IMPACT AND AQEUOUS STRATIGRAPHY IN HOLDEN CRATER AS REVEALED BY HIRISE. J. A. Grant[1], R. P. Irwin, III[1], J. P. Grotzinger[2], R. E. Milliken[2], L. L. Tornabene[3], A. S. McEwen[3], C. M. Weitz[4], S. W. Squyres[5], T. D. Glotch[6], B. J. Thomson[6], and the HiRISE Team. [1]Smithsonian Institution, National Air and Space Museum, Center for Earth and Planetary Studies, 6th at Independence SW, Washington, DC, 20013, grantj@si.edu, [2]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA, 91125, [3]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, 85721, [4]Planetary Science Institute, 1700 E. Fort Lowell, Tucson, AZ, 85719, [5]Department of Astronomy, Space Sciences Building, Cornell University, Ithaca, NY 14853, [6]Jet Propulsion Lab, Caltech, 4800 Oak Grove Dr, Pasadena, CA 91109.

Introduction: Holden crater in Margaritifer Terra, Mars (26°S, 326°E) is 154 km in diameter and formed during the Noachian [1-3] into the western slope of the Chryse trough [4, 5]. Crater formation interrupted the through-flowing Uzboi-Ladon-Margaritifer (ULM) segmented outflow channel system [6] and excavated ULM sediments in the pre-existing Early Noachian Holden basin [7]. The newly formed crater rim was ~900 m higher than the floor of Uzboi Vallis to the southwest, damming its lower reach where it previously debouched into Holden basin. The –2300 m elevation of the crater floor is the lowest exposed surface of its size within a ~700 km radius and is lower than a possible groundwater source for late discharge into Ladon Valles to the east [6], favoring ponding of emergent groundwater.

Deep tributary alcoves were incised into the higher western and southern rim of the crater and sourced multiple alluvial fans, which coalesced into a large bajada along the western wall [8, 9]. The northern and eastern sides of the rim are lower and poorly dissected, possibly reflecting an orographic influence on precipitation.

Previous investigators recognized a light-toned sedimentary unit associated with alluvial fans [1] overlain by a darker-toned unit exhibiting distinct alluvial morphology [1, 6, 10]. These prior studies relied on images of >1-m/pixel and hypothesized that layered sedimentary deposits in Holden and elsewhere on Mars represented lacustrine, air-fall, or even glacial deposits [e.g., 1, 10, 11].

Seven HiRISE images of Holden, most at 28-56 cm/pixel scale, reveal impact megabreccia beneath the previously recognized sedimentary facies, whose characteristics and distribution indicate they were emplaced during two Noachian wet alluvial/lacustrine phases [12, 13]. The first wet phase was associated with early prolonged erosion of crater walls and saw deposition in fans and on the crater floor. The second wet phase was caused by high-magnitude flooding when Uzboi Vallis breached the crater rim in the Late Noachian.

Megabreccia: Several locations near the floor of Holden expose large, variably rounded, poorly sorted blocks up to tens of meters across within a finer matrix (Fig. 1). Most blocks are more easily eroded than the surrounding matrix, but some stand in positive relief. Many blocks are slightly darker-toned than the matrix, but a few are brighter and at least some include phyllosilicates [14]. The texture of the blocks is typically smooth at HiRISE scales, but erosion of some darker-toned blocks produces coarser, meter-scale debris. These characteristics suggest some blocks originated as sedimentary materials excavated from the pre-impact Holden basin [12, 13].

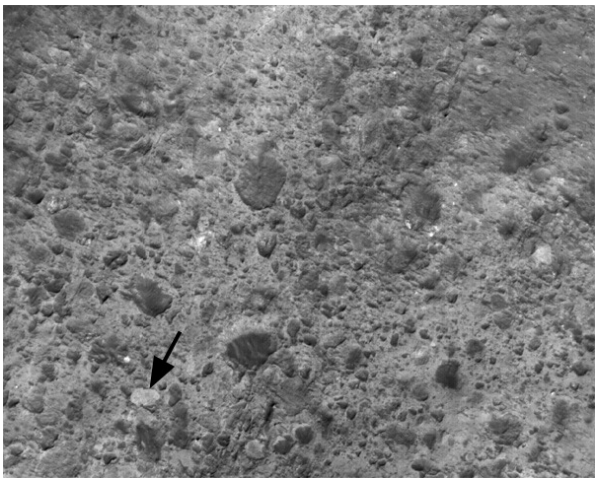

Figure 1. Outcrop of megabreccia near the southern edge of the floor of Holden crater. Large rounded block near the center of the image is ~30 m in diameter. Most blocks are relatively dark-toned, but arrow depicts a light-toned megabreccia block. North is down. Portion of HiRISE image PSP_001666_1530_RED of ~28 cm/pixel scale.

Blocks comparable in size to those in Holden are observed in Popigai Crater, Russia [15], suggesting the Holden deposits represent impact-fragmented megabreccia [16] buried beneath impact melt and other crater-filling deposits [17]. The varying roundness and distribution of some megabreccia blocks indicates some transport and mixing, likely during slumping of the crater walls late in crater formation or emplacement as fall-back debris. HiRISE images enable distinction of megabreccia occurrences in at least 5 additional

locations outside of Holden, thereby suggesting these impact deposits may be common.

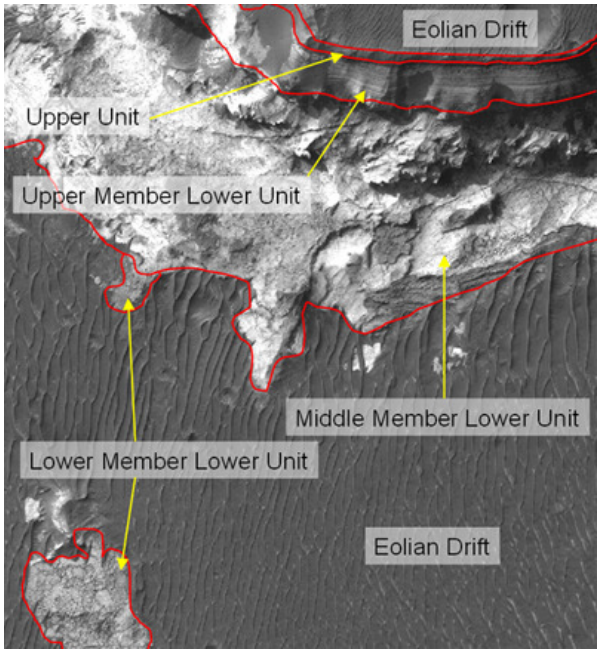

Figure 2. Sedimentary stratigraphy in Holden. Scene is ~600 m across and north is up. Image PSP_001468_1535_RED of ~28 cm/pixel scale.

First Wet Phase: A lower unit (Figs. 2 and 3) overlies the megabreccia and includes three members distinguished by varying reflectance, bed thickness, and phyllosilicate abundance [14, 18, 19]. These lower unit strata reach –1960 m elevation in the southwestern part of the crater [1].

The lower and middle members of the lower unit display meter-scale flat-lying beds apparently devoid of complex stratal geometries (e.g., truncating beds). Lower unit beds are typically dark and traceable for hundreds of meters, whereas middle member beds are brighter, and occurrence of more extensive outcrops permit beds to be traced for up to kilometers (Fig. 2). The contact between lower and middle members appears gradational and conformable, and many outcrops are expressed as slopes (Fig. 2), implying low resistance to erosion.

Upper member beds are flat-lying and thinner than middle and lower member beds and are sometimes separated by lensoidal accumulations of meter-scale darker-toned blocks (Figs. 2 and 3). Upper member strata are lighter-toned than lower member beds, can be traced for kilometers, and are capped by a thin, darker layer commonly exhibiting 4–5-m-diameter polygonal fractures A HiRISE image of the eastern crater reveals likely upper member rocks, suggesting a widespread distribution. The upper member is typically expressed as cliffs and may be stronger than lower members, whereas the contact between middle and upper members typically appears gradational.

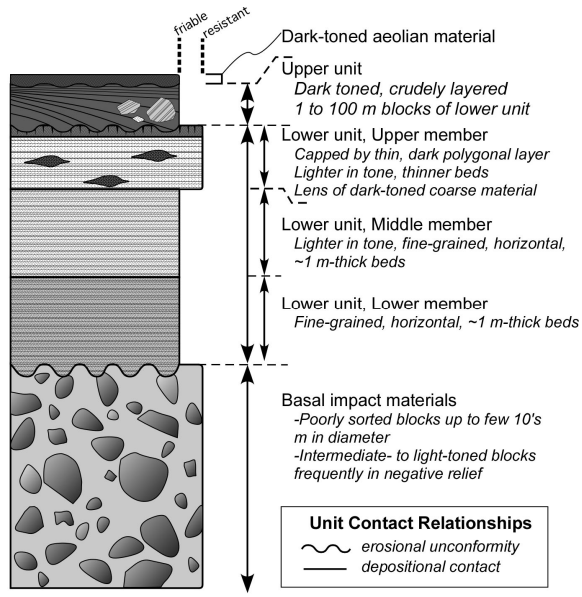

Figure 3. Schematic, simplified stratigraphic column for exposed section in Holden crater and depicted in Figure 2. Thicknesses of various units/members not to scale.

The thin bedding, lateral continuity, and restriction below a common elevation point to a water-lain origin for all the lower unit beds. Aeolian deposits would be less likely restricted below a common elevation, as thinly bedded, or to incorporate coarse clasts. The absence of nearby volcanic constructs or deposits [2] argues against a primary volcanic origin and the overall block-poor nature, composition, parallel bounding surfaces, and elevation distribution are not consistent with emplacement as impact ejecta.

Distinguishing a distal alluvial versus lacustrine depositional setting for the lower unit is challenging [20-22]. The lower unit outcrops in eroding alluvial fan fronts and incorporates some large rocks, suggesting an alluvial origin. The close spacing of relict fan distributaries, however, implies greater lateral variability of bedding in these sub-fan outcrops than is observed (Fig. 4). Restriction of horizontal strata below a common elevation, the lateral continuity of upper unit beds relative to alluvium (Fig. 4), and detection of apparent upper member beds in the eastern crater favor a lacustrine origin for at least the upper member.

One depositional model consistent with the characteristics of the lower unit includes rapid stripping of debris from the crater walls to form fans extending onto the crater floor that sourced the lower and middle members. As crater walls stabilized, an expanding

lacustrine system, perhaps fed in part by groundwater, deposited upper member beds onlapping the lower members. Pulses of alluvial activity caused local progradation of fans over the upper member deposits (Fig. 4) and account for blocky lenses in the upper member [23]. Polygonally fractured upper member material may represent a terminal playa phase.

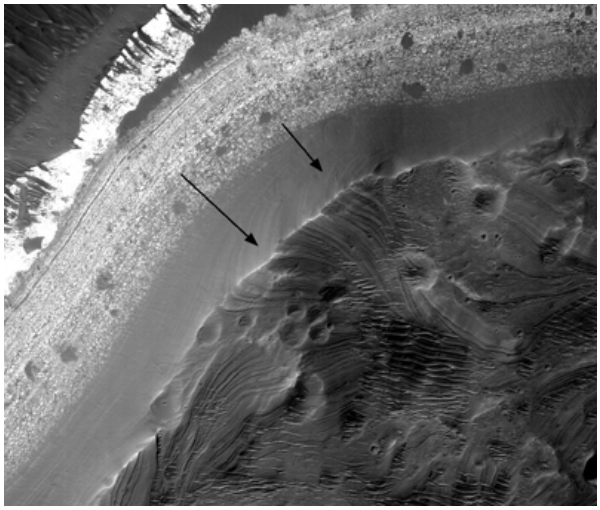

Figure 4. Outcrop of darker alluvial fan materials over probable lacustrine upper member lower unit beds near the south wall of Holden. Outcrop was created when later discharge from Uzboi Vallis flowed across and incised the fan and underlying beds. Arrows point to more steeply dipping beds in the fan relative to flat lying, more continuous upper member lower unit beds beneath. Scene is ~920 m across and north is up. Image PSP_003077_1530_RED of ~28 cm/pixel scale.

Second Wet Phase: Water impounded in Uzboi Vallis eventually overtopped the southwest crater rim, incising a full entrance breach, eroding lower unit deposits (Figs. 4 and 5), and emplacing a dark upper unit [1, 6, 10] that includes low angle fans located at varying distances from the entrance breach. The largest fan reaches 60 m above the surrounding surface and outcrops reveal coarse bedded deposits capped by flat-lying beds. Much of the ramp onto the fan is covered by bedforms interpreted to be subaqueous dunes [6]. Outside of the fans, the upper unit consists of tens of meters of crudely layered beds that unconformably drape antecedent relief [12, 13], but are confined to elevations below –2060 m [1]. Phyllosilicates are present in the upper unit, but in lesser abundance than in the lower unit [14]. Proximal beds are often traceable for tens of meters before truncating at low angles, whereas more distal beds and those capping the unit are typically more continuous and parallel [12, 13]. Eroded blocks of lower unit deposits are enveloped in the upper unit (Fig. 5). These blocks are up to 100 m across and are frequently deposited in the lee of flow obstacles.

Characteristics of the upper unit and association with the Uzboi Vallis breach suggest that deposition occurred in a high-energy flood. Fans and truncating beds near the breach imply alluvial deposition of at least the proximal upper unit, but more flat-lying beds distally and up-section suggests a transition to a lacustrine system. An incised channel on the drained Uzboi Vallis floor is associated with the Noachian-aged Nirgal Vallis tributary [24] and constrains the second wet phase to the Noachian, but the Nirgal channel does not continue into Holden as expected for a lengthy period of post-breach discharge.

Figure 5. Blocks of first lake phase material eroded during second phase flooding and deposited ~10 km form the Uzboi Vallis rim breach. Image is ~210 m across, flow was from the bottom, and north is up. Portion of HiRISE image PSP_001468_1535_RED of ~26 cm/pixel scale.

Exposed stratigraphy in Holden crater represents a unique opportunity to evaluate a potentially habitable setting during much of Noachian Mars. For example, some megabreccia blocks may preserve Early Noachian sedimentary material excavated from the pre-existing Holden basin. By contrast, lower unit stratigraphy and incorporation of relatively more phyllosilicates [14, 18, 19] suggests emplacement in a relatively quiescent, distal alluvial/lacustrine setting. Finally, the upper unit reflects Late Noachian deposition in a higher-energy, shorter lived alluvial/lacustrine depositional system that incorporated less phyllosilicates [14]. The decreasing abundance of phyllosilicates higher in the sedimentary section is consistent with decreasing exposure of phyllosilicates in the crater walls and available for transport over time, but may not preclude *in situ* formation [12, 13]

While the original depositional environment associated with any of the megabreccia blocks remains poorly defined, the lower unit rocks and their incorporation of phyllosilicates [14, 18, 19] reflect a setting likely to preserve geochemical, lithological, or biogenic signatures related to habitability [25]. The higher-energy and shorter-lived Late Noachian second wet phase environment recorded by the upper unit suggests indicators of habitability were less likely to be preserved [26]. Overall, the diverse aqueous history recorded in outcrops in Holden makes the crater a candidate target for the 2009 Mars Science Laboratory rover.

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