.g., 16]. Interestingly, ~100 ka is the timescale for most recent obliquity variations and changes in insolation on Mars [17], which suggest that changes in climate (including winds) could be responsible for the relative inactivity in eolian processes during the past ~100 ka.

References: [1] Soderblom, L. et al. (2004) *Science 306*(5702). [2] Sullivan R. et al. (2005) *Nature 436|7*. [3] Daubar I. & McEwen A. (2009) *LPSC 40*, #2419. [4] Malin M. et al. (2006) *Science 314*, 1573-1577. [5] Ivanov B. (2008) *LPSC XXXIX*, #1221, (2009) *LPSC 40*, #1410. [6] Mittlefehldt D. et al., this conference. [7] McEwen A. et al. (2005) *Icarus 176*, 351–381. [8] Tornabene L. et al. (2006) *JGR 111*, E10006. [9] Hartmann W. (2005) *Icarus 174*, 294–320. [10] Kreslavsky M. (2009) *LPSC 40*, #2311. [11] Mellon M. et al. (2000) *Icarus 148*, 437– 455. [12] Putzig N. et al. (2005) *Icarus 173*, 325–341. [13] Ivanov B. (2001) *Space Sci. Rev. 96*, 87–104. [14]Zimbelman J. (2009) *Icarus 203*, 71–76. [15] Malin M. & Edgett K. (2001) *JGR 106*, 23429–23570. [16] Golombek M. et al. (2006) *JGR 111*, E12S10. [17] Lasker J. et al. (2002) *Nature 419*, 375-377.