Fluid lava flows in Gusev crater, Mars

Ronald Greeley,[1] Bernard H. Foing,[2] Harry Y. McSween Jr.,[3] Gerhard Neukum,[4] Patrick Pinet,[5] Mirjam van Kan,[2] Stephanie C. Werner,[4] David A. Williams,[1] and Tanja E. Zegers[2]

Received 12 January 2005; revised 3 March 2005; accepted 13 April 2005; published 21 May 2005.

[1] Rocks on the floor of Gusev crater are basaltic in composition, as determined from measurements by the Mars Exploration Rover, Spirit. On the basis of compositional data, models of the basaltic lavas at the time of their emplacement suggest viscosities of 2.3 to 50 Pa · s (dependent on the number of phenocrysts and vesicles that were present), which would be more fluid than terrestrial tholeiitic lavas and comparable to mare lavas on the Moon or Archean high-Mg basalts on Earth. Morphological data and crater counts derived from the High Resolution Stereo Camera on Mars Express and other orbiters suggest that the lavas flooded Gusev crater at about 3.65 b.y. and postdate older floor materials, such as putative sediments emplaced by Ma'adim Vallis.

Citation: Greeley, R., B. H. Foing, H. Y. McSween Jr., G. Neukum, P. Pinet, M. van Kan, S. C. Werner, D. A. Williams, and T. E. Zegers (2005), Fluid lava flows in Gusev crater, Mars, *J. Geophys. Res.*, *110*, E05008, doi:10.1029/2005JE002401.

1. Introduction

[2] Gusev crater is the landing site for Spirit, the first of two Mars Exploration Rovers (MER) [*Squyres et al.*, 2004]. This site (Figure 1) was chosen because the floor deposits were hypothesized to include sedimentary materials deposited by the channel, Ma'adim Vallis, which incised the south rim of the crater as mapped by *Kuzmin et al.* [2000] and *Cabrol et al.* [2003]. However, these and other authors recognized that deposits of other origins could also be present on the floor [*Greeley*, 2003; *Golombek et al.*, 2003; *Milam et al.*, 2003].

[3] Analysis of the rocks on the floor of Gusev crater using MER instruments reveals a dominance of likely picritic basaltic lava compositions [*McSween et al.*, 2004]. This result is based on chemical compositions measured by the Alpha Particle X-ray Spectrometer [*Gellert et al.*, 2004] and mineral compositions derived from the Miniature Thermal Emission Spectrometer (MiniTES) [*Christensen et al.*, 2004] and the Mössbauer Spectrometer [*Morris et al.*, 2004]. Basaltic compositions are also consistent with spectra from Pancam multispectral images [*Bell et al.*, 2004] and textures observed using the Microscopic Imager on MER [*Herkenhoff et al.*, 2004]. These results apply to the rocks observed at the landing site and on the traverse along the floor of Gusev crater toward the Columbia hills, some 2.5 km to the east.

[4] On the traverse to the Columbia hills, Spirit did not encounter any outcrops. Consequently, all of the rocks analyzed are inferred to be ejecta from local impacts, including Bonneville crater [*Grant et al.*, 2004]. Moreover, none of the rocks analyzed yielded results indicative of primary sedimentary origins, although there is compelling evidence that some of the rocks have been altered by weathering processes involving liquid water [*McSween et al.*, 2004].

2. Analysis

[5] We suggest that the basaltic rocks around the Spirit landing site were erupted as one or more very fluid lava flows which were emplaced on older floor-filling materials. Eruptions could have occurred within Gusev crater or exterior to the crater. The lava flow(s) were subsequently "impact-gardened" to produce the fragmental surface layer over which Spirit traversed. We consider the proposed flows and style of eruption to be analogous to most mare lava flows on the Moon, which involved very fluid mafic magmas erupted as flood lavas [*Head*, 1976, 1982]. For example, Figure 2 shows the floor of Gusev crater imaged by the High Resolution Stereo Camera (HRSC) [*Neukum et al.*, 2004] on board the Mars Express orbiter compared with Grimaldi crater on the Moon, which was flooded with basaltic lavas but has no indication of the source vents. Lunar mare lavas are considered to have been so fluid and massive that vestiges of vent structures, such as spatter cones, were buried by the flows, did not form, or were destroyed by high-volume eruptions [*Greeley*, 1976]. This style of eruption is consistent with estimates of the viscosity of the lunar lavas derived by *Murase and McBirney* [1970, 1973] based on compositions of the Apollo 11 basalts. They produced synthetic lunar lavas and determined the viscosity

[1]Department of Geological Sciences, Arizona State University, Tempe, Arizona, USA.
[2]European Space Agency, European Space Research and Technology Centre, Noordwijk, Netherlands.
[3]Department of Geological Sciences, University of Tennessee, Knoxville, Tennessee, USA.
[4]Department of Earth Sciences, Freie Universität Berlin, Berlin, Germany.
[5]UMR 5562/CNRS/GRGS, Observatoire Midi-Pyrénées, Toulouse, France.

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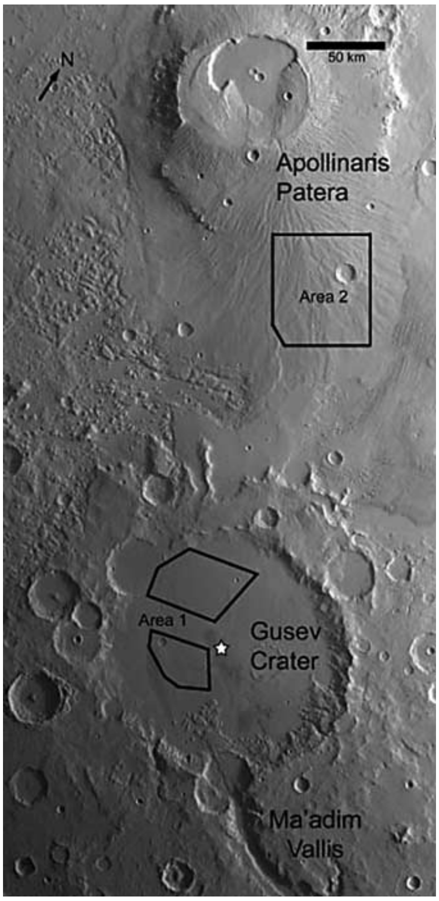

Figure 1. High Resolution Stereo Camera (HRSC) image of Gusev crater and the volcano, Apollinaris Patera. Ma'adim Vallis is the channel that apparently emptied into Gusev crater, breaching the crater rim from the south. Areas 1 and 2 show where crater size frequencies were obtained (Figure 5). The star shows the landing location of the rover, Spirit.

to be about 0.45–1 Pa · s, similar to motor oil at room temperatures. Such flows would be capable of flooding extensive areas, such as the floors of craters, especially if erupted at the high rates of effusion inferred for the Moon.

[6] In order to gain insight into the possible rheological properties of the basaltic rocks on the floor of Gusev crater at the time of their eruption, we used the compositions obtained from the Spirit rover [*McSween et al.*, 2004] to model their properties and compared the results to those for lunar and terrestrial lavas. Table 1 shows that basaltic lavas in Gusev crater could have had liquid viscosities of ~2.8 Pa · s (more fluid than terrestrial tholeiitic lavas), somewhat similar to the synthetic lunar lavas. However, we note that if olivine or other crystals were present upon eruption, as suggested in some of the rocks in Gusev [*McSween et al.*, 2004], then the bulk viscosity of lavas would have been higher [see, e.g., *Pinkerton and Stevenson*, 1992]. For example, if 10% crystals were present in the magma upon eruption, then our modeling indicates that the bulk viscosity of the flow increases to ~8 Pa · s. If 25% crystals are present in the magma upon eruption, then the bulk viscosity of the flow increases to 50 Pa · s, which is still more fluid than tholeiitic flood basalts in the Columbia River Plateau. The presence of vesicles in the lava would have increased the effective viscosity, so that these values should be considered as lower limits on the potential viscosity of the Gusev lavas. Nevertheless, it seems likely that the Gusev lavas were very fluid at the time of eruption, and were emplaced as flood lavas.

[7] As shown in Figures 3 and 4, the morphology of features on the floor of Gusev is comparable to lunar mare surfaces in many respects. Notable is the presence of mare ridges (so-called "wrinkle ridges") and benches along the contact with the crater wall. Although the ridges on the Moon and Mars are probably structural in origin (resulting from crustal folding and faulting [e.g., *Golombek et al.*, 1991]), their presence is thought to reflect the style of deformation typical for massive basalt flows that involved

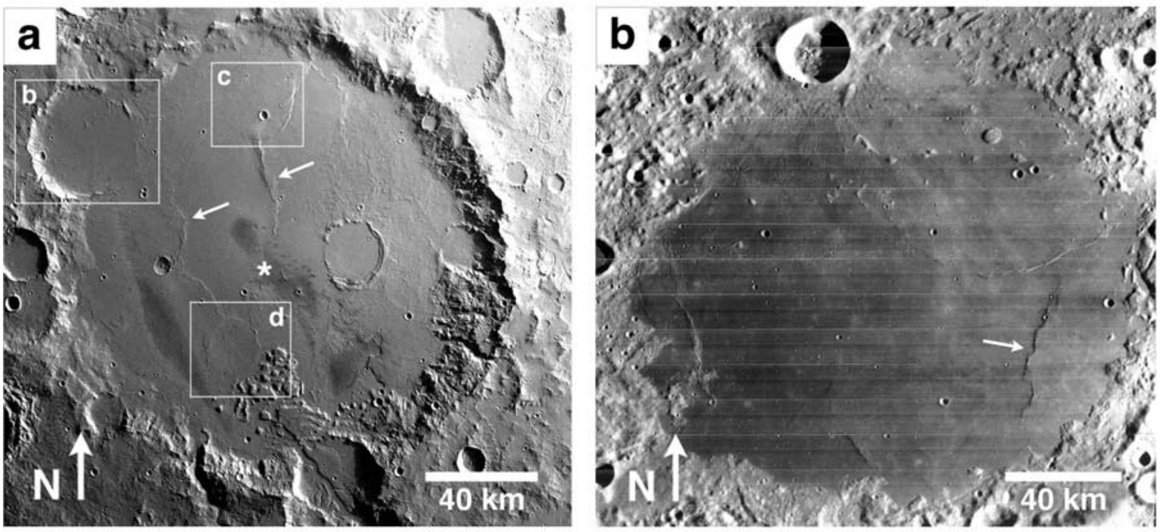

Figure 2. (a) The floor of Gusev crater imaged by HRSC showing mare-type "wrinkle" ridges (arrows) and the locations of Figures 2b, 2c, and 2d. The star indicates the location of the Spirit landing (HRSC image h0648_0000.nd3). (b) Grimaldi crater on the Moon, which is partly filled with basaltic lavas that have deformed into mare ridges (arrows) (Lunar Orbiter IV frame M-161).

Table 1. Compositions and Inferred Properties of Basalt in Gusev Crater Compared With Lunar and Terrestrial Lavas[a]

Component/Parameter	Mars: Humphrey RAT-Abraded[b]	Moon: Synthetic Mare Basalt	Moon: Low-TiO_2 Mare Basalt	Earth: Kambalda Komatiite	Earth: Katinniq Komatiitic Basalt	Earth: Tholeiitic Basalt
SiO_2	46.1	43.0	43.6	45.0	46.9	50.9
TiO_2	0.52	11.0	2.6	0.3	0.6	1.7
Al_2O_3	10.6	7.7	7.9	5.6	9.8	14.6
Fe_2O_3	2.99	-	-	1.4	-	-
FeO	15.3	21.0	21.7	9.2	14.4	14.6
MnO	0.39	0.26	0.3	0.2	0.3	-
MgO	12.2	6.5	14.9	32.0	18.9	4.8
CaO	7.70	9.0	8.3	5.3	8.6	8.7
Na_2O	2.59	0.4	0.2	0.6	0.3	3.1
K_2O	0.06	0.21	0.05	0.03	0.05	0.8
T_{liq}, °C	1270	1215[c]	1336	1638	1419	1160
ρ at T_{liq}, kg/m^3	2820	2980	2900	2770	2800	2750
c, J/kg·°C	1560	1460	1570	1790	1640	1480
μ at T_{liq}, Pa · s	2.8	0.45	0.40	0.08	0.74	86
Composition location	Gusev crater, Mars	SLS, based on Apollo 11 basalt	Apollo 12 Sample 12002	Western Australia	Cape Smith Belt, Canada	Columbia River Basalt, Washington
Reference	*McSween et al.* [2004]	*Murase and McBirney* [1970]	*Walker et al.* [1976]	adapted from *Lesher and Arndt* [1995]	*Barnes et al.* [1982]	*Murase and McBirney* [1973]

[a]Liquidus temperatures (T_{liq}) were calculated using the program MELTS [*Ghiorso and Sack*, 1995]. Lava density (ρ) was calculated using the method of *Bottinga and Weill* [1970] and the parameters of *Mo et al.* [1982]; lava viscosity (μ) was calculated using the method of *Shaw* [1972]; and specific heat (c) was calculated from the heat capacity data of *Lange and Navrotsky* [1992].

[b]A subsequent recalibration of the Spirit APXS data suggests slightly greater iron and titanium contents, but the values would not have a significant impact on the modeled viscosity.

[c]*Murase and McBirney* [1970] inferred that the liquidus temperature of the synthetic mare basalts to be between 1380 and 1300°C on the basis of observations of crystallization experiments.

cooling units 10s to 100s of meter thick [*Waters*, 1991]. On the Moon, as these lavas cooled and degassed, their surfaces subsided, leading to deformation and the formation of mare ridges (Figure 2). Where settling occurred over flooded impact craters, a circular ridge often indicates the outline of the crater. Similar features are seen on the floor of Gusev crater (Figure 3). "Ponded" basalt flows on the Moon and Earth also often leave high lava marks in the form of benches along the contact with higher topography [*Wilhelms*, 1987] and are suggested to be analogous to some of the features seen on the margin of the Gusev floor (Figure 4), consistent with the proposal by *Martínez-Alonso et al.* [2005].

[8] Our interpretation of a primary igneous origin for the basaltic materials on the floor of Gusev includes the assumption that the rocks analyzed by Spirit were excavated from lava flows by local impacts. As discussed by *Kuzmin et al.* [2000] and others, some of the surficial materials on the floor could include ejecta derived from impacts exterior to Gusev, such as Kane crater immediately west of Gusev. Thus the basalts analyzed by MER could have been emplaced exterior to Gusev crater and subsequently impacted, and the ejecta could have been thrown onto the floor of Gusev. However, we doubt that all of the material encountered by Spirit on the traverse to the Columbia Hills can be accounted for in this fashion. For example, Bonneville crater is 210 m in diameter and is considered to have formed in unconsolidated materials [*Grant et al.*, 2004]. A crater of this size would have excavated to a minimum depth of 20 m, suggesting that the fragmental basaltic layer would be at least this thick. We propose that it is more reasonable for a layer of this thickness to be derived from in situ bedrock of primary igneous origin, rather than representing a deposit of impact ejecta derived from outside Gusev crater. Moreover, the morphologic features such as the mare ridges and "benches" suggest that the basalts were emplaced as lava flows within the crater. Our interpretation for Gusev is consistent with the analysis of *Leverington and Maxwell* [2004] for a 45 km in diameter crater in the Memnonia region of Mars, which they suggest is also filled with lavas, comparable to lunar mare deposits. Our interpretation is also consistent with previous suggestions that some Martian lava flows were extremely fluid [*Schonfeld*, 1977; *Baird and Clark*, 1984].

[9] In order to gain insight into the ages of the potential volcanic materials in and around Gusev crater, we have obtained crater size-frequency distributions (Figure 5) using HRSC data from Mars Express orbits 24, 72, 283, and 335 for the units characterized by the mare-type wrinkle ridges mapped by *Kuzmin et al.* [2000] as Members 1 and 2 of the Gusev Crater Formation, and for flank materials on Apollinaris Patera, the volcano north of Gusev (Figure 1). On the basis of the algorithm of *Hartmann and Neukum* [2001], the crater-model age for the mare ridge units is 3.65 eons, with the suggestion of a resurfacing event at 3.31 eons, while the flank unit of Apollinaris is 3.76 eons. Although there is controversy within the planetary community with regard to ages estimated for Mars based on crater counts, especially for small craters [e.g., *McEwen*, 2004], these results are based primarily on craters ∼>100 m in diameter and can be used for assessing the relative ages for the units analyzed. We suggest that the proposed emplacement of lava flows on the floor of Gusev crater occurred at about the same time as

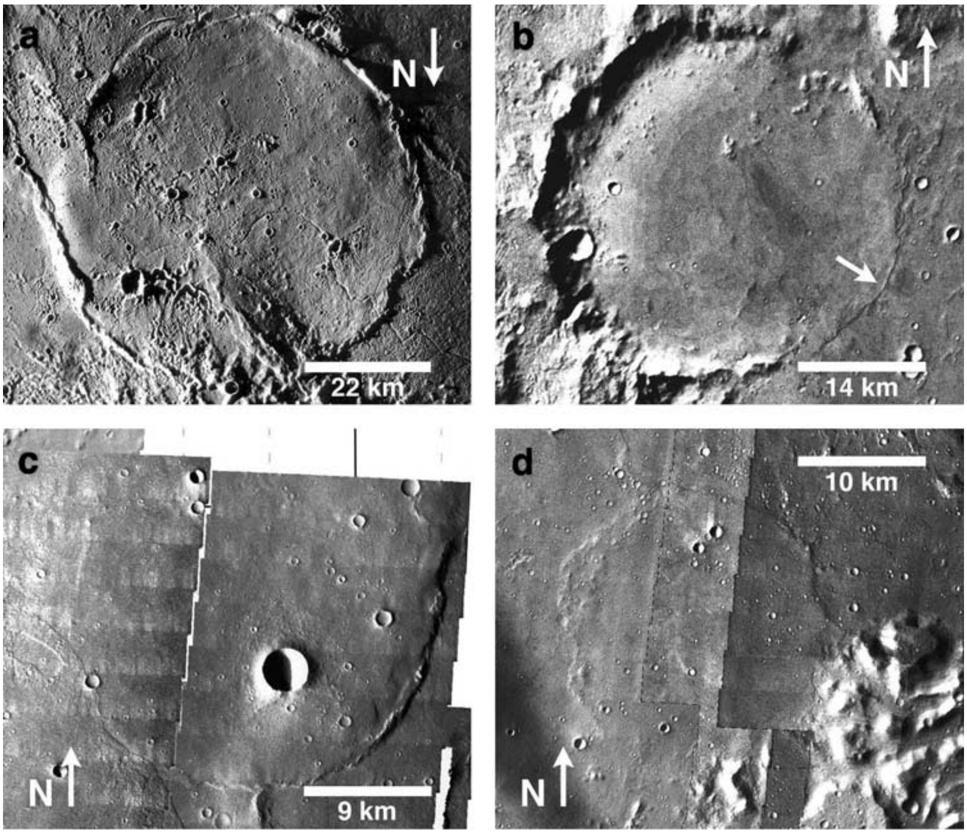

Figure 3. (a) Lunar crater Lambert R, in which mare ridges developed over the crater rim as the lavas subsided, leaving an outline of the crater (Apollo 15 frame M-1011 [from *Wilhelms*, 1987]). (b) Viking Orbiter image mosaic of the northwest corner of Gusev crater, showing circular ridge (arrow) that outlines a partly flooded crater. (c and d) Mars Odyssey THEMIS images showing circular ridges inferred to represent buried crater on the floor of Gusev crater.

the volcanic activity on the southern flank of Apollinaris Patera, which could reflect a general period of volcanism in the region.

3. Conclusions

[10] Summarizing from previous work [*Kuzmin et al.*, 2000; *Cabrol et al.*, 2003; *Golombek et al.*, 2003], the impact that formed Gusev crater would have generated brecciated rock fragments and impact melt, which would constitute the earliest deposits in Gusev. Subsequent flooding from Ma'adim Vallis is thought to have emplaced sedimentary materials. The results from mapping of Gusev crater in combination with Spirit rover data now show that basaltic rocks were among the latest materials emplaced on the floor of the crater, disregarding surficial deposits such as windblown sand and dust. Our analysis of the inferred properties and morphology of the proposed basalts suggest that they were emplaced as very fluid lava flows, analogous to the mare basalt flows on the Moon. It is likely that the origins and emplacement sequence of all of the materials in Gusev is substantially more complex, with the possibility of multiple influxes of materials from Ma'adim Vallis, multiple eruptions of basalts, and deposition of windblown dust and other materials from the atmosphere. However, if our interpretation of the emplacement of fluid basalts in

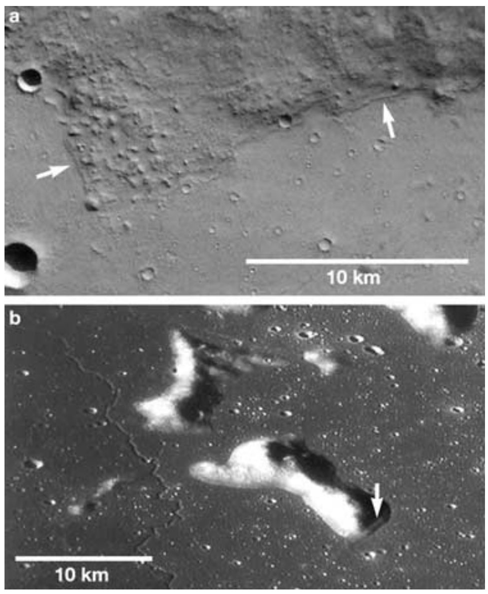

Figure 4. (a) Benches (arrows) on the western margin the Gusev crater floor compared to (b) similar features on the Moon thought to represent "high lava marks" left as lava flow(s) cooled and contracted.

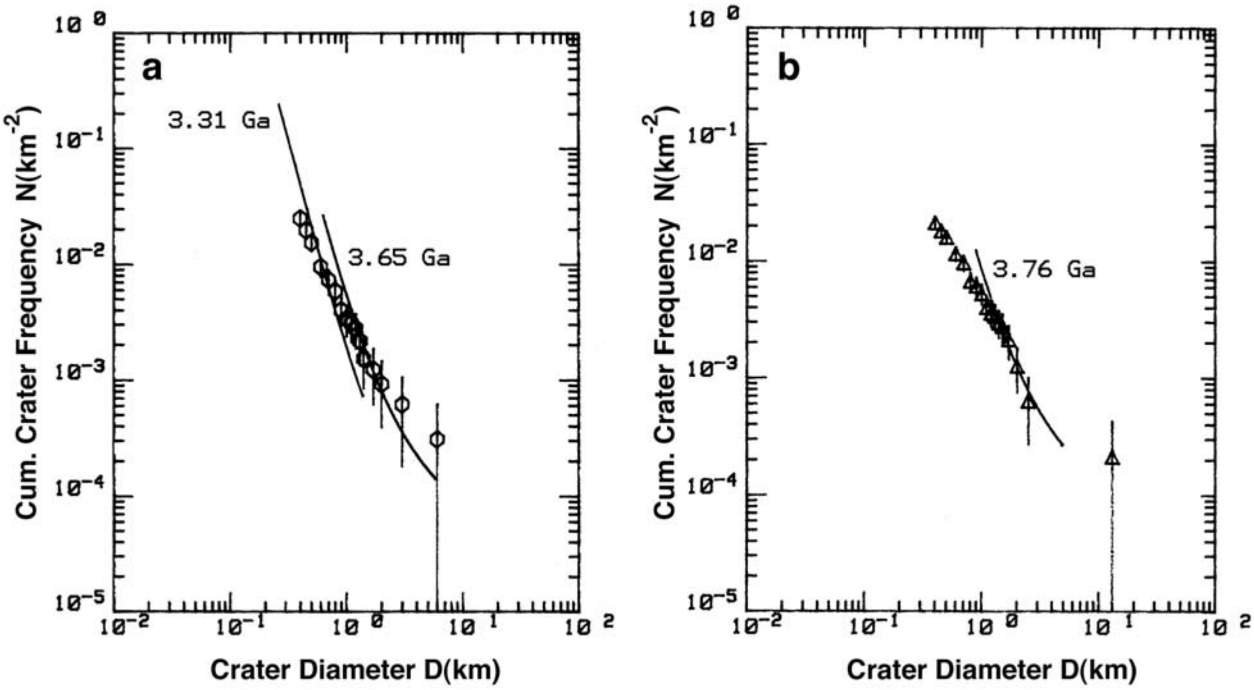

Figure 5. Crater size-frequency diagrams and estimated crater-retention ages for (a) the putative basalt flow on the floor of Gusev crater, based on 125 craters (Area 1 of Figure 1), and (b) flank materials on the volcano, Apollinaris Patera, based on 139 craters (Area 2 of Figure 1).

Gusev crater is correct, then other smooth-floored craters on Mars should be reassessed for their potential partial filling by lavas, as suggested by *Leverington and Maxwell* [2004]. Moreover, if the sequence proposed here is correct, then the ages estimated for the primary unit would suggest that eruptions occurred at 3.65 b.y., with the inferred sedimentary materials beneath the lavas to have been deposited even earlier.

[11] **Acknowledgments.** We thank the Mars Express and HRSC flight team for the successful acquisition of data used in this study. We are grateful for the helpful comments by Pater Lanagan, Nathalie Cabrol, and Michael Lesher. This investigation was supported by NASA, DLR, ESA, and CNES through individual grants and contracts.

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B. H. Foing, M. van Kan, and T. E. Zegers, European Space Agency, European Space Research and Technology Centre, P.O. Box 299, 2200 AG Noordwijk, Netherlands. (t_zegers@rssd.esa.int)

R. Greeley and D. Williams, Department of Geological Sciences, Arizona State University, Box 871404, Tempe, AZ 85287-1404, USA. (greeley@asu.edu)

H. McSween Jr., Department of Geological Sciences, University of Tennessee, Knoxville, TN 37996-1410, USA. (mcsween@utk.edu)

G. Neukum and S. C. Werner, Department of Earth Sciences, Freie Universität Berlin, Malteserstrasse 74-100, Building D, D-12249 Berlin, Germany. (gneukum@zedat.fu-berlin.de)

P. Pinet, UMR 5562/CNRS/GRGS, Observatoire Midi-Pyrénées, Toulouse, France. (patrick.pinet@cnes.fr)