Salt tectonics and collapse of Hebes Chasma, Valles Marineris, Mars

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ABSTRACT

A photogeologic and physical modeling study indicates that Hebes Chasma, Mars, formed by collapse of the megaregolith. Local heating facilitated drainage of ~10^5 km^3 of brines and entrained particulates through fractures in the chasma floor and into a regional aquifer. A megaregolith rich in salts and water is implied by massive, low-gradient allochthonous flows that terminate in deep pits and troughs, by emergent diapirs, and by arching of Hebes Mensa. These structures are consistent with plastic and viscous deformation but inconsistent with collapse of basalt flows and/or tephra. Spectral measurements confirm that hydrated sulfate salts are spatially associated with allochthonous flows from depth and light-toned deposits. Collapse features and flows are present in many other chasmata in Valles Marineris, suggesting that widespread salt tectonics and dissolution may have shaped the region.

INTRODUCTION

The great chasmata of the Valles Marineris complex, Mars, have been attributed to many processes, including excavation by floods, wind, ice, or lava, formation of grabens by crustal extension or subsidence over dikes or ice wedges, and subsidence by subsurface removal of fluids (for reviews see Spencer and Fanale, 1990; Lucchitta et al., 1992; Schultz, 1998; Montgomery et al., 2009). Hebes Chasma (Fig. 1) lacks a surface outflow channel; therefore the flood hypothesis can be eliminated, and the other hypotheses that entail surface excavation do not explain where the missing 10^5 km^3 of material went. A purely tectonic origin for Hebes is difficult to reconcile with its irregular elliptical outline, blunt ends, a floor having multiple closed depressions, and a paucity of surrounding grabens. The remaining hypothesis, i.e., subsidence due to subsurface fluid flow, has been considered for Valles Marineris generally (e.g., Spencer and Fanale, 1990; Montgomery and Gillespie, 2005), but it has not been examined in detail for Hebes. Our paper summarizes the results of two new tests of the subsidence hypothesis for Hebes: photogeologic mapping produced a stratigraphic framework for interpreting the collapse structures, and scaled physical modeling reproduced key physiographic features caused by collapse from subterranean fluid withdrawal.

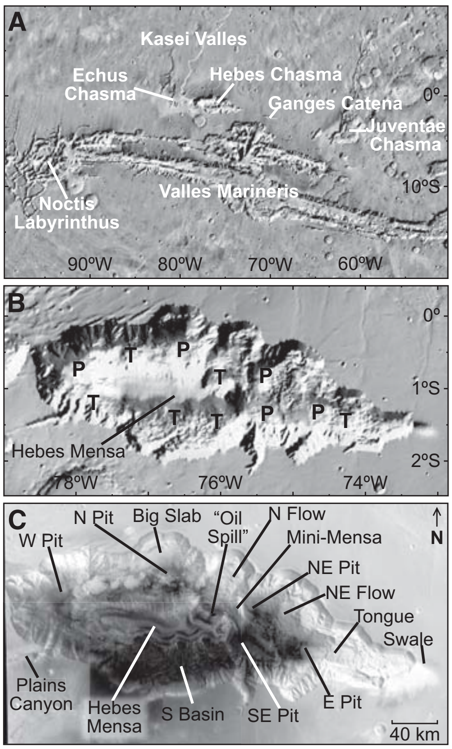

Figure 1. A: Valles Marineris showing location of Hebes Chasma. B: Mars Orbiter Laser Altimeter shaded relief map of Hebes Chasma showing locations of closed depressions, pits (P), and troughs (T) on chasma floor. C: Visible mosaic of Hebes Chasma. Mars Express High Resolution Stereo Camera. N—North, S—South, E—East, W—West, NE—Northeast, SE—Southeast.

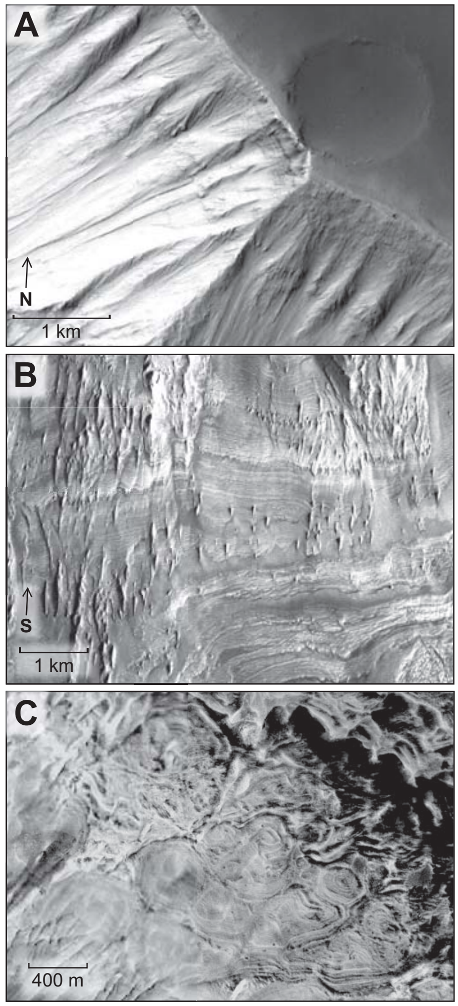

Figure 2. A: Resistant layers of Upper Hebes Formation (UHF) on northeast rim of Hebes Chasma above talus slope of Lower Hebes Formation (LHF). UHF is not disturbed by impact crater on plains in upper right, implying post-impact formation by diagenesis. CTX (Mars Reconnaissance Orbiter Context Camera) image P15_006810_1783. B: Layered, upper LHF on north slope (20°) of Hebes Mensa. CTX image P03_002129_1790. C: Botryoidal structures on top of Hebes Mensa resulting from fluid escape or diapirism. Mars Global Surveyor, Mars Orbiter Camera image E1700518.

GEOLOGY OF HEBES CHASMA

The rocks exposed in Hebes Chasma are designated here as the Hebes Group, which comprises two stratigraphic units: the Upper Hebes Formation (UHF) and the Lower Hebes Formation (LHF). The upper formation consists of ~600 m of resistant, layered rocks that rim the chasma (Fig. 2A). Individual layers within UHF vary in albedo and thickness (<5–100 m) and rarely can be traced along strike for more than a few kilometers before pinching out or ending in faults or slumps. Lucchitta et al. (1992) and Treiman et al. (1995) reported that the same unit is present throughout Valles Marineris. Because it is continuous across plains and impact ejecta of different ages, Treiman et al. (1995) interpreted this resistant cap as the product of aqueous diagenesis at the planet's surface. At Hebes Chasma, UHF also crops out on benches, inward-tilted slabs, landslides, and flows in deep parts of the chasma (Fig. 3). Thus, UHF and the cratered-plains surface, both

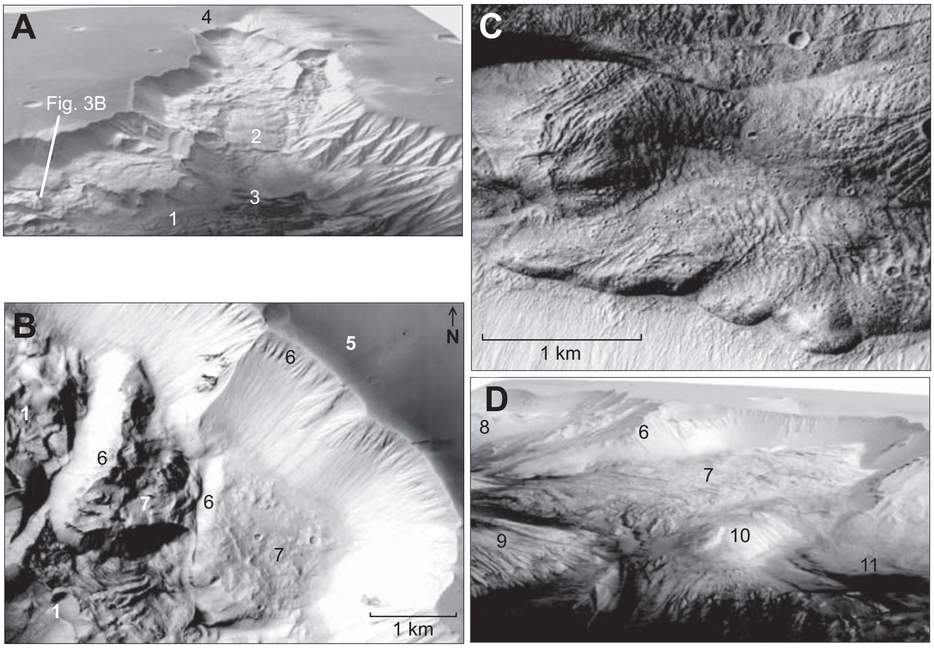

Figure 3. A: Oblique view of east Hebes Chasma and North Pit. Mars Express High Resolution Stereo Camera (HRSC); vertical exaggeration = 2×. 1—Northeast Flow; 2—Tongue; 3—East Pit; 4—Swale. B: Detail of headwall of Northeast Flow. Plains surface (5) and Upper Hebes Formation (UHF) (6) were dropped by normal faults and formed benches (7). Benches foundered; UHF developed hummocky surface with flow lobes. Mobile UHF and Lower Hebes Formation formed Northeast Flow (1). CTX (Mars Reconnaissance Orbiter Context Camera) image 15_006810_1783. C: South side of Tongue, showing wrinkled surface and flow lobes. Mars Orbiter Camera image M2301309. D: Oblique view of north-central Hebes Chasma. HRSC image; vertical exaggeration = 2×. 6—UHF dipping inward; 7—North Flow; 8—Big Slab; 9—Hebes Mensa; 10—Mini-Mensa; 11—North Pit.

of which predate the chasma, provide markers for understanding the structures and processes within Hebes.

LHF, which may be >8000 m thick, underlies UHF. On the chasma walls and in the plains canyons that join the chasma, LHF is massive, relatively easily eroded, and masked by talus. On Hebes Mensa, the upper ~600 m of LHF consists of layers that may be depositional and/or structural (Fig. 2B). A distinctive 100-m-thick subunit at the top of Hebes Mensa and on "Mini-Mensa" (Fig. 1C) contains botryoidal concentric upwelled structures that we interpret as fluid-escape cells in eruptive spring deposits, or small, nested diapirs (Fig. 2C). Layers of LHF in the Southeast Pit may be stratigraphically lower than those on the flanks of Hebes Mensa (Hauber et al., 2008), although structural evidence for diapirism suggests that they may be displaced upper LHF.

Early stages in the subsidence of Hebes Chasma are preserved at its eastern tip, where the plains surface and UHF were deformed into a swale 18 km long, 10 km wide, and 750 m deep. The Swale is aligned with the east-west axis of the chasma and with Ganges Catena, a chain of pit craters 130 km to the east (Figs. 1A and 1C). Shallow grabens along the north and south margins of the Swale define zones of extension. Parallel ridges define a zone of shortening along the Swale axis. The inward dips of UHF and a compensating central zone of shortening indicate sagging, rather than pure extension. Similarly, along the rims of the plains canyons and the chasma, layers of UHF dip inward. The walls of the plains canyons and the chasma typically slope 20°–30°, and in many places the dips of UHF layers approach that slope angle. The resulting near-dip slopes cause map patterns of UHF to vary greatly even though the thickness of UHF is relatively constant.

West of the Swale, faults displaced the cratered plains surface and UHF >1000 m below the chasma rims. Balanced cross sections that match the volume of talus at the bases of the walls with the volume of overlying UHF indicate the presence of normal faults that dip toward the axis of the chasma. Although bounded by extensional faults, the floor of the east end of the chasma is hummocky and appears to have been shortened by crowding, suggesting subsidence that echoes the Swale. Further subsidence deepened and widened the chasma to the west, leaving remnants of the cratered floor and UHF perched as benches along the chasma walls (Figs. 3A and 3B). Westward along the deepening axial zone, the cratered floor has viscous-flow structures that include longitudinal ridges and grooves, lateral lobes, and a wrinkled, elephant-hide appearance (Fig. 3C). This flow (the "Tongue") extends for 40 km at a slope of 4° from one or more extensional scarps to the East Pit. No material accumulated at its terminus, implying that the pit was a drain. Flow to the pit, 8100 m below the chasma rim, signifies an advanced stage of chasma subsidence in which LHF became more mobile at depth, probably owing to higher temperatures.

Besides the Tongue, two other large flows are consistent with viscous flow into drains. The Northeast Flow and the North Flow (Fig. 3) originate from the base of the north wall and both have overall slopes <5°. Each flow ends in a pit or trough without accumulated deposits. The main branch of the Northeast Flow is 70 km long and ends in the East Pit. The North Flow is 50 km long and ends in the trough at the base of Hebes Mensa. The chasma wall between the two flows is a hinged slab tilted 20° toward the North Pit. Erosional incision of the slab removed much of UHF to expose softer LHF in valleys, a pattern repeated elsewhere around the chasma walls. One hinged slab (Big Slab) on the north wall is not incised (Fig. 3D). This 17-km-long ramp of UHF, with the cratered plains surface largely preserved, dips 15°–20° into the North Pit. Parallel normal faults broke the bottom edge of the slab where it meets the pit, suggesting that underlying LHF drained into the depression, carrying with it a deformed skin of UHF, similarly to the Tongue. The early stages of collapse are obscured by later, basal flows of LHF into the pit. Numerous additional flows of LHF along the base of the north wall terminate in the trough between the north wall and Hebes Mensa (Fig. 4A).

Hebes Mensa rises to within a few hundred meters (about the thickness of UHF) of the chasma rims. This loaf-shaped, doubly plunging antiform is defined by light-toned layers of LHF that dip 10°–25° (e.g., Hauber et al., 2006). Flows on all sides imply that the structure has been unroofed (Fig. 4B), which would explain the absence of UHF and a plains surface if the mensa is interpreted as an arched remnant of chasma-wall material. An alternative hypothesis, that the light-toned deposits of the mensa are a younger infill (e.g., Lucchitta et al., 1992), is unlikely at Hebes. That scenario requires that a preexisting chasma be excavated, then filled nearly to the rim with >8000 m of material from an unknown source, followed by reexcavation to form the present chasma. There is no evidence for such multiple episodes of chasma formation or for the sources of infill.

Dark fluid flows also occur on the sides of Hebes Mensa, the base of the chasma walls adjacent to the pits and troughs, and along fissures on the chasma floor. The conspicuous braided flow from the northeast alcove of Hebes Mensa,

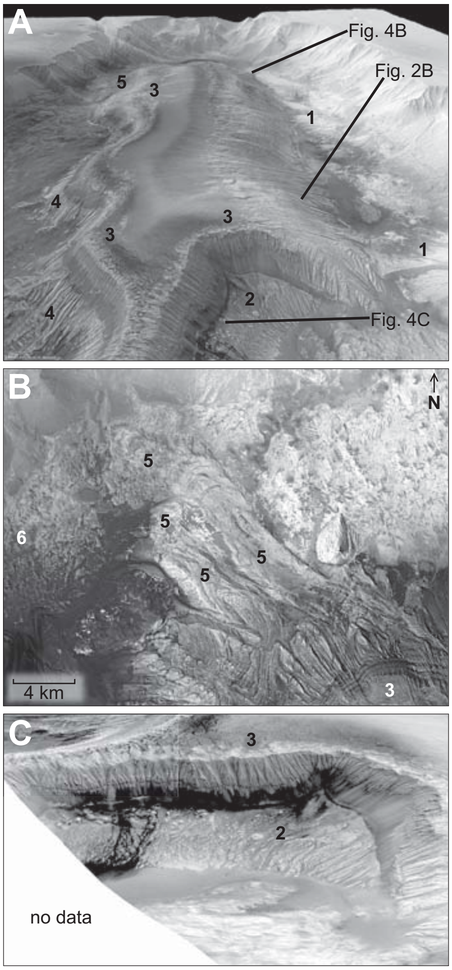

Figure 4. A: West-oblique view of Hebes Mensa. 1—North Pit and trough showing light-toned flows of Lower Hebes Formation (LHF) from Mensa and base of north wall; 2—"Oil Spill" collapse alcove with dark flows; 3—botryoidal layer; 4—flows of LHF into South Basin; 5—flows of LHF into West Pit. Mars Express High Resolution Stereo Camera (HRSC) image; vertical exaggeration = 2×. B: Flows of light-toned LHF (5) from slopes of Hebes Mensa into West Pit (6). HRSC nadir. C: West-oblique view of collapse alcove in northeast Hebes Mensa (2) showing "Oil Spill" and other dark flows from faults. HRSC image; vertical exaggeration = 2×.

here dubbed the "Oil Spill" (Fig. 4C), was interpreted by Ori et al. (2005) as a low-viscosity lava flow; however, a Mars Reconnaissance Orbiter Context Camera image shows that the braided channels are smooth ridges and that the terminal deposit has a feather edge that grades into the surrounding, paler surface. We interpret the Oil Spill as particulates (basaltic tephra?) derived from LHF and entrained in aqueous springs along fracture zones. Dark material may have accumulated in the Oil Spill channels as water evaporated. Similarly, dark flows from myriad fractures left particulate deposits on the north and west sides of Hebes Mensa, many of which blend with paler materials at the bases of the slopes. Other faults and fractures produced dark talus fans on the south wall of Hebes Mensa that are consistent with aqueous spring deposits, but their abundance and small size are inconsistent with magmatic vents.

PHYSICAL MODELS

For insights into the mechanics of karst-like collapse, we built physical models of Hebes Chasma with a length scale of 2 mm to 1 km using layers of dry sand (UHF), glass beads (upper LHF), and ductile silicone polymer (lower LHF). The silicone and granular materials drained slowly by gravity through sinuous slots in the base of the model. The slots were patterned after the topography of the deep parts of Hebes Chasma floor to simulate postulated major fracture zones.

Four experiments reproduced most of the features of Hebes Chasma. Time-lapse videos of the models' evolution revealed all stages of the collapse, not just the end result preserved on Mars (Fig. 5). Viscous silicone flowed toward and into the sinks, causing collapse of the upper brittle layers. The originally horizontal upper layers evolved through swales, grabens, tilted slabs, and landslides. In the lower ductile layers, collapse produced allochthonous flows, diapirs, and sutured drainage creases along former axial thrusts. Features of Hebes produced by the model included normal faults along the rims, arcuate rim segments and alcoves, inward-tilted slabs of plains surface, slump blocks, closed pits, and reverse and thrust faults at the base of walls. In the models, Hebes Mensa began as a horizontally layered remnant of the plains, but it arched diapirically when its crest was stretched and unroofed as material tilted and flowed into the surrounding drains.

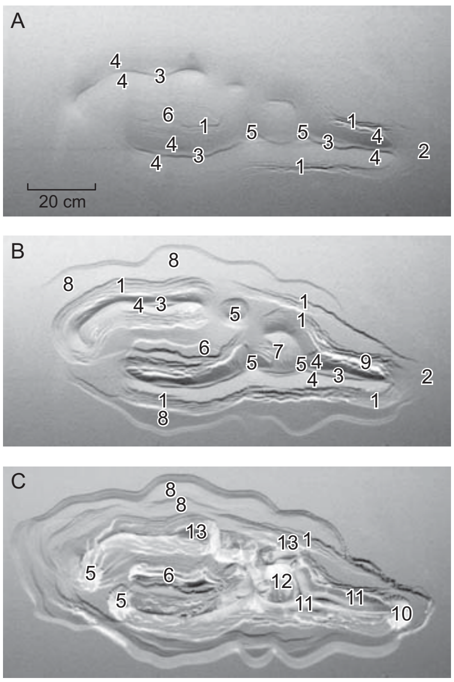

Figure 5. Vertical view of evolving laboratory model of Hebes Chasma. A: Early stage of evacuation. B: Intermediate stage. C: Advanced stage. 1—graben; 2—swale; 3—thrust along trench axis; 4—inward-tilted slabs; 5—pit; 6—Hebes Mensa; 7—radial faulting in diapir roof; 8—downfaulted plains surface; 9—light-toned Lower Hebes Formation (LHF) unroofed by extension; 10—light toned LHF exposed by landslide; 11—inward allochthonous flows; 12—buried diapir after unroofing; 13—emergent diapir.

DISCUSSION

An explanation for the formation of Hebes Chasma must account for the missing volume of material and for the geological observations, including lack of a fluvial outlet, layers that dip toward pits and troughs, extensive mass flows into the pits on negligible gradients, and the lack of accumulation at the ends of flows. All this evidence is consistent with the hypothesis that material was evacuated through drains in the floor. In contrast, an origin purely by extension is not consistent with the shape of the chasma, the lack of extension outside its rims, the dipping layers, and the flows into pits and troughs.

A fluid-evacuation hypothesis severely limits the composition of the materials, which must be solid in the walls but able to melt and/or flow upon gentle heating. For Hebes, these constraints eliminate blocky, thick basalt flows (e.g., McEwen et al., 1999), as argued from other data by Bigot-Cormier and Montgomery (2007). Melting of a megaregolith consisting mainly of ice would readily satisfy the requirement to remove a large volume through the drains; however, it is unlikely that such walls could be supported, given that ice is expected to flow at depths much less than that of the chasma (Spencer and Fanale, 1990). The geology of Hebes is, however, consistent with karstic removal of mixtures of salts, water ice, and basaltic tephra, as proposed for the origin of Valles Marineris in Montgomery and Gillespie (2005) and Montgomery et al. (2009), wherein evidence was presented that magmatic or global heat flow could cause dewatering of hydrous salts and melting of ice, releasing large volumes of fluid from pressurized aquifers into outflow channels.

Near-infrared spectra obtained by OMEGA (Observatoire pour la Mineralogie, l'Eau, les Glaces et l'Activité) Mars Express show evidence for a few patches of hydrated sulfate salts in Hebes Chasma (Fig. 6). Using the methods of Combe et al. (2008), we detected kieserite ($MgSO_4 \cdot H_2O$) on the floors of the Southeast, North, and West Pits. Hydrated sulfates were

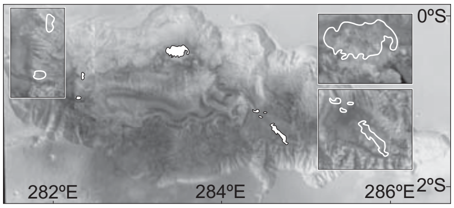

Figure 6. Map of kieserite in Hebes Chasma measured by OMEGA (see text) near-infrared spectroscopy. Mars Express High Resolution Stereo Camera visible mosaic.

detected at those same localities by Gendrin et al. (2005) and Hauber et al. (2006, 2008). Patches of kieserite coincide with massive, light-toned diapiric flows of LHF and adjacent dark particulate material. Small patches of kieserite also coincide with layered LHF and associated dark material on the lower wall of the Southeast Pit below Mini-Mensa. Sulfate salts are not confined to light-toned or layered materials and appear absent from the layered materials of Hebes Mensa and from the chasma walls. The spectral measurements do not preclude salts elsewhere in the chasma; other salts such as anhydrite or halite may be undetected because they lack diagnostic H_2O absorption bands in the near infrared, and local rehydration could have formed kieserite (Mangold et al., 2008). The available evidence hints that hydrated sulfates, which at Hebes occur only on structures upwelled from depth, may be remnants of the salt-rich lower part of LHF, most of which dissolved and drained into a regional aquifer. The layered materials of UHF and the upper part of LHF may be salt poor, although perhaps rich in undetected minerals such as opaline silica or diagenetic, spring-deposited cements (Treiman et al., 1995; Milliken et al., 2008; Rossi et al., 2008). It is important to determine the composition of these deposits, because the photogeologic evidence indicates that they currently dominate surface exposures within the chasma.

We have presented evidence that Hebes Chasma evolved by collapse of a salt-rich megaregolith. Features similar to those in Hebes are widespread in Valles Marineris, and local instances of salt structures have been reported in Tithonium Chasma (Popa et al., 2007; Baioni and Wezel, 2008) and in Candor Chasma (Millikin et al., 2007). Although all Martian chasmata in Valles Marineris may not have evolved exactly the same way, the Hebes example suggests that salt tectonics was important in shaping the much-debated topography of the Valles Marineris region.

ACKNOWLEDGMENTS

This study was funded in part by National Aeronautics and Space Administration Mars Data Analysis Program (MDAP) grant NNX07AV77G to Gillespie, and by the Applied Geodynamics Laboratory consortium. Victor Baker and an anonymous reviewer provided helpful comments. We thank Darrel Cowan, Matt Smith, and Amit Mushkin for stimulating discussions. Laura Gilson and Harvey Greenberg assisted with the illustrations. Tom McCord and John Weeks generously provided computer assistance. Published with permission of the Director, Bureau of Economic Geology.

REFERENCES CITED

Baioni, D., and Wezel, F.C., 2008, Similarities of a Martian dome with terrestrial salt domes: Bollettino della Societa Geologica Italiana, v. 127, no. 3, p. 453–465.

Bigot-Cormier, F., and Montgomery, D.R., 2007, Valles Marineris landslides: Strength limit to Martian relief?: Earth and Planetary Science Letters, v. 260, p. 179–186, doi: 10.1016/j.epsl.2007.05.028.

Combe, J.-P., Le Mouelic, S., Sotin, C., Gendrin, A., Mustard, J.F., Le Deit, L., Launeau, P., Bibring, J.-P., Gondet, B., Langevin, Y., Pinet, P., and the OMEGA Science Team, 2008, Analysis of OMEGA/Mars Express hyperspectral data using a multiple-endmember linear spectral unmixing model (MELSUM): Methodology and first results: Planetary and Space Science, v. 56, p. 951–975, doi: 10.1016/j.pss.2007.12.007.

Gendrin, A., Mangold, N., Bibring, J.-P., Langevin, Y., Gondet, B., Poulet, F., Bonello, G., Quantin, C., Mustard, J., Arvidson, R., and LeMouélic, S., 2005, Sulfates in Martian layered terrains: The OMEGA/Mars Express view: Science, v. 307, no. 5715, p. 1587–1591, doi: 10.1126/science.1109087.

Hauber, E., 14 others, and the HRSC Co-Investigator Team, 2006, Integrated study of interior layered deposits in Hebes Chasma, Valles Marineris, Mars, using MGS, MO, and MEX data: Lunar and Planetary Science XXXVII, abs. 2022.

Hauber, E., Gwinner, K., Gendrin, A., Fueten, F., Stesky, R., Pelkey, S., Reiss, D., Zegers, T., MacKinnon, P., Jaumann, R., Bibring, J.-P., Neukum, G., 2008, Hebes Chasma, Mars: Slopes and stratigraphy of interior layered deposits: Lunar and Planetary Science XXXIX, abs. 2375.

Lucchitta, B.K., Clow, G.D., Geissler, P.E., McEwen, A.S., Schultz, R.A., Singer, R.B., and Squyers, S.W., 1992, The canyon system on Mars, *in* Kieffer, H.H., et al., eds., Mars: Tucson, University of Arizona Press, p. 453–492.

Mangold, N., Gedrin, A., Gondet, B., LeMouelic, S., Quantin, C., Ansan, V., Bibring, J.-P., Langevin, Y., Masson, P., and Neukum, G., 2008, Spectral and geological study of the sulfate-rich region of West Candor Chasma: Icarus, v. 194, p. 519–543, doi: 10.1016/j.icarus.2007.10.021.

McEwen, A.S., Malin, M.C., Carr, M.H., and Hartmann, W.K., 1999, Voluminous volcanism on early Mars revealed in Valles Marineris: Nature, v. 397, p. 584–586, doi: 10.1038/17539.

Millikin, R.E., Grotzinger, J., Beyer, A., Murchie, S., McEwen, A., and the CRISM Science Team, 2007, Evidence for salt tectonics in Valles Marineris, Mars: Seventh International Conference on Mars, Lunar and Planetary Science Institute, abs. 3383.

Milliken, R.E., Swayze, G.A., Arvidson, R.E., Bishop, J.L., Clark, R.N., Ehlmann, B.L., Green, R.O., Grotzinger, J.P., Morris, R.V., Murchie, S.L., Mustard, J.F., and Weitz, C., 2008, Opaline silica in young deposits on Mars: Geology, v. 36, p. 847–850, doi: 10.1130/G24967A.1.

Montgomery, D.R., and Gillespie, A., 2005, Formation of Martian outflow channels by catastrophic dewatering of evaporite deposits: Geology, v. 33, p. 625–628, doi: 10.1130/G21270.1.

Montgomery, D.R., Som, S.M., Jackson, M.P.A., Schreiber, B.C., Gillespie, A.R., and Adams, J.B., 2009, Continental-scale salt tectonics on Mars and the origin of Valles Marineris and associated outflow channels: Geological Society of America Bulletin, v. 121, p. 117–133, doi: 10.1130/B26307.1.

Ori, G.G., Pacifici, A., Komatsu, G., Neukum, G., and the HRSC science team, 2005, A probable fluid lava flow in the Hebes Mensa (Mars) studied by HRSC images: Lunar and Planetary Science XXXVI, abs. 1648.

Popa, C.I., Esposito, F., Ori, G.G., Marinangeli, L., and Colangeli, L., 2007, Tithonium Chasma domes: A result of salt diapirism by means of thin-skinned extension?: Lunar and Planetary Science XXXVIII, abs. 1848.

Rossi, A.P., Neukum, G., Pondrelli, M., van Gasselt, S., Zegers, T., Hauber, E., Chicarro, A., and Foing, B., 2008, Large-scale spring deposits on Mars?: Journal of Geophysical Research, v. 113, E08016, doi: 10.1029/2007JE003062.

Schultz, R.A., 1998, Multiple-process origin of Valles Marineris basins and troughs: Planetary and Space Science, v. 46, p. 827–834, doi: 10.1016/S0032-0633(98)00030-0.

Spencer, J.R., and Fanale, F.P., 1990, New models for the origin of Valles Marineris closed depressions: Journal of Geophysical Research, v. 95, p. 14,301–14,313, doi: 10.1029/JB095iB09p14301.

Treiman, A.H., Fuks, K.H., and Murchie, S., 1995, Diagenetic layers in the upper walls of Valles Marineris, Mars: Evidence for drastic climate change since the mid-Hesperian: Journal of Geophysical Research, v. 100, p. 26,339–26,344, doi: 10.1029/95JE03223.

Manuscript received 9 January 2009
Revised manuscript received 18 March 2009
Manuscript accepted 19 March 2009

Printed in USA