

## Supplement S1

# Formation of Plateaus, Mesas, and Mounds of Stratified Rock within Martian Impact Structures

## Extraformational sediment recycling on Mars

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## FORMATION OF PLATEAUS, MESAS, AND MOUNDS OF STRATIFIED ROCK WITHIN MARTIAN IMPACT STRUCTURES

Gale crater is one of dozens of impact structures on Mars that contain a plateau, mesa, mound, or mountain of stratified rock (Malin and Edgett, 2000; Bennett and Bell, 2016; Day et al., 2016). How such landforms are created has been a matter of on-going discussion in the scientific literature for two decades.

The starting point for discussion of this phenomenon is to recognize that the upper crust of Mars is a three-dimensional patchwork of interstratified impact structures, melt, and ejecta; sediments and sedimentary rocks; regoliths and paleosols; and igneous extrusive and intrusive rocks. Many impact structures have been partly filled, filled, and even buried (Wilhelms, 1974; Schultz et al., 1982; Raitala, 1988; Frey et al., 2002; Buczkowski et al., 2005; Frey, 2006; Edgar and Frey, 2008; Zabusky et al., 2012). Depending on proximity to volcanic regions, the fill material can be mostly sediment, mostly lava, or some of both (De Hon, 1982; Malin and Edgett, 2000; Edgett and Malin, 2002; Rodríguez et al., 2005; Vaucher et al., 2009; Caprarelli and Leitch, 2009; Zabusky et al., 2012). Exhumed or partly exhumed impact structures are also common across the surface of Mars (Baker and Milton, 1974; Malin, 1976; Schultz and Lutz, 1988; Malin and Edgett, 2001; Edgett and Malin, 2002; Newsom et al., 2010; Warren et al., 2019).

One model regarding how a mesa, mound, or mountain of stratified rock can form in an impact structure is to consider that it could be a remnant of material that previously filled, partly filled, or completely buried the impact structure (Malin and Edgett, 2000; Zabusky et al., 2012; Grotzinger et al., 2015; Bennett and Bell, 2016; Day et al., 2016). In such a case, a basin that was a net sediment sink later became a net sediment source, and it did so after sediments were deposited within it and became lithified. Exhumation of the impact structure requires the disaggregation of rock as well as removal of the resulting debris from the basin. The alternative models, explored by Rossi et al. (2008), Niles and Michalski (2012), and Kite et al. (2013), suggest that little material is actually removed from the basins; instead, the intracrater mounds

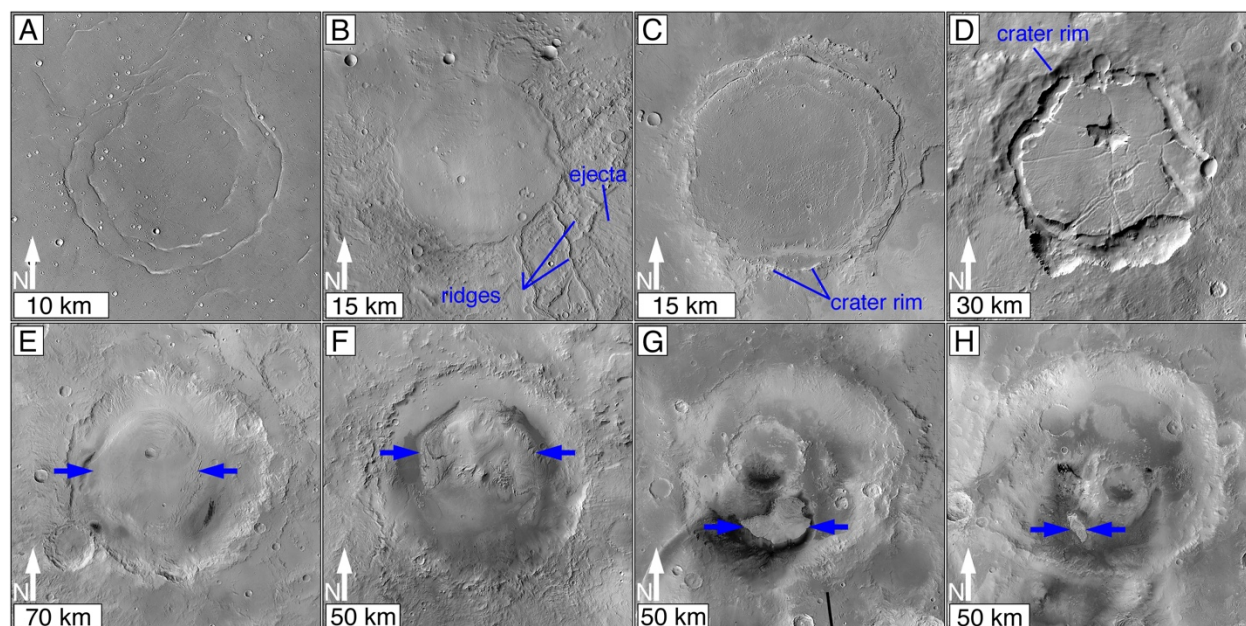
are built up, as mounds, in place. Such models involve a role for precipitation of chemical sediments from springs or the retention of aeolian sediment by ice.

Because of its high relevance to extraformational sediment recycling on Mars, we briefly explore, here, the model that involves impact structure filling, partial filling, or complete burial, in which the majority of fill material is sediment that becomes lithified before exhumation (*sensu* Twidale and Bourne, 2017) of the impact structure.

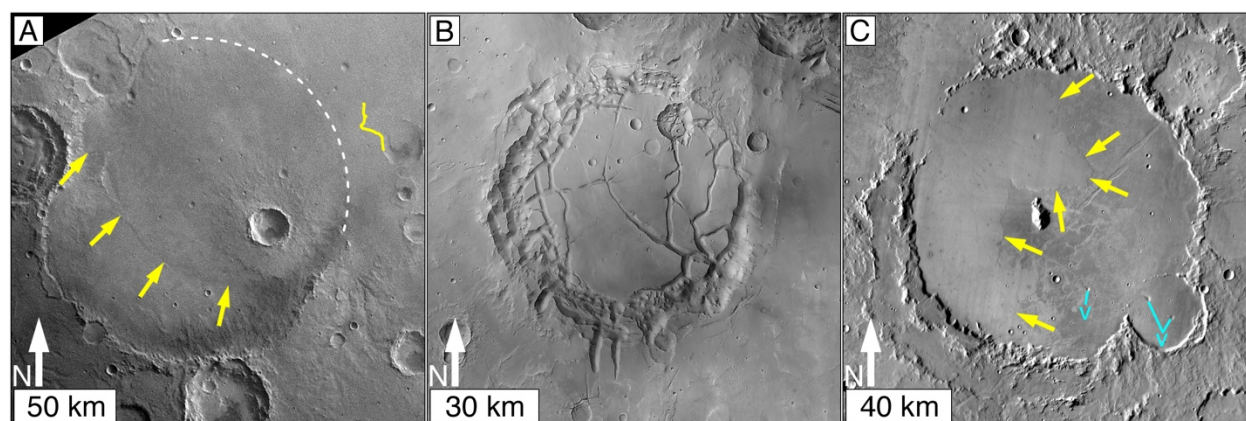
**Figure S1-1** shows an updated view of the sequence of impact structure exhumation proposed by Malin and Edgett (2000) for sediment-dominated cases on Mars. In the first panel (**Fig. S1-1A**), an impact structure is completely buried but the overburden is fractured in arcs that bracket the buried crater rim (cf. McGill and Hills, 1992; Buczkowski and Cooke, 2004). These fractures provide an opportunity for weathering and erosion to eventually widen them (e.g., scarp retreat) and re-expose the buried structure. The second panel (**Fig. S1-1B**) shows a case in which an impact structure is still buried, but material has been eroded away from the terrain surrounding the structure, re-exposing the crater's formerly buried impact ejecta. In this case (**Fig. S1-1B**), the scarp that circles the edge of the crater fill material would eventually retreat toward the impact structure center. The third panel (**Fig. S1-1C**) shows an impact structure that is still mostly filled and buried by stratified rock but some of the original crater rim has begun to be re-exposed. In the fourth panel (**Fig. S1-1D**), the material that filled an impact structure has begun to separate from the buried crater walls. Slopes formed in the fill materials retreat toward the walls and toward the crater center. Evaporation of water, sublimation of ice, lowering of ground water or ground ice tables, and aeolian suspension and removal of fine debris might also have contributed to the deepening and widening of the troughs. In the fifth panel (**Fig. S1-1E**), the crater walls have been exhumed and the remaining crater fill is expressed as a large mesa (Day and Catling, 2020). The sixth panel (**Fig. S1-1F**) shows Aeolis Mons in Gale crater. In the seventh panel (**Fig. S1-1G**), the stratified, intracrater mound could be interpreted as a small remnant of something like Aeolis Mons. Given enough time, such a mound could be even further reduced in size, like the example in **Figure S1-1H**. Such former crater-filling material could eventually disappear—leaving a fully exhumed impact structure with no evidence that it was previously buried.

Mars also presents variations on the theme illustrated in **Figure S1-1**. For example, some of the crater rims and walls of the formerly buried impact structure in **Figure S1-2A** remain completely buried. In this case, they lie beneath the sedimentary rocks explored at the 2004–2018 Mars Exploration Rover (MER) *Opportunity* field site (Edgett, 2005). In another example, an impact structure and its fill material were broken up, forming a chaotic terrain that might have been associated with (perhaps catastrophic) subsurface removal of water (**Fig. S1-2B**; Rodríguez et al., 2005). In still other cases, some or all of the crater-filling material is lava that resists erosion relative to crater fills composed of sediment (e.g., partially filled crater in **Fig. S1-2C**). In some of these cases (e.g., **Fig. S1-1E–H, S1-2A**), the observations imply that the impact structures, and the rocks in which they occur, were more resistant to erosion than the material that filled and buried the crater. The opposite can also occur, removing crater walls and leaving fill materials behind (De Hon, 1987; Pain et al., 2007). Alternatively, both the impact structure and fill material can be completely erased from the Martian rock record.

Some investigators suggest that aeolian erosion plays a dominant role in forming intracrater mounds and removing sediment from these craters (Bennett and Bell, 2016; Day et al., 2016; Steele et al., 2018). However, Aeolis Mons in Gale crater provides geomorphic evidence for a greater range of processes that produced the final, current shape of the mountain. Aeolis Mons displays the results of fluvial incision in the form of canyons and intra-canyon channels, wind in the form of yardangs, mass movement in the form of a large landslide deposit, and rock fragmentation and redistribution by impact cratering (Malin and Edgett, 2000; Anderson and Bell, 2010; Thomson et al., 2011; Le Deit et al., 2013; Fairén et al., 2014; Newsom et al., 2015; Day and Kocurek, 2016; Palucis et al., 2016). Some investigators also proposed that cold climate processes might have contributed to the erosion of Aeolis Mons (Le Deit et al., 2013; Fairén et al., 2014; Robas García et al., 2016). Fluvial features are more unusual on the preserved surfaces of most intracrater mounds (e.g., Desai and Murty, 2016), but all of them possess evidence for a subset of the processes that are recorded on Aeolis Mons (e.g., Bennett and Bell, 2016). Fluvial and mass movement processes exclusively transport debris down slope and thus could not have removed material from a crater, but would have been vital in producing and redistributing loose sediment for export by wind under arid conditions. Removal of sediment from craters via wind would have involved aeolian suspension of fines (e.g., Edgett, 2002; Day et al., 2016), if not also climbing dunes.



**Figure S1-1.** Examples of the family of Martian impact structures that are buried, partly buried, partly exhumed, and largely exhumed. **(A)** Geomorphic indicators of a buried impact structure with fill material fractured to form circular troughs; see Buczkowski and Cooke (2004); located in Utopia Planitia near 26.4°N, 246.7°W (26.2°N, 113.4°E). **(B)** Completely filled impact structure, rim buried, with ridges recording remnants of a former fluvial system overlying exhumed crater ejecta; see Fassett and Head (2007); located downslope of Cusus Valles in eastern Arabia Terra near 16.7°N, 310.6°W (16.5°N, 49.5°E). **(C)** Impact structure filled with stratified rock, crater rim emergent on the south side; located in western Arabia Terra near 5.8°N, 8.7°W (5.8°N, 351.4°E). **(D)** Asimov crater, a nearly-filled impact structure in which the fill material has become pitted; scarps retreated toward the crater rim and toward the crater center; the capping rock might be igneous (Morgan et al., 2011); located in Noachis Terra near 47.3°S, 355.1°W (47.0°S, 5.0°E). **(E)** Henry crater, in which occurs a large mesa (between blue arrows) of stratified rock; see Day and Catling (2020); located in Arabia Terra near 10.9°N, 336.7°W (10.8°N, 23.4°E). **(F)** Gale crater; stratified mountain, Aeolis Mons, is indicated between the arrows; located near 5.5°S, 222.2°W (5.4°S, 137.9°E). **(G)** Becquerel crater, in which occurs a small mound of light-toned, stratified rock (between arrows); see Urso et al. (2018); in western Arabia Terra near 22.2°N, 8.1°W (21.9°N, 352.0°E). **(H)** Trouvelot crater, in which occurs a smaller mound (arrows) of stratified, wind-eroded rock; see Malin and Edgett (2001, Fig. 36); in western Arabia Terra near 16.3°N, 13.1°W (16.1°N, 347.0°E). Image sources: **(A–B; E–H)** MRO CTX image mosaics produced by Malin Space Science Systems. **(D)** Mars Odyssey THEMIS-IR daytime image mosaic produced by Arizona State University (Edwards et al., 2011). Individual images in each mosaic can be identified by searching the NASA archives as a function of landform center latitude and longitude.



**Figure S1-2.** Additional examples of the family of partly-filled, partly-exhumed Martian impact structures. **(A)** Miyamoto crater; its north and east rim is buried (dashed white arc) beneath the sedimentary rocks that compose the bedrock of Meridiani Planum (Edgett, 2005; Wiseman et al., 2008). Arrows indicate the retreated margin of the crater-fill material; the crater is only partly exhumed. Yellow trace indicates the 2004–2018 *Opportunity* rover traverse across rock that buries the proximal ejecta blanket of Miyamoto. Located near 2.9°S, 7.1°W (2.8°S, 353.0°E). **(B)** Chaotic terrain formed in rock that filled an impact structure located southeast of Aram Chaos; located near 0.1°S, 22.8°W (0.1°S, 337.3°E). **(C)** Pickering crater, an impact structure partly filled by lava; arrows indicate leading margin of flows that entered the crater from the northwest (Caprarelli and Leitch, 2009); “v” indicates depressions that might be volcanic vents; located near 33.8°S, 132.8°W (33.5°S, 227.3°E). Image sources: **(A)** Portions of a mosaic of Viking 1 orbiter images 653A57 and 653A59. **(B)** MRO CTX image mosaic produced by Malin Space Science Systems. **(C)** Mars Odyssey THEMIS-IR daytime image mosaic produced by Arizona State University (Edwards et al., 2011). Individual images in each mosaic can be identified by searching the NASA archives as a function of landform center latitude and longitude.

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