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Quantifying the amount of impact ejecta at the MER landing sites and potential paleolakes in the southern Martian highlands

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[1] Applying previous equations for estimating ejecta thickness to Mars, tens of meters of ballistically-emplaced impact ejecta might be expected over the heavily-cratered southern Martian hemisphere. The calculated thickness of ejecta material, even accounting for large uncertainties in methods of estimation, is not enough to fully explain observed depth discrepancies in Gusev Crater or in other potential Martian paleolakes. Ejecta contributed to the Spirit landing site in Gusev Crater is largely derived from local craters while distal ejecta from large, faraway craters dominates the contribution to the Opportunity landing site in Meridiani Planum. However, emplacement of this type of ejecta probably predates the present surfaces. Thira crater may have excavated impact-melt products created by Gusev, samples of which would provide a unique insight into the composition of the bulk Martian crust. Though ballistically-emplaced crater ejecta contribute a relatively small amount of material to any given site, this type of material provides important lithologic diversity.

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1. Introduction

[2] Mars, like other terrestrial planets, has been extensively modified by impacts large and small: from the heavily-cratered, presumably ancient southern highlands terrane [*Strom et al.*, 1992] to small rocks tossed out by the tiny Bonneville crater near the Spirit landing site [*McSween et al.*, 2004]. However, unlike the abundant impact breccias in the lunar and meteorite collections, the igneous nature of the Martian meteorites provides little information about impact mixing and comminution on Mars. In contrast, the Mars Exploration Rovers (MER) and future highly-capable missions such as the Mars Science Laboratory afford the opportunity to discover abundant, in situ Martian impact-affected material.

[3] The MER landers, Spirit and Opportunity, arrived at Mars in January 2004, with the science goal to assess the history of environmental conditions at sites that may once have been wet and favorable to life. Spirit landed in Gusev Crater, a 160-km-diameter impact crater and suggested paleolake in the southern highlands. The interior of Gusev Crater is currently a rock-strewn plain covered with basaltic rocks that have only thin coatings and veins caused by aqueous activity [*Squyres et al.*, 2004a]. Opportunity landed at Meridiani Planum and discovered hematite concretions, sulfate-salt minerals, and ripple patterns. These features have been suggested as evidence that the rocks were either formed in water or extensively exposed to water [*Squyres et al.*, 2004b], or deposited as an aqueously-altered impact-surge deposit [*Knauth et al.*, 2005].

[4] Martian paleolakes have been offered as landing sites for *in situ* and sample-return missions because of their high probability of containing climatic and hydrologic records and potential biomarkers. Prospective paleolake sites have been identified in closed craters based on discrepancies between the craters' expected and measured depths and interpretation of associated fluvial and lacustrine features [e.g., *Cabrol and Grin*, 1999]. Many of these sites have unequivocal evidence of at least some modification due to liquid water, such as river channels or deltas. However, it is difficult to infer the total thickness of inferred fluvial or lacustrine sediment packages in these craters. For instance, Gusev crater is shallower than expected and has a clear fluvial system running into it [*Cabrol et al.*, 1998], but numerous sediment sources beside fluvial and lacustrine have been suggested as being able to at least partially fill Gusev, including aeolian deposits, ashfall from Appolinaris Patera [*Milam et al.*, 2003], and basaltic lava flows [*Martinez-Alonso et al.*, 2005; *McSween et al.*, 2004]. This paper gives constraints on the maximum thickness of ballistically-emplaced crater ejecta that might be present at several sites on Mars to examine its importance relative to the numerous other sedimentation processes operable on Mars.

2. Calculations

[5] The thickness of ejecta (Th) as a function of distance from an impact crater (r) can be estimated based on terrestrial and lunar craters [*Pike*, 1974] using the transient-crater radius R: $\mathrm{Th} = 0.033 \times R \times (r/R)^{-3.0}$. The total ejecta thickness sums this calculation over all craters on the surface younger than the point of interest. Calculations using alternative estimates [e.g., *Housen et al.*, 1983] predict smaller thicknesses at equivalent distances, so the calculations presented here can be considered upper limits. This simple scaling relationship appears to hold for the terrestrial and lunar cases and so should be applicable to many Martian craters. However, this formula does not take into account curvature of the planetary surface, antipodal thickening of ejecta, ejecta blankets vs. rays; variable impact angles, asymmetry of the ejecta deposit; or mixing of local material with ejecta to form a thicker layer of mixed debris [*Petro and Pieters*, 2004]. This type of calculation

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Table 1. Ejecta Thickness Calculations

Site/Crater	Lat	Lon	D, km	Measured d, km	Calculated d, km	Δd, km	Th, m	% fill	Reference
Opportunity	−2.0	5.9					44		*Squyres et al.* [2004a]
Spirit	−14.6	184.7	160	1.9	4.9 ± 0.7	3.0 ± 0.7	45	2	*Squyres et al.* [2004b]
A	−72.9	204.7	55.8	3.2	2.8 ± 0.3	-0.4 ± 0.3	256	−64	J. M. Boyce (personal communication, 2005)
B	−72.0	82.3	64.7	2.3	3.0 ± 0.4	0.7 ± 0.4	131	19	J. M. Boyce (personal communication, 2005)
Vishniac	−76.6	84.1	78.3	2.2	3.3 ± 0.4	1.1 ± 0.4	107	10	J. M. Boyce (personal communication, 2005)
FH	18.4	282.3	40	0.4	2.3 ± 0.2	2.0 ± 0.2	24	1	*Fassett and Head* [2005]
CG26	26.0	31.5	66	0.6	3.0 ± 0.4	2.4 ± 0.4	8	0	*Cabrol and Grin* [1999]
CG27	24.6	32.0	34	0.5	2.1 ± 0.2	1.6 ± 0.2	14	1	*Cabrol and Grin* [1999]
CG28	22.0	7.0	152	0.5	4.7 ± 0.7	4.2 ± 0.7	129	3	*Cabrol and Grin* [1999]
CG33	17.2	32.4	30	0.7	2.0 ± 0.2	1.3 ± 0.2	13	1	*Cabrol and Grin* [1999]
CG38	12.1	21.0	36	0.7	2.2 ± 0.2	1.5 ± 0.2	237	16	*Cabrol and Grin* [1999]
CG40	11.5	20.5	34	0.7	2.1 ± 0.2	1.4 ± 0.2	257	18	*Cabrol and Grin* [1999]
CG41	11.0	337.0	160	1.4	4.9 ± 0.7	3.5 ± 0.7	91	3	*Cabrol and Grin* [1999]
CG42	10.3	16.7	38	0.6	2.3 ± 0.2	1.7 ± 0.2	68	4	*Cabrol and Grin* [1999]
CG43	8.1	45.2	26	0.2	1.9 ± 0.2	1.7 ± 0.2	22	1	*Cabrol and Grin* [1999]
CG44	8.0	29.0	64	1.5	3.0 ± 0.4	1.5 ± 0.4	83	6	*Cabrol and Grin* [1999]
CG45	7.2	321.5	90	1.3	3.6 ± 0.5	2.3 ± 0.5	311	14	*Cabrol and Grin* [1999]
CG46	5.5	27.0	120	1.2	4.2 ± 0.6	3.0 ± 0.6	23	1	*Cabrol and Grin* [1999]
CG47	5.5	22.7	42	0.6	2.4 ± 0.3	1.8 ± 0.3	38	2	*Cabrol and Grin* [1999]
CG49	4.0	16.2	30	0.7	2.0 ± 0.2	1.3 ± 0.2	57	4	*Cabrol and Grin* [1999]
CG50	4.0	16.0	18	0.3	1.5 ± 0.1	1.2 ± 0.1	29	2	*Cabrol and Grin* [1999]
CG53	2.5	16.0	80	0.8	3.4 ± 0.4	2.6 ± 0.4	27	1	*Cabrol and Grin* [1999]
CG55	1.2	39.2	90	1.1	3.6 ± 0.5	2.5 ± 0.5	33	1	*Cabrol and Grin* [1999]
CG56	0.2	331.3	54	0.7	2.7 ± 0.3	2.0 ± 0.3	193	9	*Cabrol and Grin* [1999]
CG58	0.0	255.8	28	0.3	1.9 ± 0.2	1.6 ± 0.2	20	1	*Cabrol and Grin* [1999]
CG59	0.0	331.1	54	1.1	2.7 ± 0.3	1.6 ± 0.3	178	11	*Cabrol and Grin* [1999]
CG60	−0.2	270.4	30	0.4	2.0 ± 0.2	1.6 ± 0.2	58	4	*Cabrol and Grin* [1999]
CG61	−0.8	234.2	7	0.3	0.9 ± 0.1	0.6 ± 0.1	53	8	*Cabrol and Grin* [1999]

was developed primarily for ballistically-emplaced ejecta rather than the fluidized ejecta morphologies common on Mars. Nevertheless, distal ejecta deposits from large craters are observed on the Martian surface and this simple calculation gives some insight into the order of magnitude of this type of ejecta.

[6] I sidestep uncertainties in the Martian impact flux [*Hartmann and Neukum*, 2001; *Neukum et al.*, 2001] by directly utilizing The Catalog of Large Martian Impact Craters [*Barlow et al.*, 2000], containing impact craters measured from the Viking 1:2,000,000 photomosaics. Because the northern lowlands were resurfaced stratigraphically recently, only craters in Viking quadrangles 11–13 and 19–30 (southern cratered highlands) were included; a symmetric global impact flux is assumed. This inventory was further pruned to exclude Hellas, Argyre, and other large basins, degraded craters (Dc), and all craters smaller than 7 km (the simple-complex crater transition diameter on Mars, D_{tr}). Applying these criteria, 26,883 of the original 42,283 craters remain. For each remaining crater, I calculated the distance between it and the point of interest using the Haversine formula [*Sinnott*, 1984] and the mean Martian radius, and its transient crater diameter (D_{tc}) based on the measured crater diameter (D) using the equation of *Croft* [1985]: $D_{tc} = D^{0.85} \times D_{tr}^{0.15}$. This formulation has the advantage of taking target differences into account through the term containing D_{tc}. Using alternate estimates of transient-crater diameter ($D_{tc} = 0.5 - 0.65$ D) [*Grieve*, 1991] yields cumulative thicknesses that are smaller at every site by 25–70%. Again, these calculations can thus be considered maximum estimates.

[7] Table 1 shows the calculated cumulative ejecta thickness from all craters in the southern highlands (multiplied by two to simulate the global flux) at 29 sites of interest on the Martian surface, including the MER landing sites, several relatively deep craters used as control sites (Vishniac and two unnamed craters, J. M. Boyce, personal communication), and potential paleolakes in the cratered highlands [*Cabrol and Grin*, 1999; *Fassett and Head*, 2005]. I calculated the unfilled, post-modification depth (d) at each of the sites of interest using *Garvin et al.*'s [2000] empirical relationship based on observed diameter; the depth discrepancy (Δd) is the difference between the expected depth and the observed depth. Table 1 also shows the computed ejecta thickness as a percentage of the depth discrepancy for each crater, i.e., how much of the observed sediment can be attributed to crater ejecta. This thickness estimate is a maximum value, based on assumptions about scaling laws (as discussed above) and assuming that the site of interest is the oldest point and contains ejecta from all subsequently-formed craters. On the other hand, the contribution to distal ejecta blankets from secondary craters is neglected and may be sizable [*Haskin et al.*, 2003; *McEwen et al.*, 2005]. Given the uncertainties, the thickness estimates in Table 1 are only guides, but show that in general, several tens to hundreds of meters of crater ejecta is the maximum expected at most points on the Martian surface. Table 2 shows the craters that contribute a meter or more of ejecta to several illustrative sites.

3. Discussion

3.1. Fresh Craters

[8] I used several large craters in the southern highlands that have little to no discrepancy between their measured and calculated depths as control points (Vishniac and sites A and B in Table 1). These craters are relatively young and situated deep in the southern hemisphere; therefore, dou-

Table 2. Craters Contributing More Than 1 m Ejecta at Selected Sites

Name	Lat	Lon	D, km	Distance, km	Th, m
		Opportunity Landing Site			
none	−31.17	352.70	724.7	1883	5.3
Schiaparelli	−2.54	343.32	456.5	1340	3.0
none	−9.14	6.96	144.6	429	1.9
none	−2.58	8.29	49.9	144	1.3
		Spirit Landing Site			
Thira	−14.51	184.05	22.7	38	5.1
Zutphen	−13.98	185.66	37.1	66	5.0
Galdakao	−13.39	183.41	35.2	103	1.1
none	−14.91	186.09	28.5	82	1.1
		Crater FH			
none	18.29	280.37	52.5	111	3.5
none	21.06	284.25	63.5	190	1.3
		Crater CG28			
none	21.82	6.91	12.7	12	23.1
none	22.24	8.20	51.4	67	14.2
none	20.09	8.78	83.0	150	6.6
Rutherford	19.21	10.56	108.6	258	3.2
Trouvelot	16.22	12.90	152.8	476	1.6
Radau	17.07	4.67	105.9	320	1.6
none	24.27	9.40	58.8	188	1.0
none	24.36	10.79	75.3	249	1.0
none	−31.17	352.70	724.7	3256	1.0

bling the calculated thickness may be an overestimation. Nevertheless, it is clear in Table 1 that deep ejecta packages are neither expected nor observed in these craters.

3.2. Spirit Landing Site

[9] The cumulative thickness of ballistically-emplaced impact ejecta material in the interior of Gusev crater is ~45 m, demonstrating that exogenous crater ejecta can contribute only a small percent of the total current fill in Gusev crater. Table 2 shows that Thira and Zutphen craters each contribute approximately 5m of ejecta to the center of Gusev. Zutphen crater is located outside of Gusev crater and may have excavated ancient basaltic crust. On the other hand, the Thira ejecta blanket may contain a substantial portion of the Gusev fill sequence, possibly including Gusev-formed melt breccias and shocked central uplift rocks. Using estimates bounded by lunar and terrestrial relationships, 16–34 km of uplift may have occurred within Gusev crater (uplift = $0.022 \times D^{1.45}$ (lunar) $-0.086 \times D^{1.03}$ (terrestrial)) [*Cintala and Grieve*, 1998], with impact melting occurring above that. The impact-melt volume generated within Gusev is $9-20 \times 10^3$ km^3 (limits from the terrestrial and lunar cases) [*Cintala and Grieve*, 1998]. This volume, if it uniformly lined the final (modified) Gusev crater, would cover the crater floor to a depth of 0.4 to 1.0 km; more likely, it is bound in breccia lenses. Depending on how thick the Gusev fill package was at the time of Thira formation, Thira's excavation depth (~0.33 D_{tc}, or 2–3 km) [*Melosh*, 1989] may have penetrated such melt-breccia lenses. Even if Gusev is situated in an area with a crustal thickness in on the low side of the global mean, 50 ± 12 [*Wieczorek and Zuber*, 2004], Gusev impact-melt materials probably didn't sample the Martian mantle, but rather would have derived from upper crustal material. The interior of Gusev crater where the Spirit rover landed is now capped by basalt flows with no evidence for thick ejecta deposits over them, but these interesting melt materials may be present as Thira ejecta in the relatively older Columbia Hills region currently being traversed by the Spirit rover.

3.3. Opportunity Landing Site

[10] Even though there are several craters near Meridiani Planum, it is difficult to tell which postdate the current surface [*Hartmann*, 2005; *Newsom et al.*, 2003]. Table 2 shows that much of the calculated ejecta materials at the Opportunity site come from large craters relatively far from the landing site, rather than the small, nearby craters. These distal ejecta materials are emplaced with high velocities and can significantly rework the target rocks. The nature of ejecta material (fractured, shocked, unconsolidated) and the extent of reworking it causes may make ejecta at Meridiani Planum an easy target for infiltration and alteration by transient or episodic water.

3.4. Potential Paleolakes

[11] None of the craters identified as a potential paleolake in the southern highlands is likely to be completely filled by exogenous material. Though Table 2 shows that ejecta can be contributed by nearby and distant craters, depending on the site of interest, Table 1 shows that ballistically-emplaced crater ejecta contributes no more than ~20% of the thickness needed to explain the depth discrepancy in these craters, and in most cases is much less than that. The relative age of impact events and paleolake sedimentation are unknown; it seems likely that falling ejecta and other sedimentation events may be intermittent and deposits from these episodes may be interbedded and modified by each other.

4. Conclusions

[12] Based of the cases examined here, only a few tens of meters of foreign-derived material, at a maximum, may be present at any point on the current Martian surface. In some places, such as stratigraphically old craters with minimal subsequent depth modification, the sediment is probably largely contributed by crater ejecta. These sites may be good targets for places to collect rocks that represent the upper Martian crust within a several-hundred-mile radius. In other places, the ejecta component is minor compared with other sedimentation processes, such as aeolian or lacustrine activity. In particular, enclosed craters identified as potential Martian paleolakes, even those situated deep in the southern Martian highlands, cannot have their apparent depth discrepancy completely explained by filling from crater ejecta, even by doubling the estimates calculated here.

[13] The dramatic extent of aqueous alteration in the Meridiani Planum and Columbia Hills rocks reflects the old age of the material, but could also be a function of material type. Layers of impact ejecta comprise a highly brecciated mix of local and distant rock types, loosely coherent at the time of deposition, and possibly lightly shocked [*Johnson and Hörz*, 2003]. This mix of materials possesses significant chemical potentials because of material differences among neighboring clasts and strained surfaces from physical brecciation and shock; these potentials, coupled with large and possibly interconnected pore spaces, may accelerate weathering processes on the Martian surface.

[14] Impact ejecta deposits, though a small component of most sediment packages, can provide critical lithologic diversity to any particular landing site on Mars. In the example of Gusev crater, 5 m of basaltic crustal rocks are likely to be present as excavated by Zutphen crater. Analyses of these rocks would provide a comparison of the bulk crust to the Martian meteorites. Gusev impact-melt breccias may also be represented, though diluted as clasts, in a meters-thick ejecta deposit from Thira crater. Because the Gusev melt is a total melt of crustal material, a positive identification of this material would be profoundly important in pinning down the bulk Martian crustal composition, an important free parameter in most Martian evolution models. Though much of the Gusev interior is covered by basalt flows that postdate formation of Thira and possibly Zutphen, these materials might be found in the stratigraphically older Columbia Hills. On the other hand, the relatively small amount of ballistically-emplaced ejecta by this calculation implies that the majority of impact rocks found by the Spirit rover should be derived from mixing among local sources.

[15] Impact-derived material filling large Martian craters is likely situated at various levels in any sediment package, interfingered with deposits from other ubiquitous Martian surface processes such as aeolian, fluvial, and volcanic infilling. The probability of finding continuous, identifiable, distal impact ejecta layers may be small. However, ejecta deposits provide diverse material from distances far beyond the roving capability of a single lander.

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References

Barlow, N. G., J. M. Boyce, F. M. Costard, R. A. Craddock, J. B. Garvin, S. E. H. Sakimoto, R. O. Kuzmin, D. J. Roddy, and L. A. Soderblom (2000), Standardizing the nomenclature of Martian impact crater ejecta morphologies, *J. Geophys. Res.*, *105*, 26,733–26,738.

Cabrol, N. A., and E. A. Grin (1999), Distribution, classification, and ages of Martian impact crater lakes, *Icarus*, *142*, 160–172.

Cabrol, N. A., E. A. Grin, R. Landheim, R. O. Kuzmin, and R. Greeley (1998), Duration of the Ma'adim Vallis/Gusev Crater Hydrogeologic System, Mars, *Icarus*, *133*, 98–108.

Cintala, M. J., and R. A. F. Grieve (1998), Scaling impact melting and crater dimensions: Implications for the lunar cratering record, *Meteorol. Planet. Sci.*, *33*, 889–912.

Croft, S. K. (1985), The scaling of complex craters, *Proc. Lunar Planet. Sci. Conf., 15th*, Part 2, *J. Geophys. Res.*, *90*, suppl., C828–C842.

Fassett, C. I., and J. W. Head III (2005), Fluvial sedimentary deposits on Mars: Ancient deltas in a crater lake in the Nili Fossae region, *Geophys. Res. Lett.*, *32*, L14201, doi:10.1029/2005GL023456.

Garvin, J. B., J. J. Frawley, S. E. H. Sakimoto, and C. Schnetzler (2000), Global geometric properties of Martian impact craters: An assessment from Mars Orbiter Laser Altimeter (MOLA) digital elevation models, *Lunar Planet. Sci. Conf.* [CD-ROM], *XXXI*, Abstract 1619.

Grieve, R. A. (1991), Terrestrial impact: The record in the rocks, *Meteoritics*, *26*, 175–194.

Hartmann, W. K. (2005), Martian cratering 8: Isochron refinement and the chronology of Mars, *Icarus*, *174*, 294–320.

Hartmann, W. K., and G. Neukum (2001), Cratering chronology and the evolution of mars, *Space Sci. Rev.*, *96*, 165–194.

Haskin, L. A., W. E. Moss, and W. B. McKinnon (2003), On estimating contributions of basin ejecta to regolith deposits at lunar sites, *Meteorol. Planet. Sci.*, *38*, 13–34.

Housen, K. R., R. M. Schmidt, and K. A. Holsapple (1983), Crater ejecta scaling laws: Fundamental forms based on dimensional analysis, *J. Geophys. Res.*, *88*, 2485–2499.

Johnson, J. R., and F. Hörz (2003), Visible/near-infrared spectra of experimentally shocked plagioclase feldspars, *J. Geophys. Res.*, *108*(E11), 5120, doi:10.1029/2003JE002127.

Knauth, L. P., D. M. Burt, and K. H. Wohletz (2005), Impact origin of sediments at the Opportunity landing site on Mars, *Nature*, *438*, 1123–1128, doi:10.1038/nature04383.

Martinez-Alonso, S., B. M. Jakosky, M. T. Mellon, and N. E. Putzig (2005), A volcanic interpretation of Gusev Crater surface materials from thermophysical, spectral, and morphological evidence, *J. Geophys. Res.*, *110*(E1), E01003, doi:10.1029/2004JE002327.

McEwen, A. S., B. S. Preblich, E. P. Turtle, N. A. Artemieva, M. P. Golombek, M. Hurst, R. L. Kirk, D. M. Burr, and P. R. Christensen (2005), The rayed crater Zunil and interpretations of small impact craters on Mars, *Icarus*, *176*, 351–381.

McSween, H. Y., et al. (2004), Basaltic rocks analyzed by the Spirit Rover in Gusev Crater, *Science*, *305*, 842–845.

Melosh, H. J. (1989), *Impact Cratering: A Geologic Process*, 245 pp., Oxford Univ. Press, New York.

Milam, K. A., K. R. Stockstill, J. E. Moersch, H. Y. McSween, L. L. Tornabene, A. Ghosh, M. B. Wyatt, and P. R. Christensen (2003), THEMIS characterization of the MER Gusev crater landing site, *J. Geophys. Res.*, *108*(E12), 8078, doi:10.1029/2002JE002023.

Neukum, G., B. A. Ivanov, and W. K. Hartmann (2001), Cratering records in the inner solar system in relation to the lunar reference system, *Chronology Evol. Mars*, *96*, 55–86.

Newsom, H. E., C. A. Barber, T. M. Hare, R. T. Schelble, V. A. Sutherland, and W. C. Feldman (2003), Paleolakes and impact basins in southern Arabia Terra, including Meridiani Planum: Implications for the formation of hematite deposits on Mars, *J. Geophys. Res.*, *108*(E12), 8075, doi:10.1029/2002JE001993.

Petro, N. E., and C. M. Pieters (2004), Surviving the heavy bombardment: Ancient material at the surface of South Pole–Aitken Basin, *J. Geophys. Res.*, *109*, E06004, doi:10.1029/2003JE002182.

Pike, R. J. (1974), Ejecta from large craters on the Moon: Comments on the geometric model of McGetchin et al., *Earth Planet. Sci. Lett.*, *23*, 265–274.

Sinnott, R. W. (1984), Virtues of the Haversine, *Sky Telesc.*, *68*, 158.

Squyres, S. W., et al. (2004a), The Spirit Rover's Athena Science Investigation at Gusev Crater, *Mars, Science*, *305*, 794–800.

Squyres, S. W., et al. (2004b), The Opportunity Rover's Athena Science Investigation at Meridiani Planum, Mars, *Science*, *306*, 1698–1703.

Strom, R. G., S. K. Croft, and N. G. Barlow (1992), The Martian impact cratering record, in *Mars*, edited by H. H. Kieffer et al., pp.383–423, Univ. of Ariz. Press, Tucson.

Wieczorek, M. A., and M. T. Zuber (2004), Thickness of the Martian crust: Improved constraints from geoid-to-topography ratios, *J. Geophys. Res.*, *109*(E1), E01009, doi:10.1029/2003JE002153.

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