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Aqueous Deposits Related to the Formation of Hale Crater in Southern Margaritifer Terra, Mars

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INTRODUCTION

Hale crater (35.7°S, 323.6°E) is a 137 km-diameter impact structure that formed near the Amazonian-Hesperian boundary [1] or in the early-to-middle Amazonian [2]. The formation of Hale destroyed the probable head of the Uzboi-Ladon-Morava meso-scale outflow channel and blocked the southern end of the Uzboi Vallis segment of the system (**Fig. 1**). During and after the impact event that formed Hale, fluidized debris flows and channels sourced near the crater rim incised or modified the ejecta deposit (**Fig. 2** [2]). Mapping reveals these water-driven flows [2] extend considerably further north than previously mapped, reaching the floor of Uzboi Vallis just south of Nirgal Vallis (**Fig. 3**) [3-5].

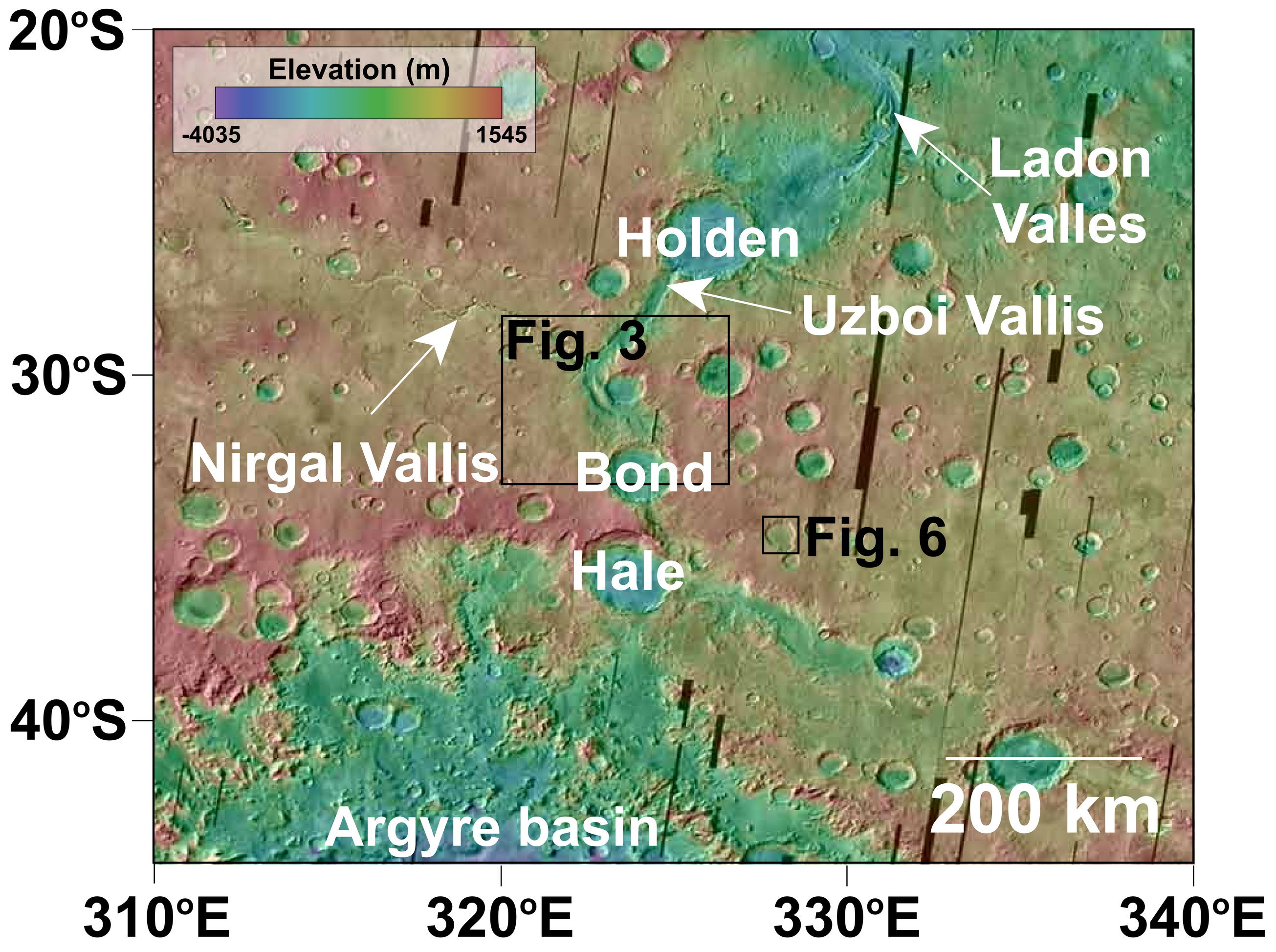
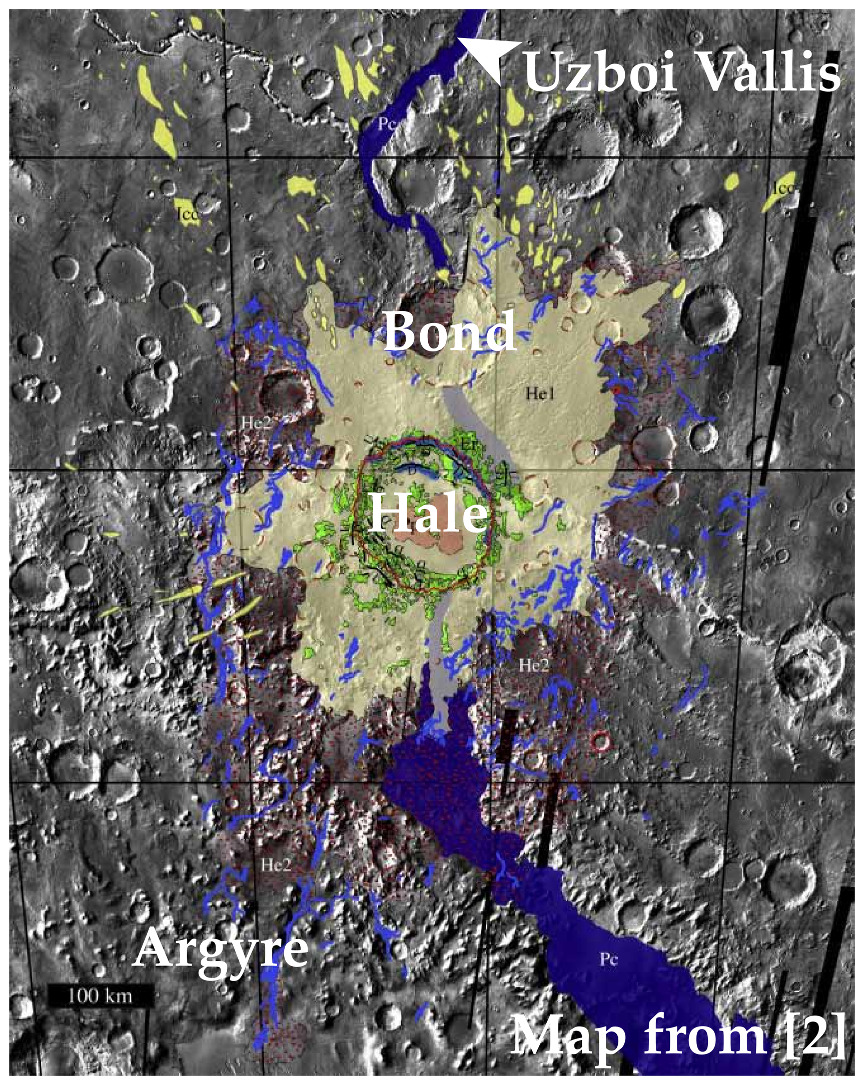


Figure 1. Southwestern Margaritifer Terra preserves a long record of aqueous activity. The once through-flowing Uzboi-Ladon-Morava outflow system stretching from Argyre to the northern plains was interrupted by impact events such as Holden, Bond and Hale. The formation of Hale near the Hesperian-to-Amazonian boundary was accompanied by emplacement of deposits which extend a considerable distance from the impact and reach into the region in and around southern Uzboi Vallis. MOLA topography over subframe of global THEMIS daytime IR mosaic. Black boxes show locations of **Figs. 3 and 6**. North toward the top.



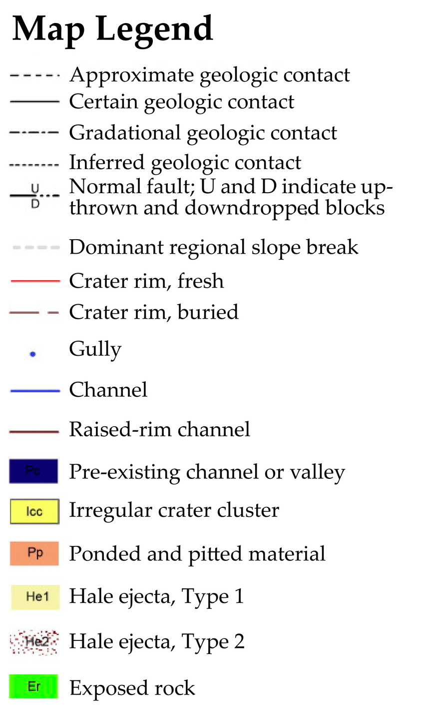


Figure 2. Geomorphic map of Hale crater and surrounding ejecta reproduced from Figure 2 in [2]. Mapped on a 1:500,000 THEMIS daytime-IR mosaic with a resolution of ~100 m pixel−1 in a sinusoidal projection centered on Hale's latitude [2] (see **Fig. 1** for context). Two types of ejecta are mapped by [2]: He1 is proximal, primary ejecta and He2 is thinner, smoother, more distal ejecta [2]. Several channels (light blue lines) are mapped within the Hale ejecta. Irregular crater clusters (unit Icc) are likely secondary craters from the Hale impact. Uzboi Vallis (unit Pc) extends to the north of crater Bond and its assumed outlet from Argyre is mapped south of Hale. Our mapping indicates these channels and associated deposits extend even farther to the north. North is towards the top.

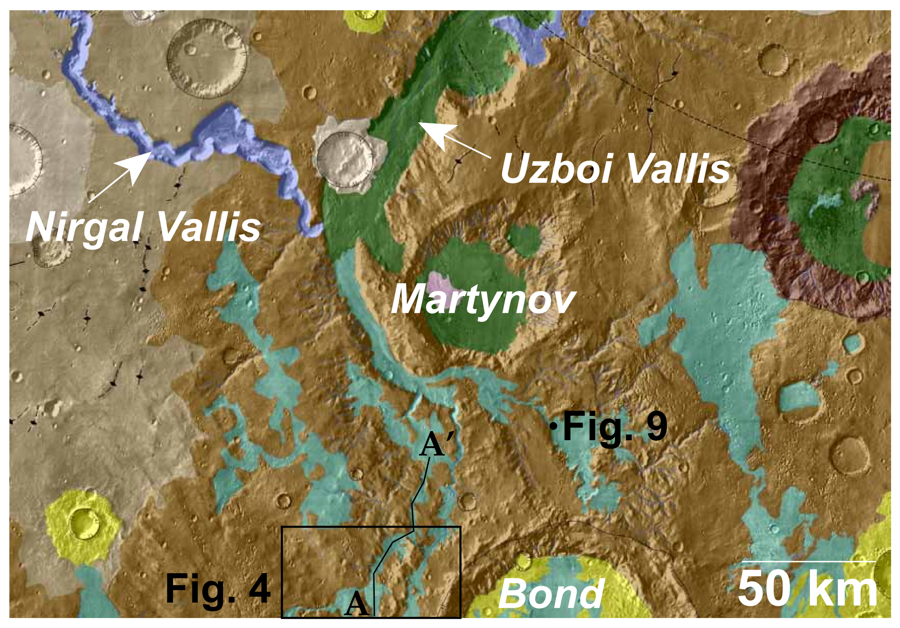


Figure 3. Geologic map (1:500,000 scale) of a portion of Margaritifer Terra north of Hale crater (centered on 30.5°S, 323.5°E) that shows the Hale flow deposits (light teal) reaching well beyond the Hale ejecta (yellow along bottom right side) [6]. Cratered uplands and plains are brown, valleys are purple, and lacustrine and ponded water deposits are green. Location of **Figs. 4 and 9** and profile in **Fig. 10** approximately indicated by transect from A to A'. North towards top.

EXPRESSION OF LATE FLOW DEPOSITS

The deposits associated with the Hale impact vary in expression from relatively thin veneers along newly incised segments and within pre-existing valleys and topographic lows (**Fig. 4**) to thicker lobes where materials accumulated behind and below topographic constrictions (**Fig. 5**). Incised reaches and streamlined forms are sometimes present downstream of constrictions that appear to have slowed and partially blocked the flows [4, 5]. In other locations, close to two crater diameters north of Hale, the material ponds and shallowly embays local relief in a large crater (**Fig. 6**). The material deposited by the flows is darker-toned than bounding surfaces and is mostly smooth and featureless at scales of 10s to 100s of meters. The deposits embay Hale secondary craters and appear to generally thin to the north (distally).

Thicker flow lobes have distinct margins and capping ridges are typically oriented perpendicular to the flow direction [5]. Where exposed at flow fronts (**Fig. 7**), cross-sections show no obvious layering and deposits are sometimes crossed by fractures (**Fig. 8**). Despite an overall morphology that sometimes appears broadly similar to volcanic flows, the local erosion of the digitate, distal margins produces isolated remnants by what appears to be deflation due to the absence of bounding erosional deposits (**Fig. 7**). This implies a significant fine-grained component: there are few boulders or other coarse fragments observed with the exception of the tops of some thicker flow lobes.

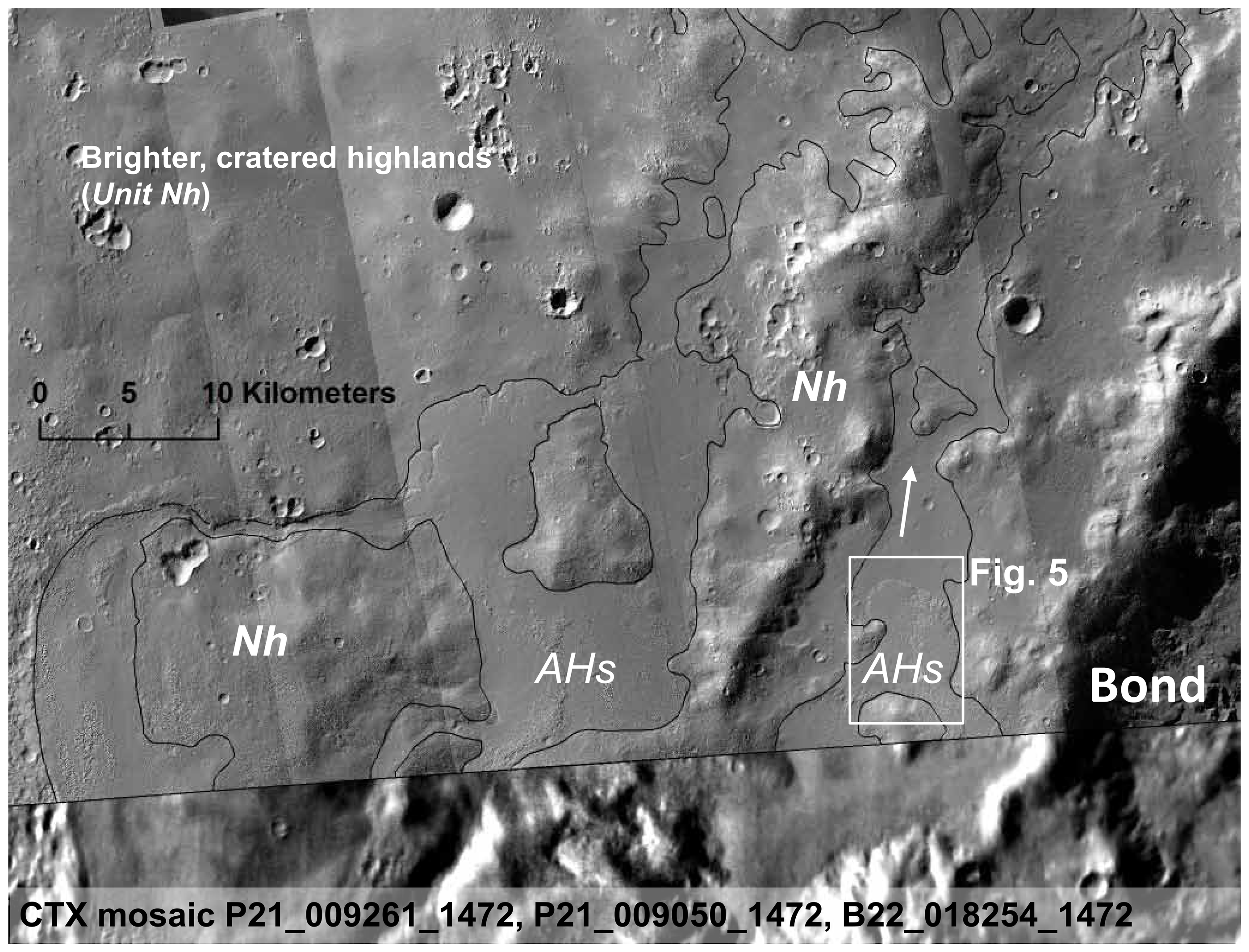


Figure 4. Hale deposits (AHs) within pre-existing valleys and topographic lows in the Noachian Highlands and Terra units (Nh and NHt) west of crater Bond (see **Fig. 3** for context). White box shows location of **Fig. 5**. CTX mosaic over THEMIS daytime IR. North towards top.

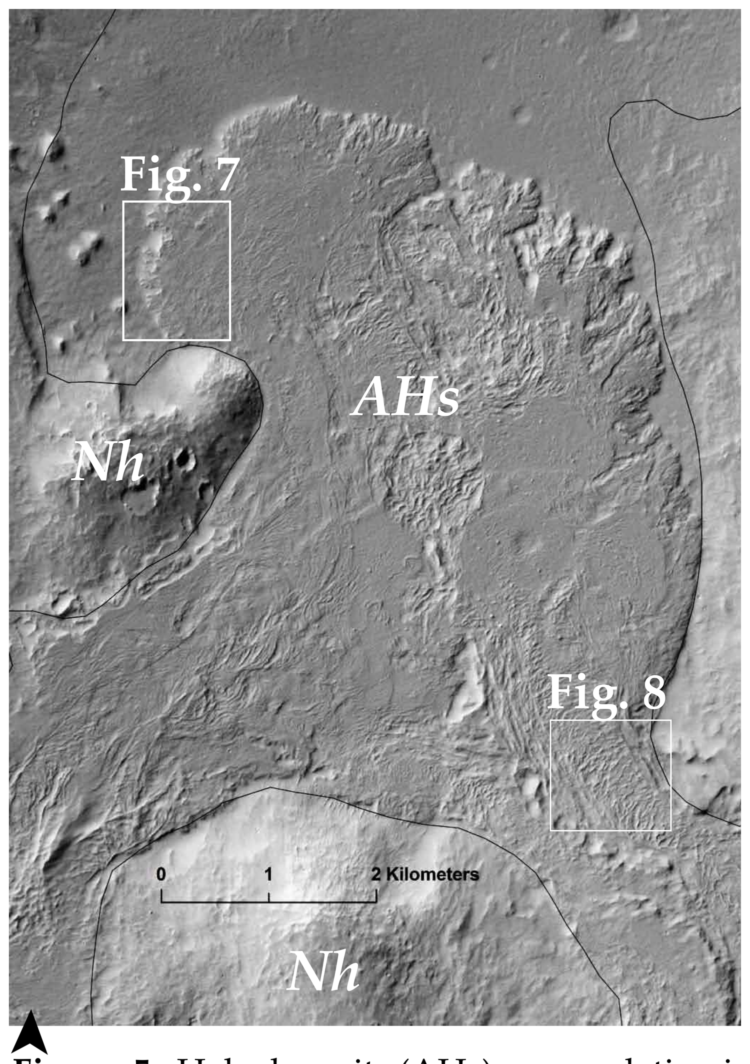


Figure 5. Hale deposits (AHs) accumulating in and below a topographic constriction in Noachian Highlands (Nh) west of crater Bond (see **Fig. 4** for context). The fluidized lobes (unit AHs) have distinct margins and the ridges are oriented perpendicular to the direction of flow, similar in morphology to some lava flows. CTX image B22_018254_1472. White boxes show locations of **Figs. 7 and 8**. North towards top.

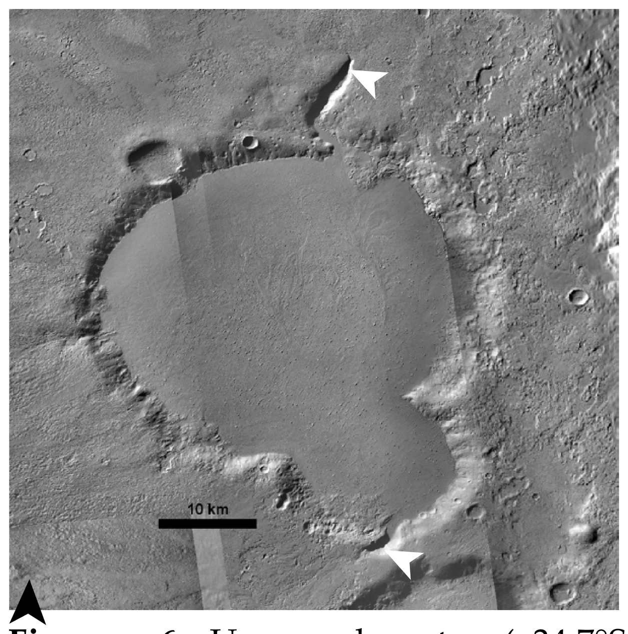


Figure 6. Unnamed crater (~34.7°S, 328°E) approximately 150 km east of Hale's eastern rim (see **Fig. 1** for context) is apparently filled with deposits derived from Hale crater. Deposits drained into the crater from surrounding surfaces via the valleys in the north and south (white arrows). CTX images B19_017133_1471, G17_0247 15_1443, D21_035475_1434, B18_0167 77_1461 and B09_013243_1436. North to top.

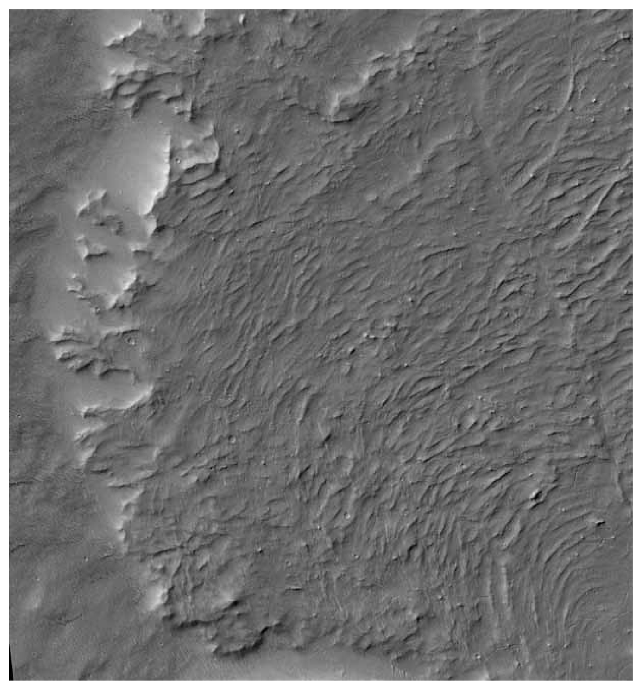


Figure 7. Digitate ends of Hale deposit. Erosion and absence of associated coarse lag deposits implies deflation of constituent fines. HiRISE PSP_008259_1470. Image is ~1.5 km across (see **Fig. 5** for context). North towards top.

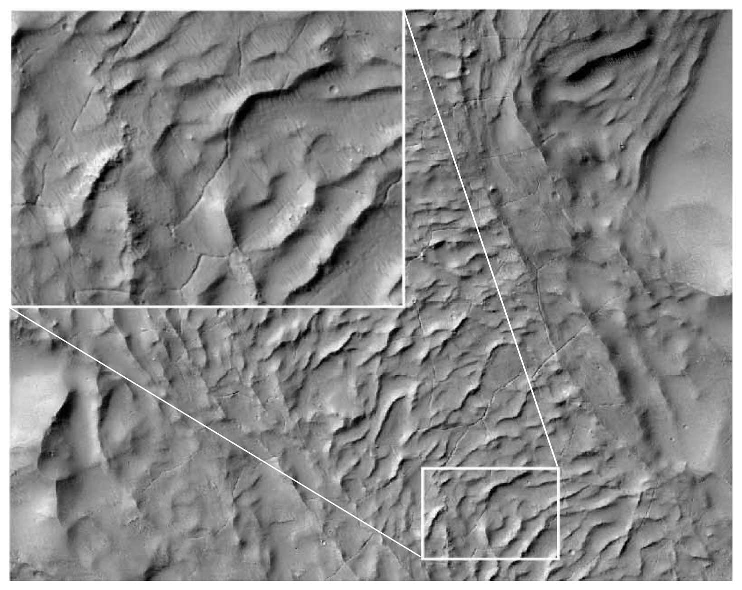


Figure 8. The surface of the fluidized lobes have light toned blocks, extensive cracks and no obvious layering at HiRISE scale. Ridges are oriented perpendicular to the northward direction of flow. HiRISE image P07_003565_1479. Base image is ~1.7 km across (see **Fig. 5** for context). North towards top.

TIMING RELATIVE TO OTHER REGIONAL EVENTS

One of the last, regional events in southern Margaritifer Terra prior to the formation of Hale crater was the occurrence of a 4000 km^2 lake within Uzboi Vallis [7]. Hale flow deposits superpose the Uzboi lake deposits and in the southern reaches of Uzboi extend across a degraded crater where a series of meter-scale bedforms occur (**Fig. 9** [7]). These may represent primary depositional structures or later eolian reworking of the Hale deposits [7]. If the former, the bedforms imply water depths greater than the scale of the structures was present locally over a crater diameter from Hale. The Hale deposits were the last water-driven activity in the region.

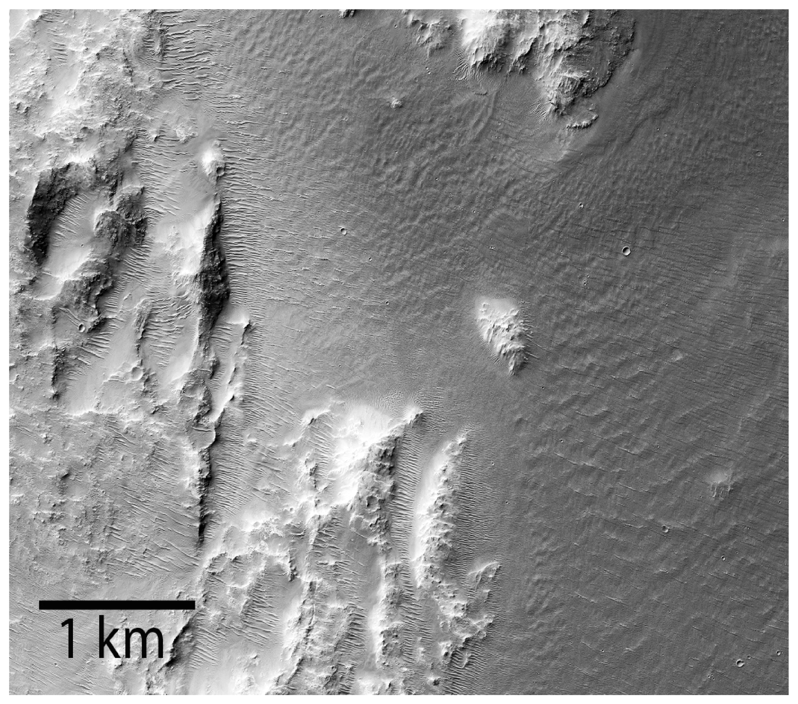


Figure 9. The Hale deposits extend across the floor of a degraded crater near the present head of Uzboi Vallis and to the north of Bond crater. These deposits were originally associated with a lake occurring within Uzboi Vallis [7], but more detailed mapping suggests they are related to the Hale impact event. The crests of a series of m-scale bedforms are oriented at angles to younger eolian drift deposits and are interpreted to represent either reflect primary depositional structures within the deposit or were created as water draining from the deposit headed lower into Uzboi. If the latter, water depths associated with the drainage were greater than the scale of the bedforms and suggest appreciable discharge was at least locally associated with drawdown of water from the deposits. See **Fig. 3** for context. Subframe of HiRISE ESP_015920_1485 (52 cm pixel-scale) with north towards top.

ORIGIN OF THE DEPOSITS

Because most deposits occur within topographic lows and some can be traced back to the channels emerging from the Hale ejecta (**Fig. 1**), their origin appears related. There are more isolated occurrences where the connection to Hale is not obvious (**Fig. 1**). The apparent absence of layering in flow fronts points to their emplacement during a single event Nonetheless, pulses of flow cannot be ruled out. Emplacement likely occurred shortly after the Hale impact based on the embaying relation between the deposits and Hale secondary craters.

The water-driven flows north of Hale occurred near the Amazonian–Hesperian boundary or even later [1, 2] when climate was likely cold and characterized by mostly below freezing temperatures [8], thereby implying rapid freezing would be expected. Almost half the distance traversed by the flows, however, was across warm Hale ejecta that would have slowed or even precluded freezing [9]. Additional water sourced from the within and beneath the Hale ejecta may have contributed to discharge. Once beyond the ejecta, freezing at the surface of the flows likely created an insulating layer of ice that enabled the underlying water-sediment mix to continue downslope [10]. Freezing may also have occurred at the bottom of the flows, but constrictions and steeper grades likely created higher velocities and the local incision observed. Slower moving, locally thicker accumulations (**Fig. 3**) could have developed a thicker, more rigid ice crust that fractured to create observed capping boulders. Continued cooling and further con-traction caused additional fracturing. Once halted, the water in the flows could sublime away, leaving behind the thin deposits observed in many locales.

Gradients along the depressions traversed by the flows are often relatively low and some reaches include local relief the flows would have had to overcome (**Fig. 10**). Two relatively long reaches trending SSW-NNE just west of Bond crater (**Fig. 3**) have average gradients of slightly less than 10 m/km. Coupled with the long runout, this suggests flow viscosities and velocities were relatively low, characterized by transport rates that may not have exceeded several meters/second. If correct, these velocities are broadly consistent with the inference that the flows carried mostly fine-materials [11, 12], perhaps aided by freezing at the bed that limited entrainment of large fragments from all but the locally steepest reaches. Nevertheless, such velocities would enable the flows to reach two crater diameters from Hale in a few days, thereby implying they could relate to very short-lived conditions and events.

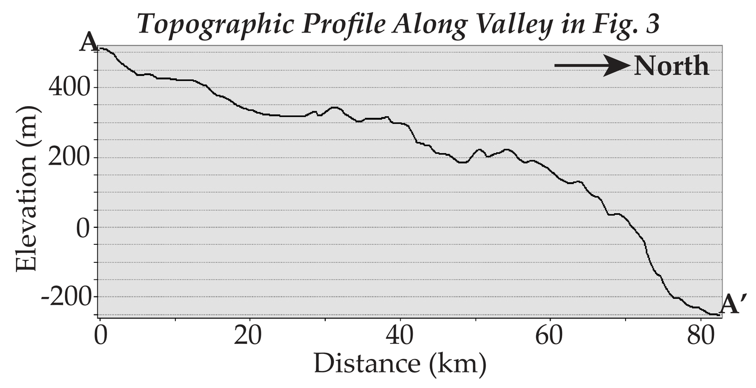


Figure 10. Profile of fluidized flow that occupied a pre-existing depression west of crater Bond. Average gradient of the flow surface is about 10m/km. See **Fig. 3** for location of the transect.

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[1] Cabrol et al., 2001, Icarus, 154, 98–112, doi:10. 1006/icar.2001.6661. [2] Jones et al. (2011), Icarus, doi:10.1016/j.icarus.2010.10.014. [3] Wilson et al., (2013), Abs. Ann. Mtg. Planet. Geol. Mappers, Washington, DC. [4] Wilson et al. (2013), LPSC Abst. 2710. [5] Wilson et al., (2013), Abs. Ann. Mtg. Planet. Geol. Mappers, Flagstaff, AZ. [6] Wilson et al. (2015) LPSC Abst. 2492. [7] Grant et al. (2011), Icarus, doi:10.1016/ j.icarus.2010.11.024. [8] Carr (2006), The Surface of Mars, 307 pp., Cambridge Univ. Press, Cambridge, UK. [9] Mangold (2012), PSS, doi:10.1016/j.pss.2011.12.009. [10] Gregg and Greeley (1993), JGR, 98, 10,873-10,882. [11] Burr et al. (2006), Icarus, doi: 10.1016/j.icarus.2005.11.012. [12] Baker et al. (1988), Flood Geomorphology, 503 pp., Wiley Press, NY.

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