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# Modification of secondary craters on the Martian South Polar Layered Deposits

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[1] Secondary crater fields are important stratigraphic markers that can shed light on resurfacing processes that have occurred since their formation. We examine the morphologies of secondary craters formed from the ejection of material from two large impacts on the Martian South Polar Layered Deposits (SPLD): McMurdo crater at 84.5°S, 0°W, and an unnamed impact at 80.8°S, 284°W. The morphologies of these secondary craters allow us to impose constraints on the modification history of the SPLD. We have quantified crater morphologies using data sets from the Mars Global Surveyor and Mars Odyssey missions. We find a complete lack of secondary craters smaller than 300 m in diameter in both crater fields, which implies that at least the upper 30 m of the deposits have been resurfaced since the time of these impacts. Secondary crater depth-to-diameter ratios are low (average of 0.016), indicating that significant degradation has occurred since their emplacement. We find that vertical resurfacing alone is not enough to explain the observed depth-to-diameter distribution and suggest that viscous relaxation of craters coupled with a small amount of vertical resurfacing best fits the data. In the McMurdo field, high depth-to-diameter craters are found preferentially on steeper terrain associated with scarps cutting through the secondary field. This observation suggests that crater modification exhibits a dependence on slope. We comment on possible mechanisms that may explain this observation. The morphologies of secondary craters on the SPLD point to modification processes without lunar parallel and not yet fully modeled for Mars.

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## 1. Introduction

[2] Understanding the formation and evolution of the Martian South Polar Layered Deposits (SPLD) are important steps toward unraveling Mars' complex climate history. The SPLD are Amazonian-aged deposits up to a few kilometers thick that overlie older Hesperian highlands and the Prometheus impact basin (Figure 1). Parts of the surface of the SPLD are covered by the South Polar Residual Cap which is a permanent thin veneer of bright $CO_2$ frost [*Kieffer*, 1979] that overlies the central part of the SPLD (Figure 1). The SPLD are thought to be composed of a mixture of water ice and dust [*Mellon*, 1996; *Durham et al.*, 1999; *Nye et al.*, 2000; *Boynton et al.*, 2002]. The numerous scarps and troughs cutting through the surface of the SPLD reveal extensive laterally continuous layers, the rhythmic nature of which is believed to result from variations in Mars' orbital parameters [*Murray et al.*, 1972; *Toon et al.*, 1980; *Ward and Rudy*, 1991]. This paper will develop constraints on the surface modification history of the SPLD by quantitatively examining the morphologies of two secondary crater populations on the deposits (McMurdo Crater at 84.5°S, 0°W and an unnamed crater at 80.8°S, 284°W hereafter referred to as "Crater II"). The term "secondary crater" is used here to refer to craters adjacent to and created by the ejection of material from a primary, hypervelocity impact.

[3] The modification history of the SPLD can be constrained by crater count studies. Using Viking imagery, *Plaut et al.* [1988] identified 15 "likely" impact craters with diameters $D > 0.8$ km within a region covering approximately 80% of the area of the SPLD. *Herkenhoff and Plaut* [2000] used these statistics to calculate a crater retention surface age of 14.5 ± 7.2 Ma assuming a "nominal" cratering rate (2 times the lunar value) or 7.25 ± 3.6 Ma assuming a "high" cratering rate (4 times the lunar value). This age may reflect the timing of a

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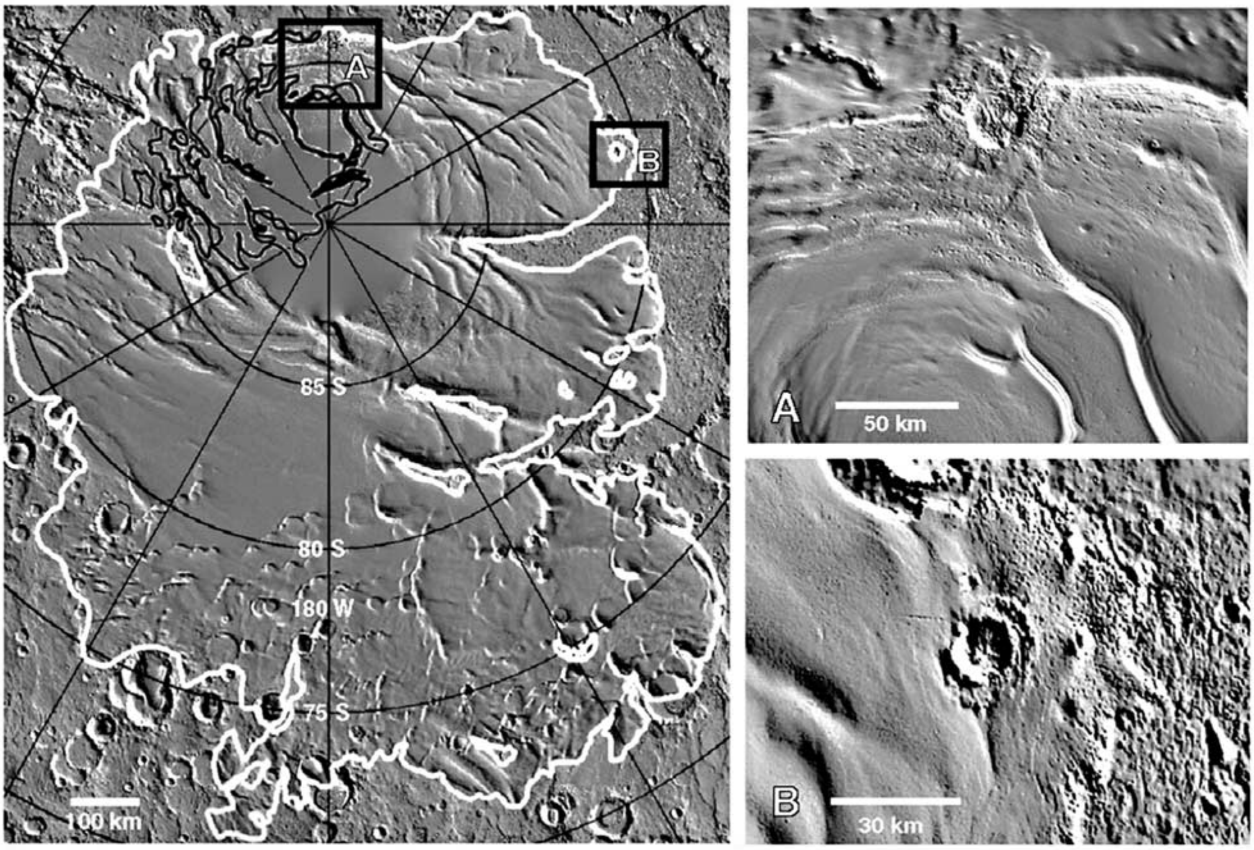

**Figure 1.** MOLA shaded relief map of the South Pole of Mars. Outlined in white is the mapped boundary of the South Polar Layered Deposits [*Kolb and Tanaka*, 2001]. The black outlined region is the location of the $CO_2$ residual cap. Black boxes show the locations of the two secondary crater fields: (a) McMurdo crater (84.5°S, 0°W) and its secondary crater field. (b) Crater II (80.8°S, 284°W) and its secondary crater field.

catastrophic SPLD-wide resurfacing event, or, alternatively, the observed SPLD crater distribution could result from ongoing resurfacing that predates the crater retention surface age [*Herkenhoff and Plaut*, 2000].

[4] *Koutnik et al.* [2002] examined Mars Orbiter Laser Altimeter (MOLA) topographic data throughout a $5.4 \times 10^5$ $km^2$ subregion of the SPLD and identified 36 "likely" craters in the diameter range 0.8 km $< D <$ 3.2 km, corresponding to a much older crater retention surface age of 100 Myr or an average resurfacing rate of 2.9 m/Myr (assuming the crater production function of *Hartmann* [1999]). Additionally, these SPLD craters are extremely shallow, with mean depth-diameter ratios of $d/D = 0.015$ [*Koutnik et al.*, 2002] that are well below the average $d/D = 0.18$ measured for fresh $D = 2$ km Martian craters by *Garvin et al.* [2003]. *Pathare et al.* [2005] showed that the size and depth distributions of SPLD craters are consistent with a modification history predominantly governed by viscous relaxation of the dusty water ice comprising the SPLD, along with relatively slow vertical resurfacing at an average rate of 0.2 m/Myr. *Pathare et al.* [2005] also noted the presence of five large $D > 8$ km impact events at the periphery of the SPLD which they inferred to be indicative of a much older crater retention surface age of at least 220 Myr. For example, a crater as large as McMurdo ($D = 23$ km) would be expected to impact a region as large as the SPLD an average of once every 300 Myr [*Pathare et al.*, 2005].

[5] Observations of the smallest SPLD craters ($D <$ 800 m) imply extraordinarily young surface ages [*Koutnik et al.*, 2002; *Murray et al.*, 2003]. *Murray et al.* [2003] examined Mars Orbiter Camera (MOC) and Thermal Emission Infrared Spectrometer (THEMIS) visible images partially covering the SPLD. They identified just 129 craters with diameters greater than 100 m, corresponding to a crater retention surface age of $10^5$ to $10^6$ years. For comparison, an unmodified 100 Myr old surface as large as the SPLD should have well over 100,000 impact craters larger than $D = 100$ m (according to the production function of *Hartmann* [1999]). To explain the observed paucity of small SPLD craters and the range of crater morphologies, *Murray et al.* [2003] postulated a catastrophic yet shallow resurfacing event within the last $10^5$ to $10^6$ years that preferentially erased small craters (and perhaps also decreased the depths of larger craters). Hence the three orders of magnitude disparity in the diameter dependence of crater retention surface ages leads to dramatically differing models of the resurfacing history of the SPLD.

[6] The morphological properties of SPLD secondary crater fields can be used to independently assess proposed modification mechanisms. Given that all of the craters in a

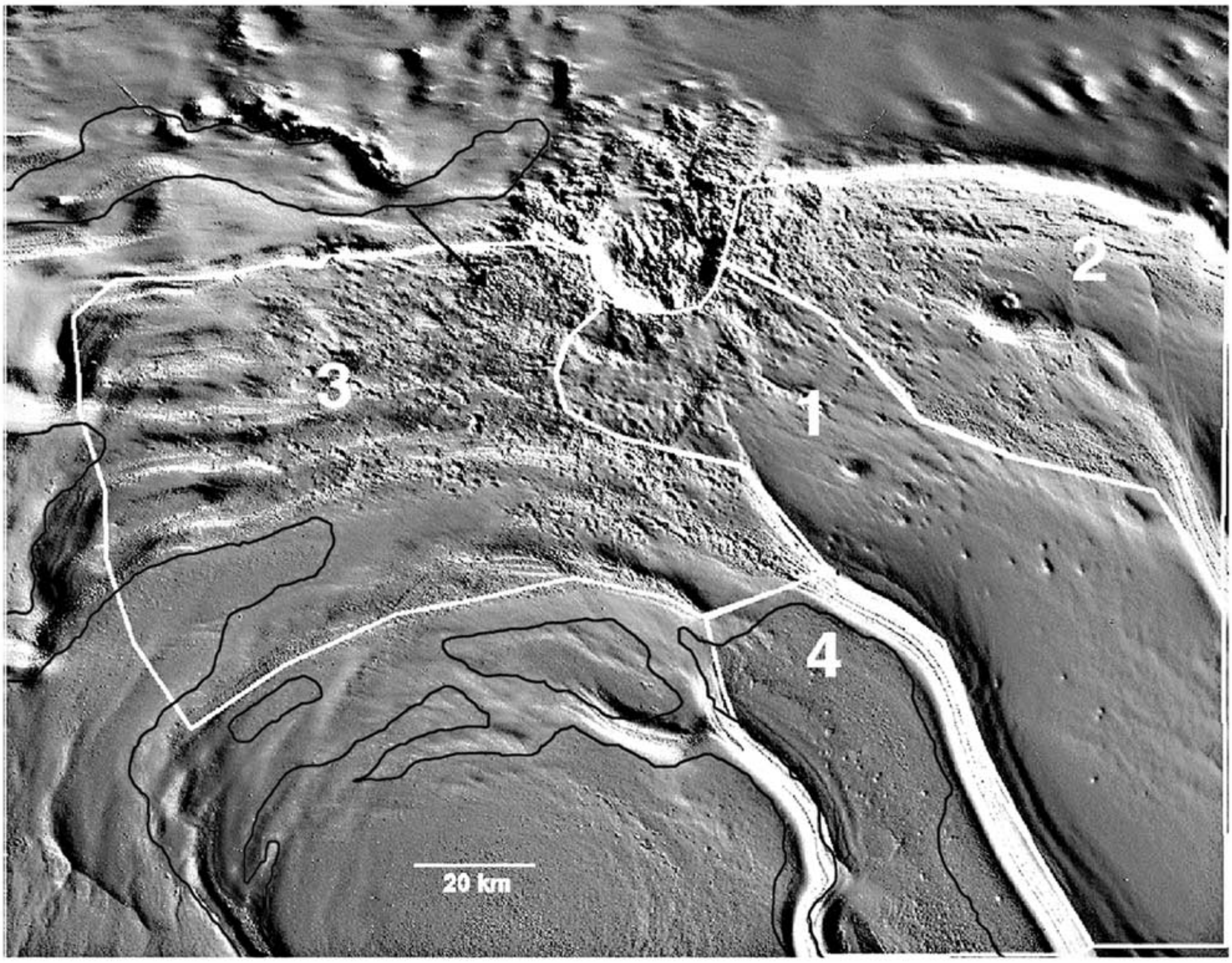

**Figure 2.** MOLA shaded relief image of McMurdo crater and secondary field showing the locations of the four separate regions. The black line outlines the location of the south polar residual $CO_2$ cap. We have divided the McMurdo field into four separate regions on the basis of the morphologies of the craters in those regions. Arrow points to the location of numerous mounds and ridges.

secondary field were emplaced at the same time, they provide a unique opportunity to study the diameter dependence of SPLD crater evolution. Previous SPLD crater studies [e.g., *Koutnik et al.*, 2002] purposely excluded obvious secondaries so as not to bias their primary crater count statistics. In this work, however, we focus specifically upon secondary crater size distributions, morphologies and depth-to-diameter ratios in order to gain insight into the relative importance of the various candidate SPLD modification processes.

## 2. Secondary Crater Fields

### 2.1. McMurdo Crater

[7] McMurdo Crater is the largest crater that has impacted into the surface of the SPLD ($D$ = 23 km), penetrating through an approximately 1500 m thick section at 84.5°S, 0°W on the margins of the SPLD (Figure 1a). The rim of McMurdo is less than 50 m high [*Tanaka et al.*, 2000], which is quite small for a crater of this size, as *Garvin et al.* [2003] found that fresh $D$ = 23 km Martian craters have an average rim height of ~280 m. Note that because the McMurdo impact penetrated through the stack of SPLD material down to the Hesperian rock below, a significant amount of the ejecta material may have been rock rather than ice. *Tanaka et al.* [2000] argued that the persistence of relatively small secondaries ($D$ < 1 km) implies minimal amounts of surface erosion (meters to tens of meters) since the time of the McMurdo impact. However, detailed inspection of the spatial distribution of the McMurdo secondary field also reveals significant differences in the extent of secondary crater preservation and degradation.

[8] McMurdo's secondary field extends southward across the SPLD with the majority of the craters contained within a semicircle of radius 100 km. The most distant obvious secondaries are over 140 km away. The distribution is distinctly asymmetric with some regions appearing more degraded than others. We have divided the McMurdo secondary field into four separate regions in order to facilitate description of secondary crater morphology (Figure 2). The most prominent surface modification feature in the McMurdo field is located between two large scarps southeast of the McMurdo impact. We define this area as "Region 1". Regions 2 and 3 lie to the east and west of

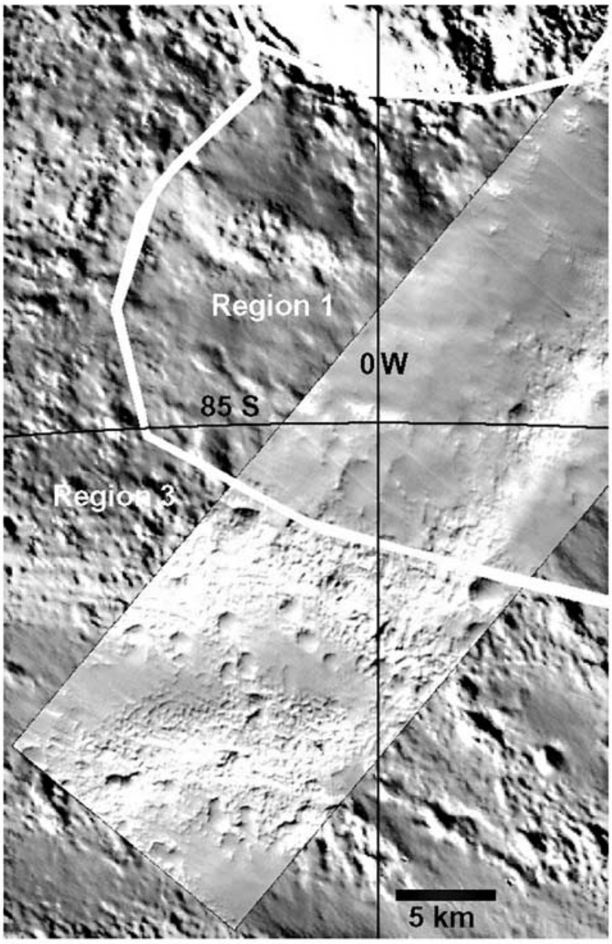

**Figure 3.** THEMIS-VIS image V06453007 overlain on the MOLA shaded relief map. Sun illumination is from the northwest. The rim of McMurdo crater is at the top of the figure. This image shows McMurdo secondary craters in Regions 1 and 3. Different states of degradation of the secondary craters in the image can be observed as well as the appearance of a blanketing layer covering the craters in the upper part of the image.

Region 1 respectively. Region 4 is located to the west of Region 1 and south of Region 3 (Figure 2).

[9] The terrain of Region 1 is quite flat and smooth compared with Regions 2 and 3 and appears to be mantled (Figure 3). The secondary craters here are shallower with less well defined rims than those in the other regions and their number density is significantly less relative to Regions 2 and 3. Region 2 craters appear better preserved but the long axis directions of many of these craters do not point toward McMurdo as would be expected if they were unmodified.

[10] Region 3 contains several scarps trending in a generally east-west direction. As with Region 2, many of the long axis directions of the craters do not point toward McMurdo (Figure 2). The long axis directions of these craters are scattered in many different directions which reflects the surprising lack of preferred azimuthal orientation relative to McMurdo for the entire secondary field. Region 3 also contains numerous small mounds, features first noted by *Tanaka et al.* [2000]. It is unclear if these mounds are ejecta from the McMurdo impact or if they are an unrelated erosional or depositional feature.

[11] The southern border of Region 3 is so drawn because the secondary craters seem to abruptly terminate approximately 70 km away from McMurdo. Given that the secondary field extends to greater than this distance to the east and southeast, and that craters in other locations are found at higher elevations than the southern edge of Region 3, we suspect that secondary craters south of Region 3 have been removed or buried since their emplacement.

[12] Region 4 is covered by the residual $CO_2$ cap. Though the craters in Region 4 are over 100 km away from McMurdo, we believe them to be McMurdo secondaries on the basis of their chain-like orientation with respect to McMurdo and their relative proximity to it (the SPLD as a whole is over 1000 km wide, as shown in Figure 1). These craters are generally quite degraded and have similar morphologies (shallowness and lack of defined rims) to the craters in Region 1.

[13] In summary, secondary craters in Regions 1 and 4 appear to have undergone significant degradation compared with most craters in Regions 2 and 3, indicating a variable modification process. This modification mechanism is most simply explained in our view by local variations in the deposition of a moderately thick blanketing layer (Figure 3). Such mantling must have significantly preceded the recent resurfacing event described later in this paper.

[14] To the north of McMurdo, both the crater rim and the secondary field are missing (Figure 2). This dramatic asymmetry raises the question: was McMurdo produced by an oblique impact that preferentially emplaced craters to the south? Ejecta deposits from impacts are symmetric for impact angles ranging from vertical (90°) down to about 45° [*Gault and Wedekind*, 1978; *Pierazzo and Melosh*, 2000; *Herrick and Forsberg-Taylor*, 2003]. At lower angles, the

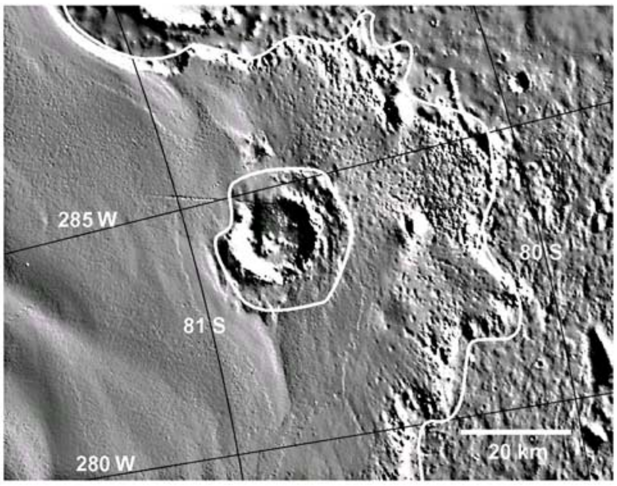

**Figure 4.** MOLA shaded relief image of Crater II and secondary field. Outlined in white is the mapped boundary of the SPLD [*Kolb and Tanaka*, 2001]. The secondary field of Crater II is located to the north of the crater on the SPLD. The secondary field to the south of Crater II has likely been buried by a younger overlying layer of SPLD material.

ejecta start to become asymmetric with more ejecta emplaced in the "downrange" direction. Below about 30° a "forbidden" zone appears in the uprange direction and the rim may be depressed there. For extremely oblique impacts (<5°) a characteristic "butterfly wing" pattern will develop with no ejecta uprange or downrange of the crater and the crater itself may be very elliptical. The "forbidden zone" for an oblique impact is generally triangular in shape and appears to cover less than 90 degrees of azimuth (see figures of *Herrick and Forsberg-Taylor* [2003] and *Melosh* [1989]). Therefore ejected material should be found in the other 270 degrees surrounding the crater. McMurdo is missing evidence of ejecta material over more than 180 degrees, and therefore this distribution of ejecta is likely not explained by an oblique impact; it must have been modified since its emplacement. In addition, McMurdo crater itself appears to be relatively circular and not elliptical, indicating that it likely was not produced by an extremely oblique impact.

[15] Therefore the current asymmetrical distribution of McMurdo secondaries implies either (1) massive lateral SPLD scarp retreat resulting in the obliteration of the northern half of the primary crater and secondary crater field or (2) initial impact into the very edge of the SPLD, followed by localized erosion/deposition that has removed/mantled all of the northern secondaries and somehow degraded the northern rim [*Tanaka et al.*, 2000]. We find the scarp retreat concept to be the more plausible explanation overall, especially given the absence of a northern rim. If significant retreat of the SPLD has occurred, it is also possible that this process enlarged McMurdo crater itself.

### 2.2. Crater II

[16] "Crater II" is the only other large SPLD crater ($D$ = 15 km) with a clearly identifiable secondary crater field (referred to as "Field II"), penetrating through the extremely thin (approximately 300 m) margin of the SPLD at 80.8°S, 284°W (Figure 4). Crater II has a maximum rim height of 215 m, which is close to the predicted initial rim height for a fresh $D$ = 15 km crater of $h$ = 195 m [*Garvin et al.*, 2003]. Yet far from appearing pristine, Crater II seems to have impacted long ago into an older section of the SPLD, an interpretation suggested by the highly degraded morphologies of the northern secondary craters and ejecta blanket (Figure 4). Field II is much less extensive than the McMurdo Field, as the most distant secondary is located about 46 km to the north. The secondary field is not observed south of Crater II, most likely because of the post-impact deposition or flow of a younger SPLD layer (Figure 4). The Crater II secondary field may also have been recently exhumed from beneath a younger layer.

## 3. Methods

[17] We have quantified secondary crater attributes using MOLA altimetry in conjunction with MOC and THEMIS imagery. The MOLA data were gridded into a 115 m per pixel Digital Elevation Model (DEM) with submeter vertical resolution [*Neumann et al.*, 2001]. Due to the high density of circumpolar observations, there is almost no interpolation in the gridded MOLA data at this latitude. All three data sets have been integrated into a GIS Arcview project developed for Mars polar analysis. Crater diameters were obtained from THEMIS VIS-band images, which cover most of the SPLD at a resolution ranging from 36 m to 72 m per pixel. Because secondary craters are often irregular in outline, both the maximum and minimum diameters of the craters are measured and then averaged to obtain the recorded crater diameter. We also recorded the ellipticity, $e$, of the crater, defined as

$$\mathrm{e} = 1 - \mathrm{D}_{\min}/\mathrm{D}_{\max},$$

and noted the azimuthal direction of the long axis diameter. Crater depths were derived from the gridded MOLA data by first circumscribing a profile around each crater to determine the average height of the surrounding terrain, and then finding the maximum depth inside each crater relative to this surrounding terrain height. Using the methodology described above, we have systematically quantified the attributes of the 379 identifiable McMurdo secondary craters and the 221 "Crater II" secondary craters. When we propagate the depth uncertainty (estimated to be about 1 m) along with the uncertainty in diameter (estimated to be 36 to 72 m on the basis of the Themis resolution) we find that the error in $d/D$ for the average secondary crater is only 7%. However, we believe that the main source of error is not the resolution of the data but the human error involved in determining the edges of the craters for the diameter measurements. Two authors separately measured the depths and diameters of one hundred secondary craters. Comparison of our individual estimates indicates that the measured $d/D$ and ellipticity generally agree to within 15% for the two separate sets of observations, and thus we adopt 15% as the estimated error for our secondary crater $d/D$ and ellipticity measurements.

## 4. Results

### 4.1. Secondary Crater Diameter Distributions

[18] Figure 5 shows histograms of secondary crater diameters for both the McMurdo Field and Field II. We identified 379 McMurdo secondaries ranging from 300 m $\leq D \leq$ 3300 m, with a median value of $D$ = 1650 m (Figure 5a), and 221 Crater II secondaries ranging from 450 m $\leq D \leq$ 2250 m, with a median value of $D$ = 1050 m (Figure 5b). We carefully examined MOC NA and THEMIS-VIS images spanning the secondary crater fields for smaller craters ($D <$ 600 m) not visible in the gridded MOLA data sets. Yet we found no secondary craters smaller than 300 m in the McMurdo field (Figure 5a) and no craters smaller than 450 m in Field II (Figure 5b), even in high-resolution MOC images that could have revealed craters as small as 20 m in diameter. The absence of small secondaries is consistent with the paucity of small SPLD primary craters noted by *Koutnik et al.* [2002] and may likewise be indicative of recent SPLD-wide resurfacing.

[19] The implied magnitude of SPLD resurfacing can be estimated if the initial depth/diameter ratio of SPLD secondary craters is known. While the initial distribution of secondary crater depth/diameter ratios is not well constrained, there have been several studies examining populations of secondary craters on Solar System bodies. *Hurst et al.* [2004] and A. S. McEwen et al. (The rayed crater Zunil and interpretations of small impact craters on

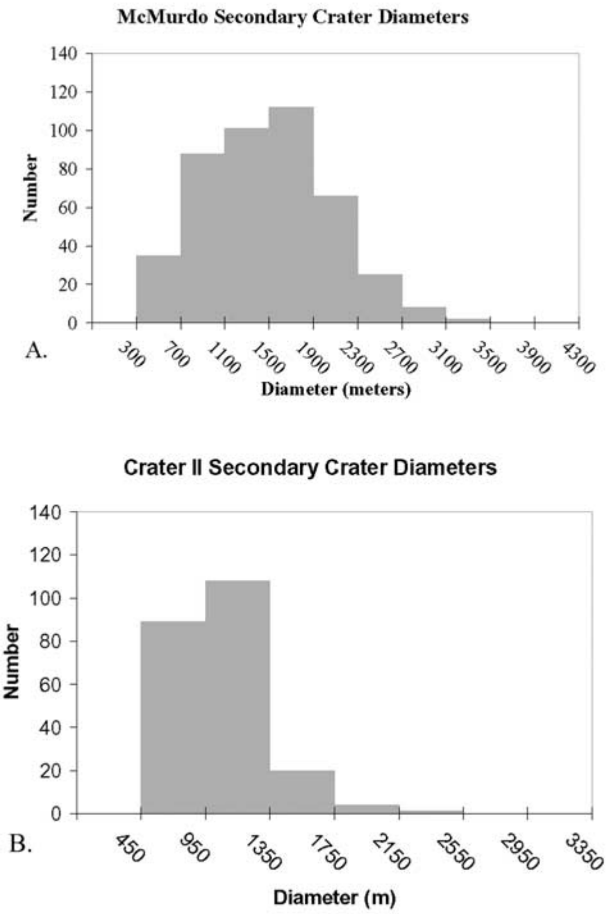

**Figure 5.** Histograms of secondary crater diameter for the (a) McMurdo and (b) Crater II fields. Crater diameters were measured using MOC (resolution 2-12 m/pix) and THEMIS-VIS images (resolution 36-72 m/pix). The resolution of these data sets is sufficient to reveal much smaller craters than were observed, indicating an actual small crater cutoff. Note: We found one crater with a diameter of 180 m in the McMurdo field. However, its morphology (circular, bowl shaped, with a raised rim all around) contrasts markedly the morphologies of all other secondary craters in the region (elliptical, shallow, rimless or having a rim on only one side of the crater). This leads us to conclude that it is a primary crater or distant secondary crater unrelated to the McMurdo impact, and thus we did not include it in the histogram.

Mars, submitted to *Icarus*, 2004; hereinafter referred to as McEwen et al., submitted manuscript, 2004) used high-resolution Digital Elevation Models to study small craters in the equatorial regions of Mars, and concluded that the freshest population of secondary craters has a mean $d/D$ value of 0.11, which is identical to the average $d/D$ for lunar secondaries reported by *Pike and Wilhelms* [1978]. *Schenk* [2002] showed that the depth dependence of fresh primary craters on icy Galilean satellites closely follows the standard $d = 0.199 \times D^{0.995}$ ($d/D \sim 1/5$) relationship derived from primary impacts of $D < 10$ km craters into the rocky regoliths of both the Moon and Mercury [*Pike*, 1988] indicating that cold ice responds similarly to rock. In addition, *Murray et al.* [2003] have found several small fresh craters on the SPLD with $d/D$ ratios of ~0.2, indicating that hypervelocity impact cratering in SPLD ice also follows this relationship. Thus we find it reasonable to assume that the Martian equatorial mean value of $d/D$ = 0.11 for secondary craters is the best estimate of initial $d/D$ of secondary impacts into the ice-rich SPLD. Therefore, in order to completely eradicate McMurdo secondaries smaller than $D$ = 300 m, as much as 33 m of vertical resurfacing is required. Similarly, to explain the lack of $D < 450$ m secondaries in Field II, roughly 50 m of resurfacing is needed.

[20] At the other end of our diameter range, the largest secondaries for McMurdo and Crater II have diameters of $D$ = 3300 m and $D$ = 2250 m, respectively, corresponding to secondary/primary crater diameter fractions of approximately 15%. This is unusual in that the largest secondary is usually less than about 5% the size of the primary [*Melosh*, 1989; McEwen et al., submitted manuscript, 2004]. However, the laboratory experiments of *Lange and Ahrens* [1987] showed that impact craters formed in ice at temperatures of 81 K and 257 K have diameters two to three times greater, respectively, than those formed in basalt, largely because the material strength of ice is less than that of rock and decreases with increasing temperature. Since the "strength regime" extends up to crater diameters of approximately 7 km on Mars [*Garvin et al.*, 2003] these results should scale and be applicable to the McMurdo and Field II secondaries. Thus we do not consider the diameters of these secondaries to be unusually large for impacts into relatively warm Martian ice.

### 4.2. Secondary Crater Depth-to-Diameter Ratios

[21] Figure 6 plots depth versus diameter for both SPLD secondary crater fields. Due to the difficulty of estimating small crater depths using THEMIS images, Figure 6 excludes 25 McMurdo and 8 Field II secondary craters with $D < 600$ m that were not well-resolved in the gridded MOLA data. The McMurdo and Field II secondaries have

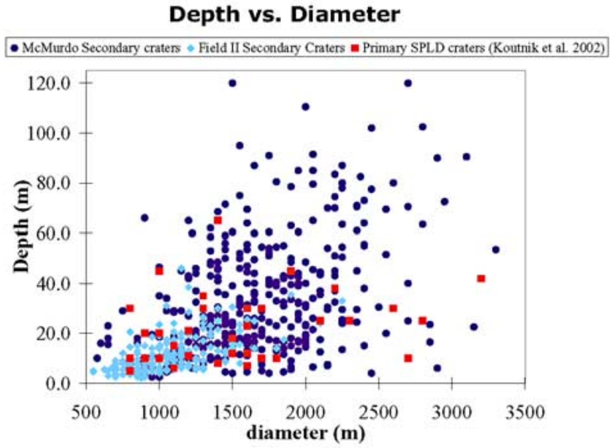

**Figure 6.** Plot of crater depth versus diameter for McMurdo (dark blue circles) and Crater II (light blue diamonds) secondary fields. Also plotted are the large primary SPLD craters (red squares) identified by *Koutnik et al.* [2002].

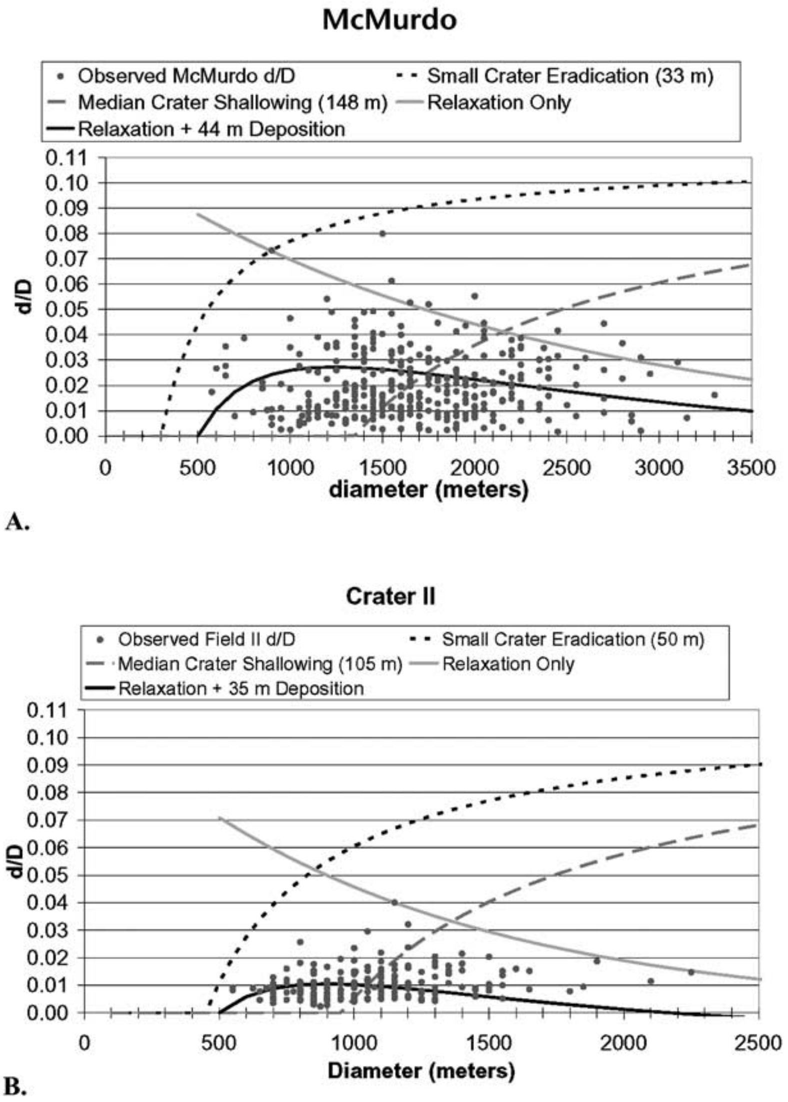

**Figure 7.** Plot of *d*/*D* ratio versus diameter for both McMurdo and Crater II secondary fields. Uncertainty in the d/D measurements is approximately 15%. (a) The circles denote actual observations of McMurdo field *d*/*D*. The upper dashed line models the minimum 33 m of vertical resurfacing required to explain the lack of secondaries with $D < 300$ m (assuming an initial *d*/*D* of 0.11 as done by *Hurst et al.* [2004]). The lower dashed line corresponds to the 148 m of vertical resurfacing needed to degrade the median crater diameter of $D = 1600$ m to the average $d/D = 0.02$ in the field. The upper solid line represents a "pure" relaxation scenario, in which the depth evolution of secondary craters depends only on diameter (the relaxation time was arbitrarily chosen to fit the observed $D = 900$ m crater with $d/D = 0.073$). The lower solid line results from a combination of viscous relaxation with 44 m of vertical resurfacing (the parameters were chosen in order to eradicate $D = 500$ m craters); this is the model that best fits the data. (b) The circles denote actual observations of Field II *d*/*D*. The upper dashed line models the minimum 50 m of vertical resurfacing required to explain the lack of secondaries with $D < 450$ m. The lower dashed line corresponds to the 105 m of vertical resurfacing needed to degrade the median crater diameter of $D = 1050$ m to the average $d/D = 0.01$ in the field. The upper solid line represents a "pure" relaxation scenario, in which the depth evolution of secondary craters depends only on diameter (the relaxation time was arbitrarily chosen to fit the observed $D = 1150$ m crater with $d/D = 0.04$). The lower solid line results from a combination of viscous relaxation with 35 m of vertical resurfacing (the parameters were chosen in order to eradicate $D = 500$ m craters).

average *d*/*D* ratios of 0.020 and 0.010, respectively. The secondary craters measured in this study are generally much shallower than the $d/D \sim 0.11$ characteristic of lunar and other Martian "fresh" secondaries [*Hurst et al.*, 2004], suggesting that significant modification of SPLD secondaries has occurred. The much greater variation of depth-to-diameter in the McMurdo field, where *d*/*D* ranges up to 0.08 (Figure 6) indicates that the McMurdo

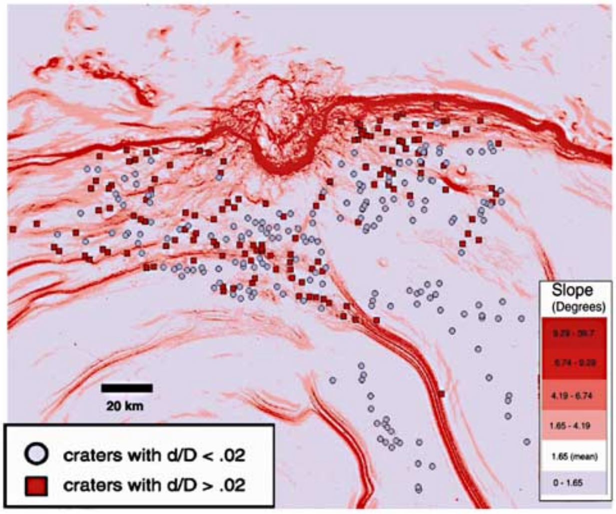

**Figure 8.** Slope map derived from the MOLA DEM. Also shown are the locations of the McMurdo secondary craters. Craters with high depth-to-diameters of $d/D > 0.2$ (shown as red squares) are often found on steeper terrain near scarps, whereas craters with low $d/D < 0.2$ (shown as blue circles) tend to be located on flat-lying areas.

Field overall has not been modified as extensively as Field II.

### 4.2.1. Diameter Dependence

[22] Resurfacing of secondary crater fields, due to either constructional mechanisms such as water ice condensation and dust deposition or destructional mechanisms such as water ice sublimation and eolian erosion, should result in the preferential shallowing of smaller craters. Note that the temporal variation of deposition or erosion rate is largely irrelevant: since every crater within the secondary field was emplaced contemporaneously, all that matters is the net magnitude of deposition or erosion (henceforth simply referred to as the "resurfacing") since the time of the primary impact.

[23] Consider Figure 7a, which plots the depth-to-diameter ratio $d/D$ as a function of diameter $D$ for McMurdo secondaries with measurable depths. If we assume that all secondaries started with an initial $d/D = 0.11$, then a minimum amount of resurfacing equal to 33 m is required to explain the lack of observed craters smaller than $D = 300$ m (Figure 5a). Yet this amount of resurfacing is clearly not sufficient to explain the shallowness of larger McMurdo secondaries. However, increasing the amount of resurfacing to 148 m (so that a McMurdo secondary with the median diameter of $D = 1600$ m is now at the average scaled depth of $d/D = 0.02$) still does not fit the data, because this level of resurfacing would produce deeper craters at larger diameters along a trend that is clearly not observed.

[24] The depth distribution of Crater II secondaries is also inconsistent with simple deposition or erosion. As shown in Figure 7b, the 50 m of resurfacing required to eradicate $D < 450$ m craters from Field II (Figure 5b) would not yield significantly shallow larger craters in accordance with the observations. But increasing the amount of resurfacing to 105 m (such that a Field II secondary with the median diameter of $D = 1050$ m is reduced to the average scaled depth of $d/D = 0.01$) is just as poor a fit. And much like McMurdo, many of the highest $d/D$ Crater II secondaries are actually found at lower diameters ($D \leq 1.2$ km). Therefore, although a limited amount of vertical resurfacing may explain the absence of very small SPLD secondary craters, we conclude that the shallow depth distributions of larger McMurdo and Field II secondaries are not consistent with either pure deposition or erosion.

[25] We now consider modification of secondary craters by viscous relaxation. Explicitly modeling crater relaxation via finite element modeling as done for primary SPLD craters by *Pathare et al.* [2005] is beyond the scope of the present work. However, we can utilize the inverse relationship between crater diameter $D$ and $e$-folding relaxation time $\tau$ (i.e., the larger the crater, the faster it relaxes) that can be readily derived for craters deforming within isoviscous Newtonian (n = 1) layers [*Scott*, 1967; *Thomas and Schubert*, 1987]. The upper solid line in Figure 7a represents a "pure" relaxation modification scenario, in which the depth evolution of secondary craters only depends on diameter (the relaxation time was arbitrarily chosen to fit the observed $D = 900$ m crater with $d/D = 0.073$). While this relaxation only model does reproduce the subtle trend of decreasing $d/D$ with increasing $D$, overall it does not provide a very good match to the observations, as the $d/D$ of most craters fall well below this line. However, combining this simplistic relaxation model with 44 m of vertical resurfacing (such that $D = 500$ m craters are completely eradicated) results in a depth distribution (Figure 7a, lower solid line) that fits the data much better than either the relaxation only (upper solid line) or resurfacing only (dashed lines) models, as roughly half of the data points lie above the combined model line and half lie below.

[26] Similarly, Figure 7b shows that combining relaxation with 35 m of vertical resurfacing (lower solid line) yields a better fit to the Field II observations than the relaxation only model (upper solid line) and resurfacing only models (dashed lines). Therefore we conclude that viscous relaxation, coupled with a small but significant amount of vertical resurfacing, is the modification mechanism most consistent

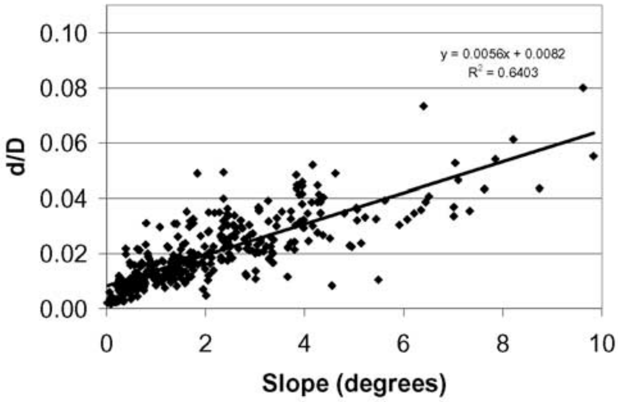

**Figure 9.** Plot of McMurdo secondary crater $d/D$ ratio versus the slope of the terrain on which the crater resides. We find a strong correlation ($R^2 = 0.64$).

**Table 1.** Depth-to-Diameter Ratios of Different Classes of Impact Craters

| Impact Crater Class | *d*/*D* |
|---|---|
| All McMurdo secondary craters | 0.020 |
| McMurdo secondary craters on slopes less than the mean slope | 0.014 |
| McMurdo secondary craters on slopes of greater than the mean slope | 0.032 |
| "Field II" secondary craters | 0.010 |
| SPLD primary craters [*Koutnik et al.*, 2002] | 0.015 |
| Expected initial secondary crater *d*/*D* [*Pike and Wilhelms*, 1978; McEwen et al., submitted manuscript, 2004] | 0.11 |

with the observed depth distributions of secondary craters within the SPLD.

#### 4.2.2. Slope Dependence

[27] Visual inspection of the MOLA DEM in the McMurdo region indicates that craters on flat regions appear shallower than those that are located on terrain near scarps (Figure 8). To quantitatively test this observation, we examined the relationship between each McMurdo secondary crater's *d*/*D* ratio and the slope of the terrain on which that crater resides. We derived a slope map from the MOLA DEM and regridded it such that each pixel was 3500 m in size. Given that every McMurdo secondary crater was smaller than one pixel, the value of the pixel at the location of each crater represents an estimate of the average slope of the terrain surrounding the crater (Figure 9). We find a significant positive correlation ($R = 0.8$) between McMurdo secondary crater *d*/*D* and the slope of the terrain on which the crater resides.

[28] Generally, secondary craters found on slopes, especially near scarps cutting through the McMurdo field in Regions 2 and 3, tend to have higher *d*/*D* ratios than those found on the flat areas typical of Region 1 and Region 4. These observations cannot be explained by a measurement bias as our measurement technique would tend to underestimate the depths of craters on slopes. In addition, all slopes are less than 10 degrees so even this effect is very minor.

[29] McMurdo secondary craters located on terrains with slopes of less than 2.3 degrees have an average *d*/*D* ratio of only 0.014, comparable to those of the *Koutnik et al.* [2002] primary craters. The McMurdo secondaries that are located on slopes of greater than 2.3 degrees have an average *d*/*D* ratio of 0.032, indicating that much less modification has occurred. This either implies that the craters on steeper slopes were protected from the degree of degradation experienced by those on flat areas or that they were preferentially deepened by the extra insolation received by the generally equatorward-facing slopes. The secondary craters surrounding Crater II are located on a flat bench with no scarps cutting through the field except at its edge. These craters have *d*/*D* ratios and slopes that are also comparable to the low slope McMurdo secondaries and the *Koutnik et al.* [2002] SPLD primary craters, though they are slightly lower (Table 1). In addition, they may be older and have experienced greater total modification.

[30] The McMurdo secondary craters on flat regions appear to have undergone the same degree of erosion (as judged by the comparable *d*/*D* ratios) as other primary craters of the same size [*Koutnik et al.*, 2002] and as the Crater II secondaries. In contrast, the McMurdo secondary craters on steeper terrain have much higher *d*/*D* ratios than any other comparably sized craters on the SPLD, most likely because these craters have been partially shielded from the depositional processes responsible for SPLD crater modification.

### 4.3. Secondary Crater Ellipticities

[31] We find a mean crater ellipticity of 0.3 for both the McMurdo and Crater II secondary fields which is consistent with the range of secondary crater ellipticities measured by *Pike and Wilhelms* [1978] and *Schultz and Singer* [1980]. We also find that McMurdo secondary crater ellipticities are generally not directed toward the McMurdo impact (Figure 10a). Instead, we find that there is an average crater orientation of 4.3° east of north (Figure 10b). This is strong evidence for secondary crater modification, since we would expect unaltered secondaries to be aligned radially relative to the primary.

[32] There are two candidate surface processes that might produce such directional modification: sublimation and eolian erosion. The nearly northward orientation of many McMurdo secondaries suggests that insolation driven sublimation may have altered the ellipticities of these craters. The slight offset to the east may be indicative of deflection by wind. One potential test of sublimation is the latitudinal variation of depth-to-diameter, which is plotted in Figure 11 for McMurdo secondaries. However, there is only a weak correlation of *d*/*D* with latitude ($R = 0.08$) that is actually operating in a direction opposite to that predicted by sublimation, because depth-to-diameter decreases closer to the poles (where insolation is on average lower). Moreover, if sublimation were responsible for increasing crater ellip-

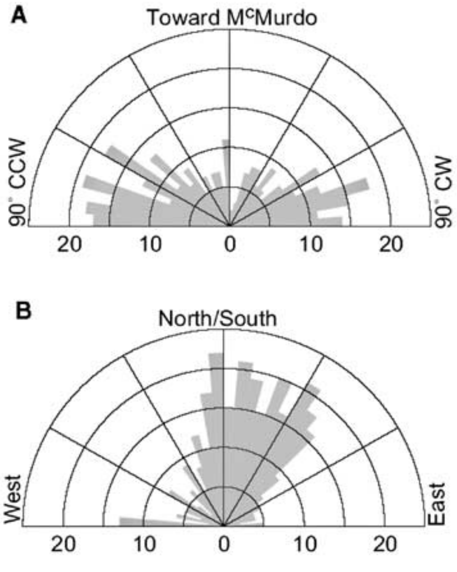

**Figure 10.** Polar histograms showing long axis orientation of McMurdo secondaries (a) relative to the direction of McMurdo crater and (b) relative to meridians. The orientations of the secondaries can be seen to have a preferred direction with a mean value 4.3° east of north (Figure 10b). There is no obvious preferred orientation toward McMurdo crater itself (Figure 10a). See text for discussion.

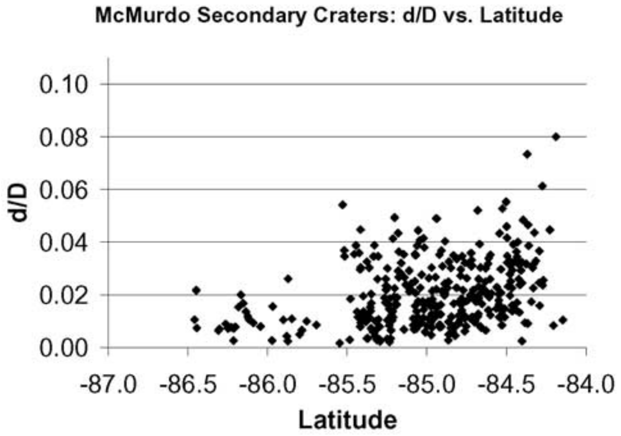

**Figure 11.** Plot of McMurdo secondary crater *d*/*D* versus latitude. A very weak correlation is observed. However, the most distant secondaries are also located on the $CO_2$ residual cap, which may be the reason why they are so shallow. If we ignore these distant secondaries, no trend is observed.

ticities, we would expect to see a positive correlation between ellipticity deflection (relative to the direction of McMurdo) and the slope on which the crater resides, which is not observed (Figure 12a).

[33] Additionally, surface processes such as sublimation and eolian erosion should preferentially alter the ellipticities of smaller craters, since the entire secondary field will be subjected to similar amounts of modification. Thus the ellipticities of smaller secondaries will be more easily re-oriented, since they have less volume to modify. But as shown in Figure 12b, ellipticity deflection is independent of crater diameter. In addition, we find no correlation between the magnitude of a crater's ellipticity and its diameter (smaller craters might be expected to be more elliptical if they were being acted upon by sublimation) nor do we find a correlation between ellipticity and the slope of the terrain on which the crater resides (Figure 13). Therefore we speculate that some combination of sublimation and eolian erosion or another mechanism altogether (e.g., subsurface flow) may be responsible for the modification of secondary crater ellipticities.

## 5. Discussion

[34] The morphologies of the secondary craters in the McMurdo and Crater II fields allow us to impose constraints on the modification history of the SPLD.

[35] 1. Vertical resurfacing rates: The small crater size limits within the McMurdo and Crater II fields indicate that at least the upper ~30 m of the surface of the SPLD has been resurfaced since the time of these impacts in order to account for the absence of craters smaller than *D* = 300 m. This is consistent with other crater studies across the SPLD which suggest that this resurfacing had to have taken place within the last $10^5$ to $10^6$ years [*Murray et al.*, 2003; *Koutnik et al.*, 2002]. There may also have been earlier resurfacing events that blanketed or degraded portions of the secondary fields prior to the most recent episode.

[36] 2. Viscous relaxation: We find that vertical resurfacing mechanisms and insolation driven sublimation alone cannot explain the depth and diameter distributions of the craters in the McMurdo and Crater II fields. For as shown by the dashed lines in Figure 7, "pure" vertical resurfacing models are inconsistent with the generally low *d*/*D* ratios and flat distribution of *d*/*D* versus diameter for both McMurdo and Crater II secondaries. We suggest that viscous relaxation acting in combination with a small amount of vertical resurfacing (~30 m) is much more consistent with the shallow depths of SPLD secondaries

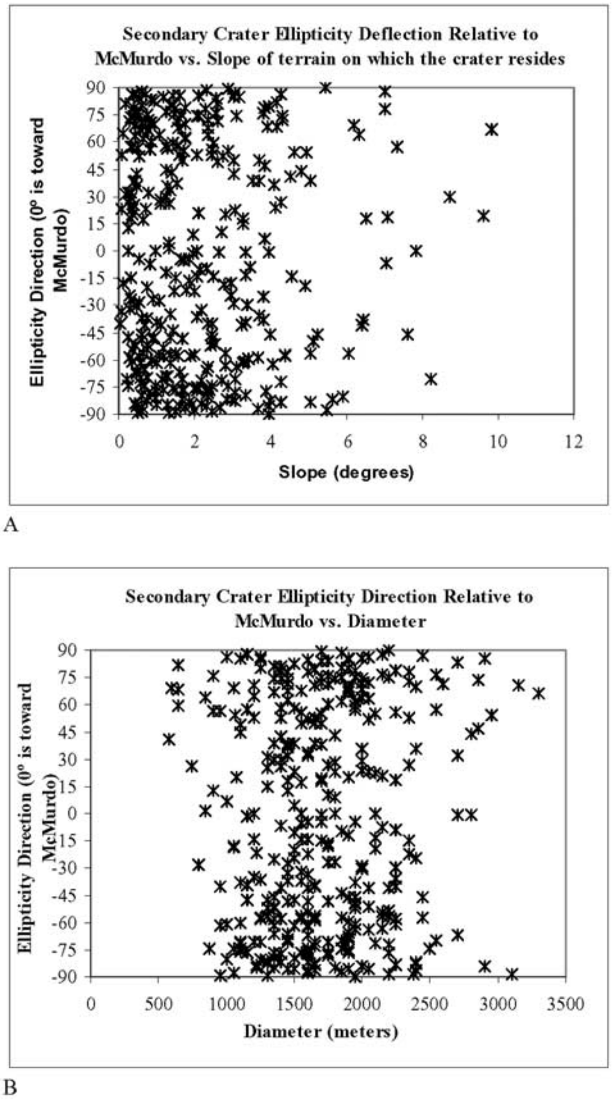

**Figure 12.** McMurdo secondary crater ellipticity deflection relative to McMurdo versus (a) slope of the terrain on which the crater resides and (b) secondary crater diameter. If sublimation were primarily responsible for crater ellipticity modification, we would expect to see the craters on slopes have more deflection away from McMurdo in their ellipticity directions than the craters on flat areas. In addition, we would expect the ellipticity directions of the smaller craters to be more deflected than the larger ones. No trend in either graph is observed.

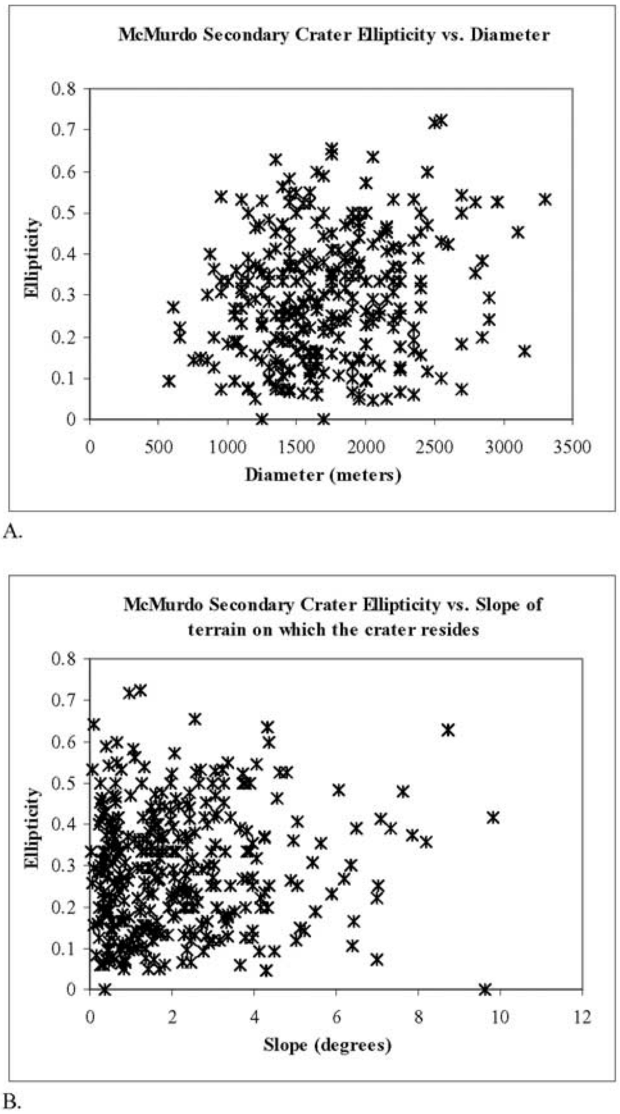

**Figure 13.** McMurdo secondary crater ellipticity versus (a) diameter and (b) slope of the terrain on which the crater resides. The magnitudes of the ellipticities of the secondary craters show no trend with diameter or slope.

(solid black lines in Figure 7). *Pathare et al.* [2005] showed that the ubiquitous shallowness of SPLD primary craters is consistent with ongoing modification governed primarily by viscous relaxation over the last 100 Myr, coupled with very slow vertical resurfacing at an average rate of $-0.2$ m/Myr. Given that the McMurdo and Crater II secondaries are in the same size range as the large *Koutnik et al.* [2002] primaries (Figure 6), and that $D > 15$ km craters only impact the SPLD on the average approximately once every 140 Myr, it follows that similar viscous relaxation processes may also have produced the shallow *d*/*D* ratios of large SPLD secondary craters. However, these mechanisms cannot account for the wide range of *d*/*D* ratios observed within the McMurdo secondary crater field (barring significant variations in relaxation time due to deviations in subsurface PLD thickness); consequently, there must be an additional factor governing crater modification.

[37] 3. Slope dependence: In order to fully constrain the secondary crater modification history it is necessary to also explain the intriguing positive correlation found in the McMurdo field between the slope of the terrain on which the crater resides and its *d*/*D* ratio (Figure 9). This correlation might be explained by several mechanisms about which we now speculate. $CO_2$ is not deposited as readily on steeper terrain as on adjacent flat areas because equatorward-facing scarps tend to be warmer. Evidence of SPLD surface erosion by "spiders" involving seasonal $CO_2$ deposition and sublimation has been presented by *Piqueux et al.* [2003]. If seasonal $CO_2$ can erode the surface under present-day conditions, then a relative lack of $CO_2$ deposition on steeper terrains might account for the slope-dependence of crater preservation. We are not necessarily suggesting that the *Piqueux et al.* [2003] mechanism is responsible for crater degradation, only that it illustrates one case in which annual $CO_2$ cycles can result in permanent surface modification. Thus we suggest that there may be a mechanism whereby deposition and removal of seasonal $CO_2$ or perhaps even a different location of the residual $CO_2$ cap would lead over time to significant modification of the underlying SPLD.

[38] Alternatively, craters on steeper slopes may be preferentially deepened by insolation driven sublimation. However, this would not explain the paucity of impact craters in flat regions relative to those on sloped areas. Modification rates might also be affected by composition or consolidation differences between the flat areas and the scarps. Such variations may be consistent with initial analyses of the SPLD from the near-IR spectrometer aboard the Mars Express mission [*Bibring et al.*, 2004]. In this case, viscous relaxation might not be as effective at lowering crater *d*/*D* on sloped terrains because of these putative compositional differences. Wind erosion may also be responsible for preserving craters on sloped terrain. If wind speeds are greater over sloped terrain, this may lead to less deposition in these areas and more deposition on flat regions when the wind speed decreases. Finally, the relationship between slope and *d*/*D* might not be causal. That is, whatever erosional process was responsible for decreasing the *d*/*D* ratios of these craters may have also acted to flatten out the slope of the surrounding terrain.

## 6. Conclusions and Lingering Questions

[39] In summary, we propose a SPLD modification model involving two distinct mechanisms. First, viscous relaxation modifies every secondary crater over millions of years, flattening all of them significantly (even the highest secondary *d*/*D* is only 0.08 compared with the expected initial *d*/*D* of 0.11). The larger craters are more affected by the viscous relaxation than the smaller ones. Subsequently, craters are resurfaced by a small scale (~30 m) surficial mechanism that eradicates the smallest craters and degrades the larger ones. We find that secondary craters on steeper slopes tend to have higher *d*/*D* ratios than those on flat-lying areas. We suggest a mechanism that preferentially reworks flatter terrains on the basis of the paucity of impact craters in these locations and speculate that deposition and removal of $CO_2$ might be responsible because $CO_2$ is not deposited as readily on slopes. Thus, in order to explain the current lack

of craters in parts of the McMurdo secondary field, we suggest that these low-slope areas (Figure 8) have been mantled, perhaps by deposition and erosion of seasonal $CO_2$ and/or by a former $CO_2$ residual cap of larger size or somewhat different location.

[40] Substantial questions remain concerning the timing of this recent eradication of small secondary craters seen in the McMurdo and Crater II fields. *Murray et al.* [2003] postulate a catastrophic yet shallow resurfacing event within the last $10^5$ to $10^6$ years to account for the paucity of small craters observed across the entire SPLD. McEwen et al. (submitted manuscript, 2004) suggest that most craters less than 1 km on Mars (the exact crossover diameter depends on the age of the surface) may be distant secondaries indicating that crater isochrons used for dating very young surfaces may need revision. Thus in order to determine the timing of the ~30 m resurfacing process that has removed small craters in the McMurdo and Crater II secondary crater fields, a better understanding of Martian global secondary and primary crater production is necessary.

[41] The McMurdo and Crater II secondary crater fields raise additional questions about the modification history of the SPLD. If, as we suggest, massive lateral scarp retreat has occurred removing the northern secondary craters, why has there only been minimal (<50 m) vertical erosion in the remaining crater field? Perhaps the McMurdo and Crater II secondary crater fields were buried long ago and only recently exhumed. Indeed the southern secondary craters of Crater II appear to be buried by a prominent overlying layer. It is conceivable that this layer once extended over the entire field and beyond. For instance, there are numerous examples of detached SPLD masses all along the SPLD boundary [*Byrne*, 2003; *Head*, 2001] which seemingly require a significant past extension of the SPLD.

[42] Full understanding of the modification processes that have occurred on the McMurdo and Crater II secondary fields will constrain models of the overall history of the SPLD and may help elucidate the effects of orbitally driven climate variations upon polar stratigraphy.

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