GEOPHYSICAL RESEARCH LETTERS, VOL. 38, L08201, doi:10.1029/2011GL046844, 2011

Late alluvial fan formation in southern Margaritifer Terra, Mars

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Received 24 January 2011; revised 24 February 2011; accepted 2 March 2011; published 20 April 2011.

[1] Crater statistics indicate alluvial fans, crater floor, and fill/mantling deposits within impact craters >50 km in diameter in southern Margaritifer Terra were likely emplaced during multiple epochs: fans formed during the Amazonian or near the Amazonian-Hesperian boundary, crater floor deposits are likely Hesperian in age, and most fill/mantling deposits are Amazonian. The regional distribution of fans points to a late period of widespread water-driven degradation. Two of the final candidate landing sites for the 2011 Mars Science Laboratory mission would land on or near some of these fans, which appear younger than previously considered. **Citation:** Grant, J. A., and S. A. Wilson (2011), Late alluvial fan formation in southern Margaritifer Terra, Mars, *Geophys. Res. Lett.*, *38*, L08201, doi:10.1029/2011GL046844.

1. Introduction

[2] Alluvial fans within impact craters have been identified throughout southern Margaritifer Terra, southwestern Terra Sabaea, and southwestern Tyrrhena Terra regions of Mars [*Moore and Howard*, 2005; *Kraal et al.*, 2008]. The morphology and age of these fans provides critical insight into the climate when they formed [e.g., *Moore and Howard*, 2005]. Previous analyses of intracrater alluvial fans primarily used visible (VIS, ~19 m pixel scale) and infrared (IR, ~100 m pixel scale) images from the Thermal Emission Imaging System (THEMIS) [*Christensen et al.*, 2004]. Determining the relative ages of these deposits via crater statistics was impeded by image resolution, incomplete coverage of VIS images, and the small area of the deposits (generally <1000 km^2) [*Moore and Howard*, 2005]. As a result, the age of fan deposits within the global framework of fluvial activity has remained uncertain, and was typically bounded by the age of their host craters. Because craters hosting alluvial fans are often Noachian in age [e.g., *Scott and Tanaka*, 1986], most fans were inferred to be late Noachian and no younger than mid-Hesperian in age [e.g., *Moore and Howard*, 2005].

[3] This study utilizes higher resolution data from the High Resolution Imaging Science Experiment (HiRISE) [*McEwen et al.*, 2007] and Context Camera (CTX) [*Malin et al.*, 2007] instruments on the Mars Reconnaissance Orbiter to reevaluate the distribution and age of alluvial fans. The coverage and resolution (~0.25 m pixel scale for HiRISE and 6 m pixel scale for CTX) of these data allowed a systematic evaluation of fans and confident identification of smaller craters, thereby allowing for more meaningful crater statistics.

2. Regional Setting and Classification of Deposits

[4] This study investigates alluvial fans and other deposits in craters >50 km in diameter in southern Margaritifer Terra (Figure 1), including Eberswalde and Holden craters, two finalists for the landing site for the Mars Science Laboratory (MSL). Based on morphology, we classified deposits in 22 craters as 1) fan deposits, 2) floor deposits, or 3) fill/mantling deposits (Figure 1).

[5] The eight craters hosting fan deposits typically have well-developed alcoves, incised walls, and occasionally etched deposits on their floors inferred to be distal alluvial, playa or shallow lacustrine deposits. In most instances, the transition from fan deposits to inferred distal alluvial, playa or lacustrine deposits is continuous so the deposits are assumed to be contemporary. Many fan surfaces preserve distributary channels and lobes that typically grade to the crater floor at a slope of only a few degrees [*Moore and Howard*, 2005]. Erosion of fan surfaces in Holden crater leaves distributary channels standing ~15 m in relief above surrounding surfaces based on analysis of a HiRISE digital terrain model (DTM). Comparable erosion of fans in some other craters is inferred from morphology of distributaries, but the absence of HiRISE DTMs precludes quantitative constraint.

[6] Six craters have floor deposits that preserve morphologic features indicative of past fluvial and/or lacustrine activity (Figure 1). These craters lack well-developed rim alcoves and extensive alluvial fans, but display incised walls. The floor deposits, although occasionally locally mantled, are generally light-toned, layered and erode to a scabby appearance. Some crater floor deposits are bound by what appear to be trim lines around the lower crater wall near the termination of the wall valleys. These crater floor deposits, therefore, may reflect deposition in a playa or shallow lacustrine setting, though limited occurrence of associated fans suggests differences in water and/or sediment discharge relative to the conditions enabling fan formation.

[7] Finally, eight craters generally located in the southern part of the study area are partially filled or mantled. For example, crater N (Figure 1 inset) is partially filled by a blocky deposit that apparently flowed into the crater, creating abrupt outward facing relief along its margin. The nature of the small mounds and dark polygonal fractures in crater N is reminiscent of volcanic materials. By contrast, the other craters in this class, such as crater I (see Figure 1 for location and auxiliary material), show hints of incised walls and light-toned outcrops reminiscent of distal alluvial fan or playa/lacustrine deposits beneath a mantle of covering materials.[1] There are a few additional

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0094-8276/11/2011GL046844

[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL046844.

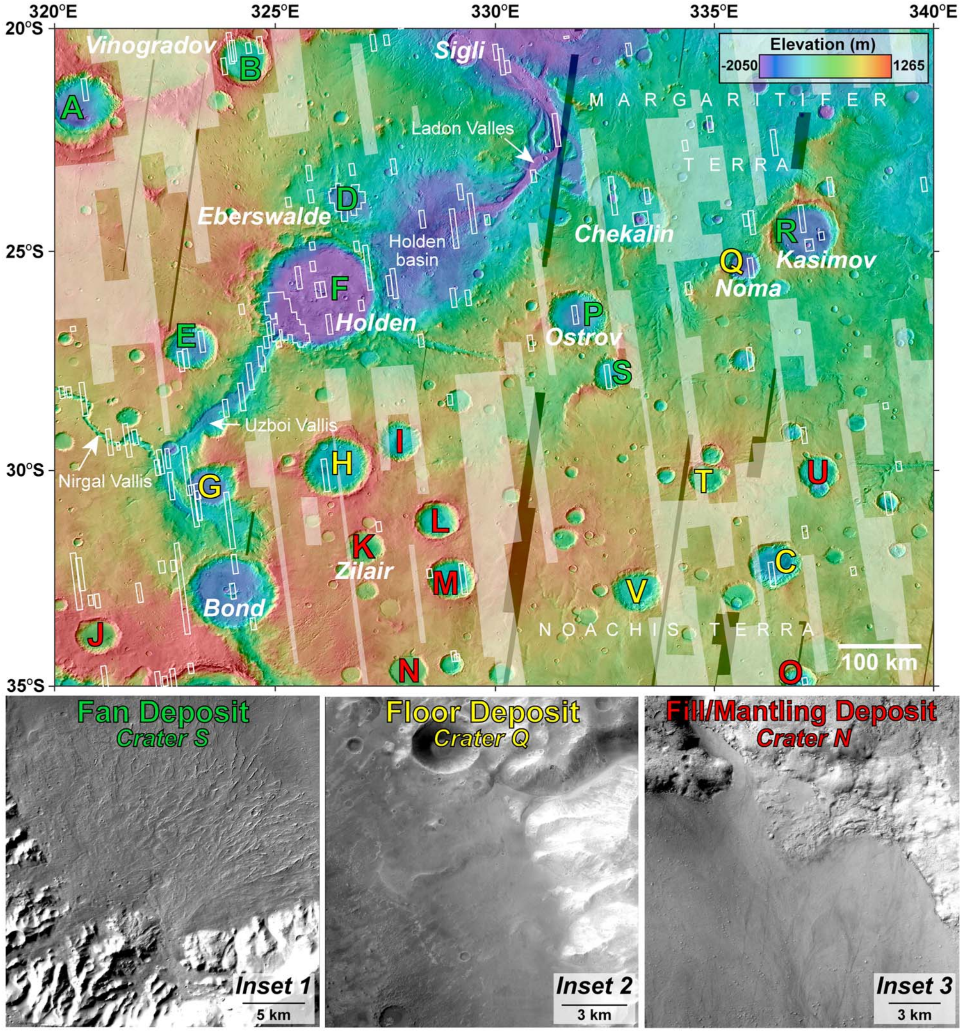

Figure 1. Study area in southern Margaritifer Terra indicating place names in text. Craters >50 km in diameter with colored letters were included in the study. Color of crater labels indicates presence of fan deposits (green, Inset 1), crater floor deposits (yellow, Inset 2) or crater fill/mantling deposits (red, Inset 3). MOLA topography over subset of THEMIS global daytime IR mosaic. Shaded white and black indicate gaps in CTX and THEMIS coverage, respectively (as of 12/2010). White boxes are HiRISE footprints (as of 12/2010). Example fan deposit in Crater S (Inset 1). Subset of CTXB01_00999_1519. Example crater floor deposit in Crater Q (Noma, Inset 2). Subset of CTX P12_005582_1561. Example mantling deposit in crater N (Inset 3). Subset of CTX P12_005701_1448. North to top of all images.

craters in the study area with diameters greater than 50 km, but gaps in image coverage or subsequent modification precluded their evaluation.

3. Methods

[8] Crater statistics were generated using areas and craters mapped on CTX data in ArcGIS using CraterTools software [*Kneissl et al.*, 2011]. All counts excluded gaps in CTX image data, obvious secondary clusters, putative lava flows, central peaks, and etched surfaces (generally based on evaluation of both HiRISE and CTX data; see auxiliary material). The resolution of CTX data enabled confident definition of craters down to approximately 20–30 m in diameter, but craters smaller than ~50 m were not included in the statistics to avoid potential effects of image resolution. For craters with fan deposits, craters were counted on fan surfaces and in some cases, the non-etched portions of adjacent putative distal alluvial and/or playa or lacustrine surfaces based on the assumption they are contemporary. For all other craters, the area included in the analysis was defined by the extent of floor or fill/mantling deposits on encompassing crater floors. Craterstats software was used to compile reverse cumulative histograms using pseudo log bins to interpret a relative age for each count [*Michael and Neukum*, 2010] based on the chronology function of *Hartmann and Neukum* [2001] and production function from *Ivanov* [2001]. Relative ages were also interpreted from the incremental plots using the variable diameter bin-size method of *Hartmann* [2005].

4. Results

[9] The areas and number of craters used to generate the crater statistics for fan deposits are generally more than 1000 km^2 and well over 100 craters, respectively (auxiliary

material). Areas and craters for craters with floor and fill/mantling deposits (Figure 1) averaged ~800 km^2 and usually more than 100, respectively (auxiliary material).

[10] In both types of plots (Figure 2), fan deposits date from the Amazonian to near the Amazonian-Hesperian boundary. Crater floor deposits are likely Hesperian, and fill/mantling deposits are mostly Amazonian except for the Hesperian or Noachian-aged deposit in crater K. Despite variations between individual counts, the clustering of results within each class relative to one another indicates distinct differences in ages. The cumulative and incremental plots yield broadly similar results and are internally consistent, though absolute ages derived from the incremental plot are systematically younger due to differences in the production function and position of hypothesized isochrones [*Hartmann*, 2005; *Carr*, 2006]. With the understanding that interpreted ages represent the minimum age of the surface, we emphasize the older values derived from the cumulative statistics (auxiliary material). We generally excluded craters smaller than ~200 m (except in crater N where the largest crater is ~280 m across) in the interpretation of ages due to deficiencies in their numbers caused by erosion as discussed below (auxiliary material).

5. Discussion

[11] The variability of relative ages for different surfaces is likely due as much to small areas considered and paucity of large craters (>1–2 km in diameter) as it is to real differences in age. One check on the general validity of the crater statistics can be made by comparing the predicted amount of erosion for the alluvial fan deposits to the onset diameter of crater deficiency in the statistics relative to the expected production population. The ~15 m erosion required to account for topographic inversion of putative distributary channels on the fans in Holden crater plus ~5 m erosion needed to account for the original depth of the channels suggests that erosion should also have destroyed some craters ~100–200 m in diameter, assuming a crater depth-to-diameter ratio of about 0.1 to 0.2 for primary and secondary craters [*Melosh*, 1989]. Examination of the statistics for the fan and floor deposits confirms a relative deficiency of craters smaller than ~250 m, similar to the expected amount. By comparison, the ejecta of a 7.5 km-diameter crater on the floor of crater R (auxiliary material) display a significantly higher crater density relative to adjacent surfaces. Compilation of statistics for the ejecta of this crater, however, reveals the higher density is due to the preferential preservation of craters <200 m in diameter relative to the adjacent fans/playa. The crater ejecta likely incorporate materials that are more resistant to erosion, perhaps excavated from beneath the fan deposits. Overall, most statistics for both the fan and crater floor deposits are consistent with the expected production population for craters with diameters ~200 m up to 1–2 km, thereby implying the absence of other intervals of burial/erosion.

[12] All but one crater containing fill/mantling deposits yield ages similar to or younger than the fan and crater floor deposits, however the range of ages is consistent with the diversity of mantling materials. Additional fan and/or distal alluvial or possible playa/lacustrine deposits may be partially buried by younger fill/mantling deposits in some craters (e.g., crater I, see auxiliary material), especially in the southern part of the study area. By contrast, there is no evidence that fill/mantling deposits were emplaced and then removed subsequent to the formation of fan deposits in this region. As noted, the fill/mantling deposits are more prevalent in the south and at least some of the deposits (e.g., putative volcanic material in crater N) appear to consist of materials that would be difficult to completely remove relative to surrounding materials (e.g., fans).

[13] The crater statistics from fans evaluated by *Moore and Howard* [2005] yielded a mid-Hesperian age, with an uncertainty ranging from near the Noachian-Hesperian boundary to the mid Amazonian. Considering the position of the fans relative to other features, *Moore and Howard* [2005] concluded the fans in Margaritifer Terra were no older than late Noachian, but could be younger. Crater statistics based on CTX data for alluvial fans in Harris crater in western Terra Tyrrhena are consistent with a Late Noachian age [*Williams et al.*, 2011], but examination of the statistics suggests the eastern fan in Harris may be appreciably younger.

[14] Although the derived age of individual fan and floor deposits varies and may overlap to some extent, the differences in the morphology of the deposits coupled with their overall grouping in age suggests the two classes of deposits have distinct origins and ages. Nevertheless, we cannot preclude the possibility they are contemporaneous. It is also possible that alluvial fan deposits bury crater floor deposits in some locations, perhaps even rejuvenating pre-existing crater wall valleys or fans. Despite such uncertainties, the statistics appear consistent with expectations based on the inferred degradation of associated surfaces and their stratigraphic position: crater floor deposits do not embay alluvial fan deposits, whereas the generally younger fill/mantling deposits may bury some crater floor and/or alluvial fan deposits in the southern portion of the study area. We therefore conclude that the fan deposits were emplaced during the Amazonian to around the time of the Amazonian-Hesperian transition. Crater floor deposits are older, likely of Hesperian age, and mantling deposits are generally Amazonian. If the fans formed as a result of precipitation in the form of rain or snow [*Moore and Howard*, 2005; *Howard and Moore*, 2011], their young age requires a climate optimum relatively late in Martian history after most precipitation-driven fluvial activity is thought to have occurred [*Howard et al.*, 2005; *Moore and Howard*, 2005; *Bibring et al.*, 2006; *Fassett and Head*, 2008].

[15] Comparison with geomorphic events inferred to have occurred in southern Margaritifer Terra and elsewhere on Mars provides a regional context. Episodes of water ponding in Holden crater and adjacent Uzboi Vallis [*Grant et al.*, 2008] in the late Noachian or well into the Hesperian [*Irwin and Grant*, 2011] was likely associated with a widespread, late interval of precipitation-driven runoff [*Howard et al.*, 2005; *Moore and Howard*, 2005; *Fassett and Head*, 2008]. The ages inferred for the crater floor deposits are broadly contemporary and may record the effects of this widespread wetter period. The inferred age of the alluvial fan deposits appear younger, however, and their formation may require an even later wet period.

[16] Formation of the fan deposits near or after the Amazonian-Hesperian boundary could relate to local, regional, or perhaps global-scale events. Local events could include the impact-induced release of volatiles, generating

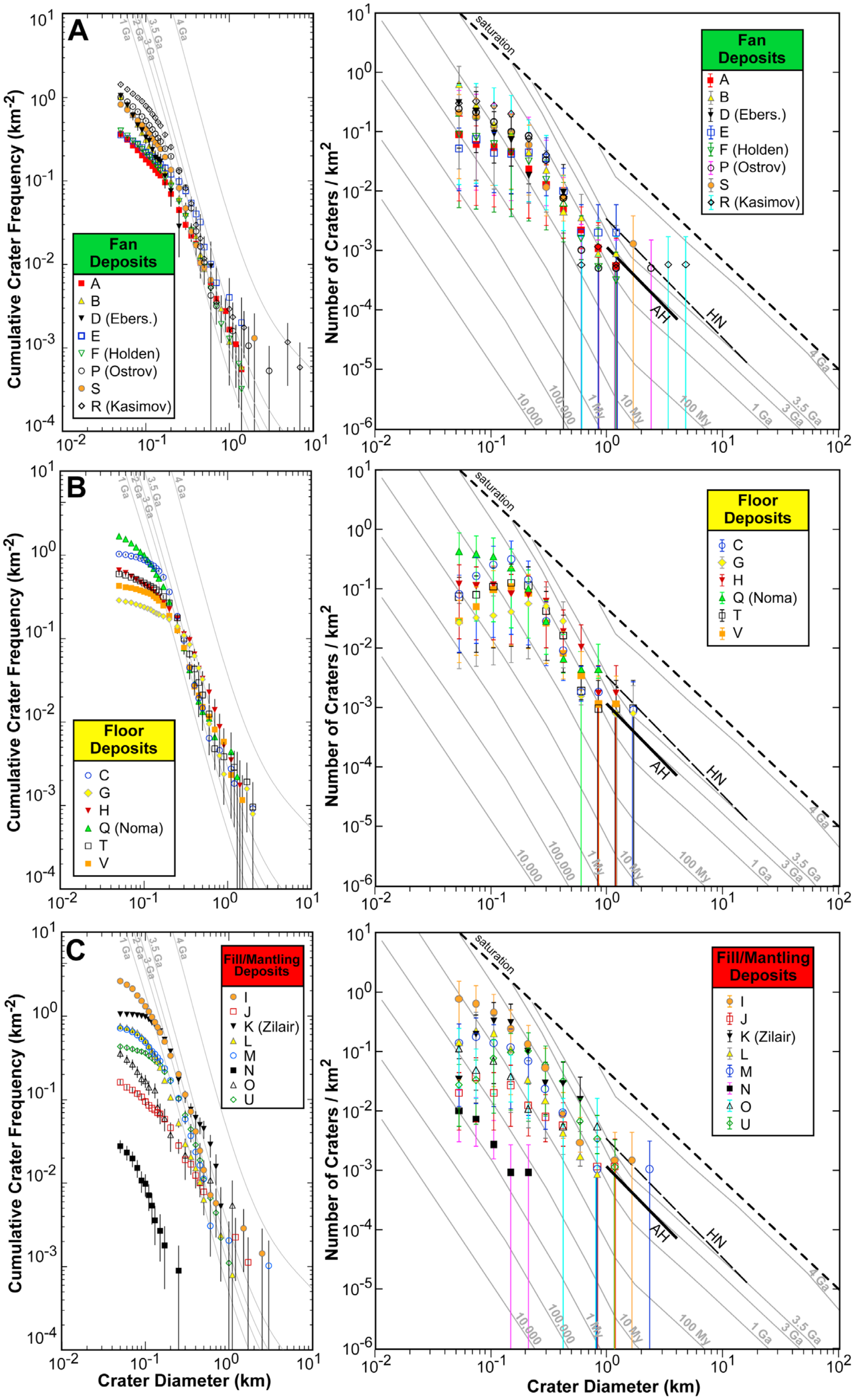

Figure 2. (left) Cumulative and (right) incremental crater statistics for (a) fan deposits, (b) crater floor deposits, and (c) fill/mantling deposits. AH and HN in incremental plots marks the hypothesized position of the Amazonian-Hesperian and Hesperian-Noachian boundary, respectively. Error bars reflect $\pm 1/N^{0.5}$ and $N \pm N^{0.5}/A$ for data points in cumulative and incremental plots, respectively, where N is the number of craters and A is the area. See text and auxiliary material for discussion.

runoff, valley incision and the formation of fluvial features on and near the crater and ejecta [e.g., *Maxwell et al.*, 1973]. Such water-driven activity is thought to be the result of excavation and melting of subsurface ice during and after the impact [*Jones et al.*, 2011] and may persist up to 10^4 or 10^5 years [*Newsom et al.*, 1996; *Abramov and Kring*, 2005].

[17] The impact that formed crater Hale, located just south of the study area (35.7S, 323.6E), is a potential source for local volatiles. The ejecta from Hale is incised by numerous valleys [*Jones et al.*, 2011] and the crater likely formed between the early to middle Amazonian [*Jones et al.*, 2011] and Amazonian-Hesperian boundary [*Cabrol et al.*, 2001]. Although the fan deposits may be contemporary, there are several aspects of the Hale valleys and the alluvial fan deposits that suggest their formation is not related. First, some of the fan deposits occur 700–800 km from Hale (e.g., in craters A, B, and R, Figure 1) and additional fan deposits may be even farther outside the study area. Second, there is little correlation between Hale and the azimuth of craters containing alluvial fan deposits as might be expected for a local source of water vapor under the influence of prevailing winds. Third, many craters with floor deposits (e.g., craters G, H, V, and T, Figure 1) are located closer to Hale than craters with fan deposits, which is the opposite of what would be expected if Hale was the source of water for the fans. Finally, many craters closest to Hale contain fill/mantling deposits (e.g., crater N, Figure 1). Hence, there is not a convincing connection between the formation of crater Hale and the emplacement of the alluvial fan deposits. Other possible impact crater-related sources of water are likely older [e.g., *Irwin and Grant*, 2011] and even less likely to be associated with fan development.

[18] The widespread occurrence of fans in Margaritifer Terra seems to require synoptic precipitation, perhaps enhanced over time and locally by orbital variations and topography. If synoptic precipitation was responsible (as either snow or rain), there should be morphologic evidence of contemporaneous/concurrent water-driven erosion elsewhere on Mars.

[19] Late intervals of water-driven erosion that may be contemporary with the fans include incision of valleys on some Martian volcanoes [*Gulick and Baker*, 1990; *Fassett and Head*; 2008], hypothesized supraglacial and proglacial valleys [*Fassett et al.*, 2010], and late geomorphic activity in Electris [*Grant and Schultz*, 1990] that included valley incision [*Howard and Moore*, 2011]. In addition, *Moore and Howard* [2005] suggested fans elsewhere on Mars formed at the same time as those in southern Margaritifer Terra, thereby implying global-scale processes. Water delivered to the northern lowlands during late outflow channel formation [e.g., *Rotto and Tanaka*, 1995] and later redistributed as precipitation in the southern highlands [*Luo and Stepinski*, 2009] is one possible source of runoff for the fans. Under this scenario, fan development occurred during a relatively short-lived late interval. Because two of the craters with fan deposits are finalists for the MSL landing site, such a relatively young age implies that MSL could sample materials emplaced later in Martian history than previously considered.

[20] **Acknowledgments.** We thank the people at the University of Arizona, Ball Aerospace, Malin Space Science Systems, the Jet Propulsion Laboratory, and Lockheed Martin that built and operate the HiRISE and CTX cameras and Mars Reconnaissance Orbiter spacecraft. Reviews by Cathy Quantin and an anonymous reviewer improved the manuscript. This work was supported by NASA.

[21] The Editor thanks an anonymous reviewer and Cathy Quantin for their assistance in evaluating this paper.

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