HiRISE imaging of impact megabreccia and sub-meter aqueous strata in Holden Crater, Mars

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ABSTRACT

High Resolution Imaging Science Experiment (HiRISE) images of Holden crater, Mars, resolve impact megabreccia unconformably overlain by sediments deposited during two Noachian-age phases of aqueous activity. A lighter-toned lower unit exhibiting phyllosilicates was deposited in a long-lived, quiescent distal alluvial or lacustrine setting. An overlying darker-toned and often blocky upper unit drapes the sequence and was emplaced during later high-magnitude flooding as an impounded Uzboi Vallis lake overtopped the crater rim. The stratigraphy provides the first geologic context for phyllosilicate deposition during persistent wet and perhaps habitable conditions on early Mars.

Keywords: Mars, stratigraphy, aqueous, megabreccia.

INTRODUCTION

Images from the High Resolution Imaging Science Experiment (HiRISE) on the Mars Reconnaissance Orbiter (MRO) (McEwen et al., 2007) at ~26–52 cm/pixel scales reveal a sequence of exposed impact megabreccia and sedimentary units in Holden crater in Margaritifer Terra, Mars (26°S, 326°E, 154 km diameter; Fig. 1). A lower light-toned sedimentary unit displaying meter- to sub-meter-scale bedding is associated with alluvial fans (Moore and Howard, 2005) and is capped by an upper dark-toned unit exhibiting distinct alluvial morphology. These sedimentary facies are at least 150 m thick and were emplaced during two wet phases: early prolonged erosion of crater walls and basin deposition in a distal alluvial or lacustrine setting was followed by high-magnitude flooding, the timing of which can be constrained to the late Noachian epoch (e.g., Reiss et al., 2004). Using >1 m/pixel images, previous workers hypothesized that these deposits were lacustrine, air fall, or even glacial in origin (e.g., Parker, 1985; Malin and Edgett, 2000; Grant and Parker, 2002; Pondrelli et al., 2005; Irwin et al., 2005).

Holden crater formed in the Noachian period (Scott and Tanaka, 1986; Grant and Parker, 2002; Moore et al., 2003), interrupted the previously through-flowing Uzboi-Ladon-Margaritifer (ULM) outflow channel system (Grant and Parker, 2002), and excavated sediments deposited by ULM within the preexisting (Early Noachian) Holden impact basin (Schultz et al., 1982) (Fig. 1). The newly formed crater rim was ~900 m higher than the floor of Uzboi Vallis to the southwest, damming its lower reach. Water impounded in Uzboi Vallis eventually overtopped the crater rim, incising a full entrance breach. The –2300 m elevation of the crater floor is the lowest exposed surface of its size within an ~700 km radius, favoring ponding of any emergent groundwater.

IMPACT MEGABRECCIA

Multiple HiRISE images reveal outcrops of impact materials in the crater walls: variably rounded, poorly sorted, chaotically arranged blocks up to 50 m across within a finer matrix (Fig. 2) often characterized by clastic dikes. The albedo of the blocks is often intermediate between the brighter matrix and darker eolian drift, and they commonly stand in negative relief relative to the more resistant matrix. These characteristics suggest a possible origin for many blocks as sedimentary materials excavated from the pre-impact Holden basin. Blocks of comparable size occur in the walls of Popigai Crater, Russia (Vishnevsky and Montanari, 1999), and are impact-fragmented megabreccia (Grieve et al., 1977) buried beneath younger crater-filling deposits (Melosh, 1989). Hence, the Holden outcrops are likely the first recognized impact megabreccia on Mars.

LOWER UNIT STRATIGRAPHY

The lower sedimentary unit overlying the megabreccia (Fig. 3) includes three members distinguished by varying albedo, bed thickness, and apparent lateral extent. Prior mapping shows outcrops and landforms associated with the lower unit reach a common elevation of –1960 m (within ~10 m) in the southwestern part of the crater (Smith et al., 1999; Pondrelli et al., 2005) and data from the MRO Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) indicate that phyllosilicates likely compose at least ~5% by weight of all three members. However, the broadly similar expression of outcrops coupled with observed changes in spectral absorptions from member to member suggest that phyllosilicate abundances are variable (Milliken et al., 2007).

The lowest member is darker toned, lacks complex bedding geometries such as cross-bedding, and displays uniform, meter-scale, flat-lying beds devoid of large clasts that would be observable at >26 cm/pixel scale. Though beds are traceable for hundreds of meters, the maximum thickness of the lower member is poorly constrained, as outcrops do not expose the underlying crater floor. Middle member beds are similar to those in the lower member, but lighter toned (Fig. 3), and larger exposures allow individual beds to be traced for kilometers. The contact between the lower and middle members appears gradational and conformable, and both lower and middle member beds are often expressed as slopes, suggesting low resistance to erosion.

Upper member beds contain lensoidal accumulations of meter-scale, darker-toned blocks that separate some beds, distinguishing them from beds in the lower members. Upper member beds are also flat lying, thinner, and lighter toned than lower member beds and can be traced for kilometers. These layers form cliffs (Fig. 3) and hence are likely stronger than lower and middle members. The boundary with the middle member is typically abrupt but conformable, although there is one possible geometric discontinuity where underlying beds may be truncated. The upper member is capped by a thin, dark-toned layer commonly exhibiting 4–5-m-diameter polygonal fractures (Fig. 3), some of which extend meters into the subsurface. A HiRISE image of the eastern crater floor reveals exposures of the upper member, suggesting that the lower unit is widely distributed in the crater.

The thin bedding, lateral continuity, and topographic restriction of the lower unit suggest a

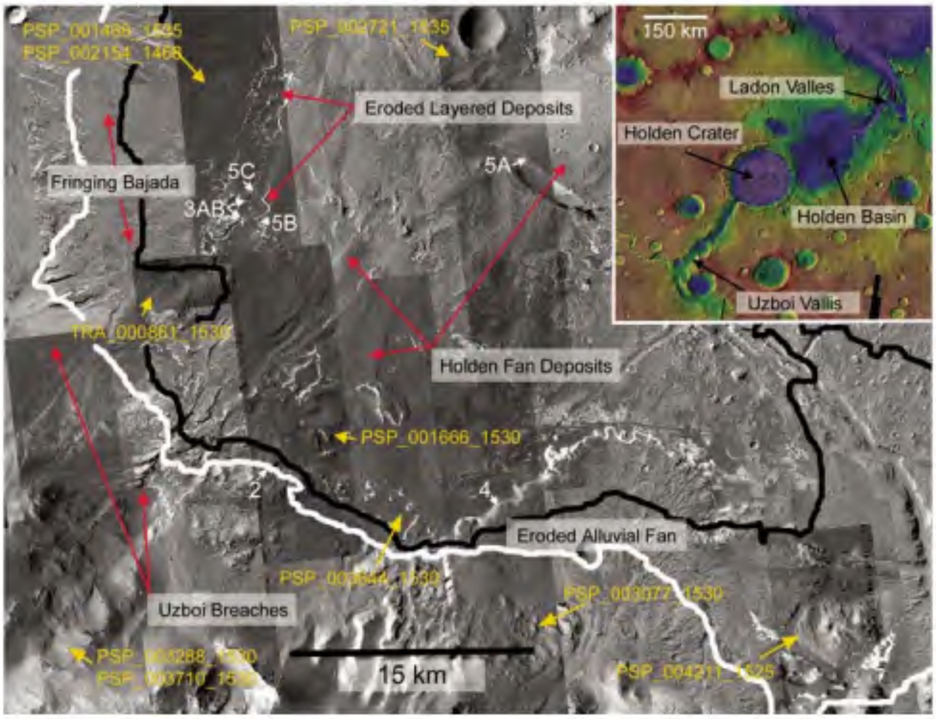


Figure 1. Elevation data (inset) and mosaic of Mars Global Surveyor Mars Orbiter Camera images over THEMIS (thermal emission imaging system) data of southwest Holden crater, layered sedimentary deposits, and rim breach created by Uzboi Vallis. Inset covers 19°S–32°S, 27°W–40°W and elevations from +2500 m (red) to –2500 m (purple). Contours indicating –1960 m (white) and –2060 m (black) are indicated. High Resolution Imaging Science Experiment (HiRISE) images within figure boundaries are labeled in yellow. White numbers indicate locations of Figures 2–5. North is up.

Figure 3. A: Upper unit and upper and middle members of the lower unit. Thin layer capping the upper unit commonly exhibits 4–5-m-diameter polygonal fractures in map view (inset), including these from ~4 km to the south. B: Middle and lower members (above and below dashed line, respectively) of lower unit. C: Idealized stratigraphic section for Holden crater. Sedimentary section in C is ~150 m thick, though the unknown thickness of lower unit, lower member, makes this a minimum estimate. Stratigraphic positions of units in A and B are indicated in C by connecting lines. North is up in A and down in B. High Resolution Imaging Science Experiment (HiRISE) image PSP_001468_1535_RED was used for A and B and image PSP_002154_1468 was used for inset in A (image scale of both is 26 cm/pixel).

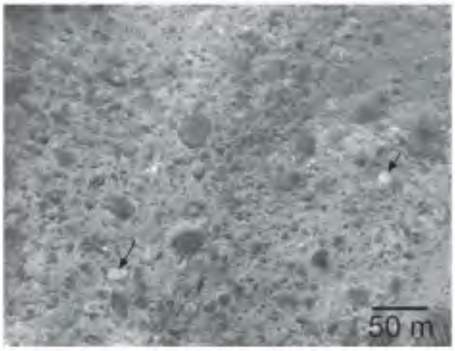


Figure 2. Example of megabreccia exposed in crater walls. Most blocks are dark toned, but some (arrows) are relatively light toned. Other impact megabreccia is revealed by High Resolution Imaging Science Experiment (HiRISE) around 12 craters to date. Portion of HiRISE image PSP_001666_1530 with image scale of 26 cm/pixel.

water-lain origin for all three members. Eolian traction deposits or dust and/or tephra air-fall mantles would not likely be as thinly bedded and/or restricted below a common elevation. Furthermore, the upper member incorporates clasts too large for eolian transport, and there are no nearby volcanic constructs or deposits that would indicate a primary volcanic origin (Scott and Tanaka, 1986). Compositional spectral data support this contention (Glotch, 2006). The generally block-poor nature, parallel bounding surfaces, and elevation distribution of the deposits argue against their emplacement as impact ejecta.

Distinguishing a distal alluvial versus lacustrine depositional environment is a challenge for the Holden lower unit deposits and some terrestrial strata (Winston, 1978; McCormick and Grotzinger, 1993). The lower unit is exposed in eroding fan fronts, and the upper member incorporates some large rocks, suggesting an alluvial origin. By contrast, the close spacing of adjacent relict fan distributaries implies that greater lateral variability of alluvial bedding should be observed in these sub-fan outcrops. Moreover, an exposed fan front near the southern edge of the crater (Fig. 4) reveals relatively steeply dipping alluvial beds over flat-lying upper member beds. Restriction of these lower unit horizontal strata below a common elevation and their broad distribution favor a lacustrine origin.

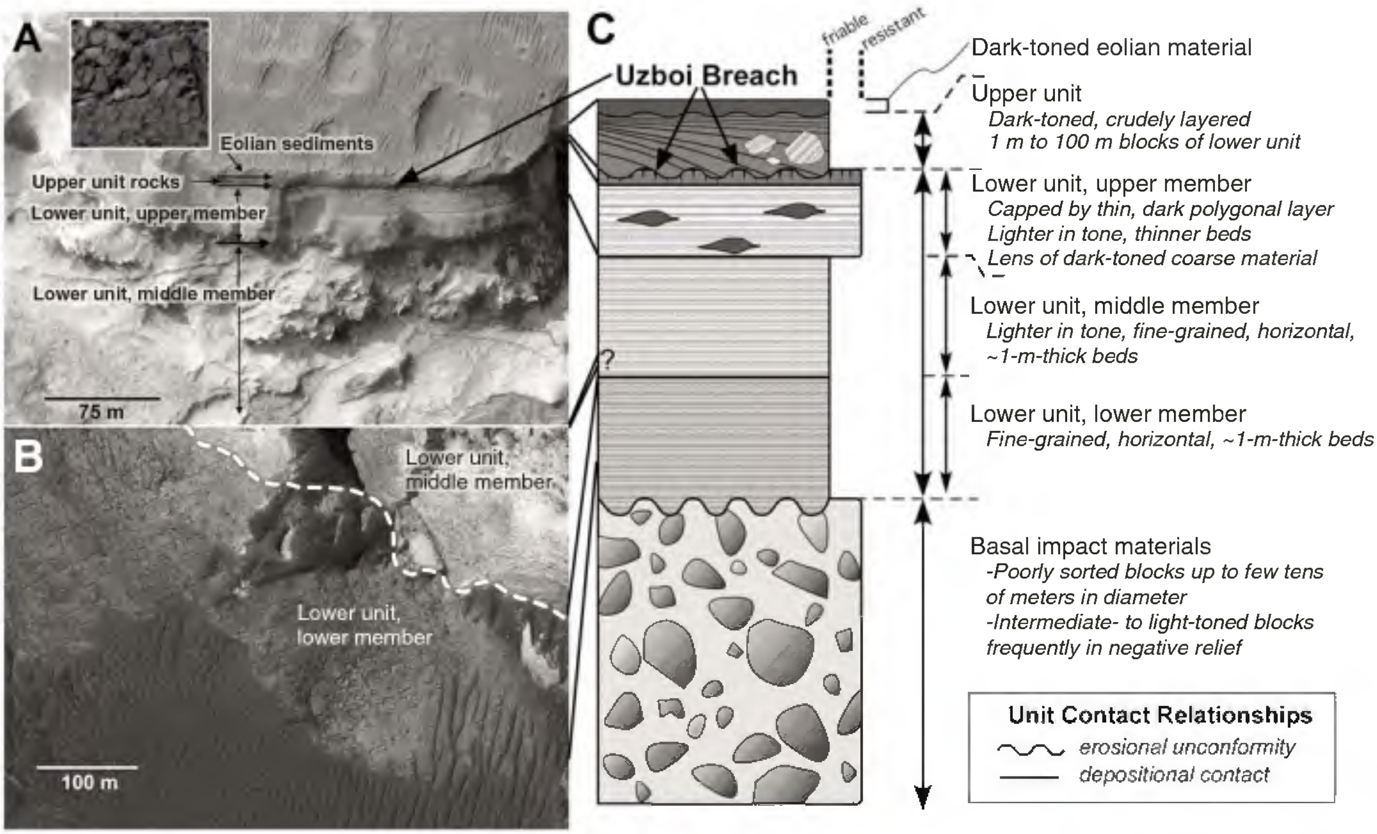
The characteristics and distribution of the lower unit members may record the transition from a distal alluvial fan to a lacustrine facies. Early, rapid stripping of debris from the crater walls extended fans onto the crater floor and sourced the thicker-bedded lower and middle members. As the crater walls stabilized, an expanding lacustrine system may have deposited the upper member beds onlapping lower members. Occasional pulses of channelized alluvium account for lenses of blocky material in the upper member (Howard et al., 2007), and the polygonally fractured material capping the lower unit may represent a terminal playa phase.

The lower unit predates the Uzboi rim breach (drainage divide) and introduction of allochthonous sediments into the crater, requiring that observed phyllosilicate spectral signatures (Milliken et al., 2007) were derived locally. If the phyllosilicates result from in situ weathering, then their varying abundance upsection likely records changing environmental conditions. Alternatively, the phyllosilicate-bearing sediments may predate the crater and were eroded from crater walls, and the varying abundance reflects changing diffusional degradation of the walls, runoff, and/or erosional exposure of more resistant materials.

UPPER UNIT STRATIGRAPHY

A second, shorter aqueous phase occurred during breaching of Holden's rim by Uzboi Vallis. Associated discharge into the crater locally eroded lower unit deposits and emplaced an upper unit consisting of a series of low-angle alluvial deltas (Grant and Parker, 2002; Pondrelli et al., 2005; Moore and Howard, 2005) and other sediments that drape lower unit strata (Fig. 1). Multiple and/or variable Uzboi discharges became focused in a single channel, depositing the radiating fan deltas at varying distance from the entrance breach, including a large fan of bedded, coarse deposits reaching 60 m above the surrounding surface (Fig. 5A). Portions of the ramps onto this and other fans are covered by bedforms that incorporate meter-scale clasts and are interpreted to be subaqueous dunes (Grant and Parker, 2002), whereas flat-lying beds cap the fans (Fig. 5A).

The upper unit consists of as much as tens of meters of crudely layered beds that are often traceable for tens of meters. These beds commonly truncate one another at low angles proximal to the breach, but typically become more



continuous and parallel distally. Phyllosilicate signatures are weak or absent. The upper unit drapes unconformably over antecedent relief and envelops blocks (to 100 m across) apparently derived from the lower unit, usually in the lee of flow obstructions (Figs. 5B, 5C). These characteristics, along with confinement below –2060 m (Pondrelli et al., 2005) and association with the Uzboi Vallis breach in Holden's rim, suggest deposition in a high-energy flood. Fans and nearby truncating beds point to alluvial deposition near the rim breach, but a transition to more flat-lying beds distally and upsection implies a shift to a lacustrine system.

Topographic data indicate that ~4000 km^3 of impounded water in Uzboi Vallis was required to overtop the Holden rim, sufficient to flood Holden to –2060 m. An incised channel on the drained Uzboi Vallis floor is associated with the Noachian-aged Nirgal Vallis tributary (Reiss et al., 2004) and constrains the second wet phase to the late Noachian epoch, but the Nirgal channel does not continue into Holden, as expected for a lengthy period of post-breach discharge. In addition, the upper unit fans exhibit mafic compositions and weak phyllosilicate signatures (Glotch, 2006; Milliken et al., 2007), consistent with sourcing from the Uzboi breach and limited duration of aqueous weathering. Finally, as a closed basin, Holden lost water via infiltration and evaporation. The former is difficult to constrain, but comparison with terrestrial evaporation rates (Kohler et al., 1959) suggests that, without

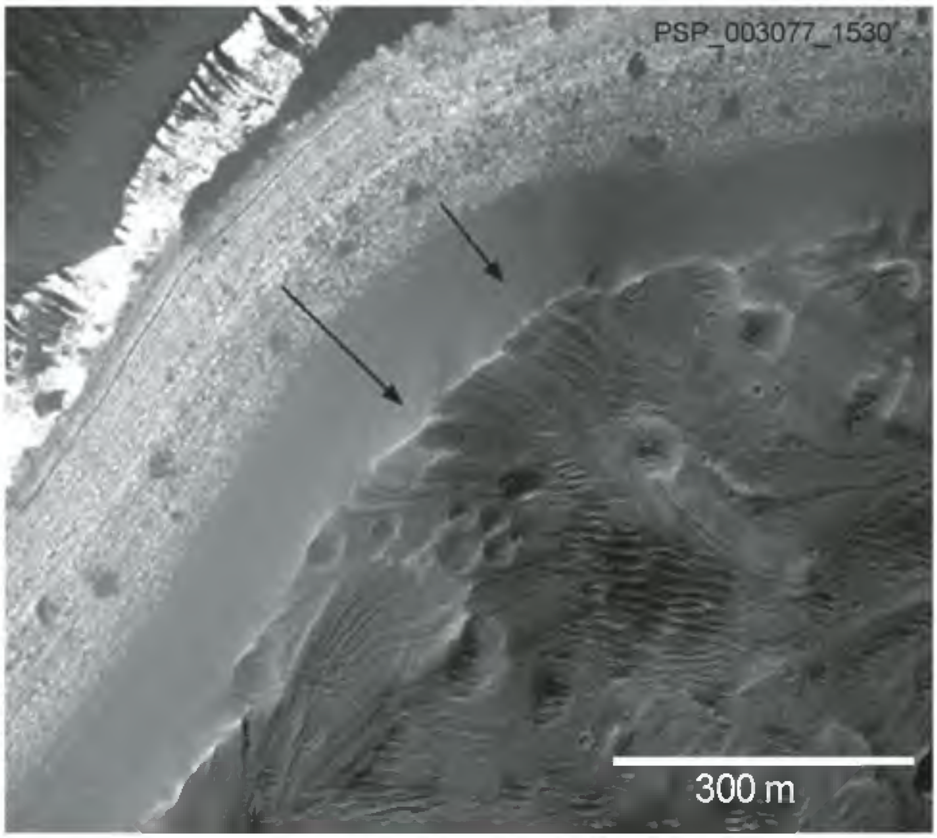


Figure 4. Alluvial fan deposits overlying upper member, lower unit beds. Outcrop was exposed when discharge from Uzboi breach drained across the fan, highlighting steeply dipping alluvial beds (arrows) that vary across tens to hundreds of meters, in contrast to more uniform, continuous, flat-lying upper member, lower unit beds below. High Resolution Imaging Science Experiment Image PSP_003077_1530_RED with image scale of 26 cm/pixel.

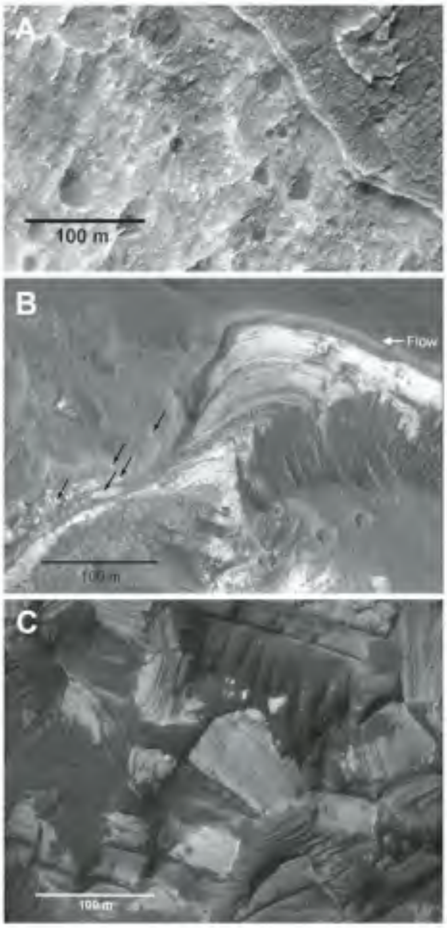


Figure 5. High Resolution Imaging Science Experiment (HiRISE) data. A: Layered upper unit fan deposit containing numerous rocks larger than 1 m and capped by flat-lying beds. B: Incised upper member, lower unit unconformably overlain by upper unit; base of incision is lined with blocks (arrows) of lower unit material. C: Enormous lower unit blocks eroded and deposited in the lee of flow obstacles within matrix of upper unit sediments. Images PSP_002721_1530_RED (A) and PSP_001468_1535_RED (B and C), both with image scale of 26 cm/pixel.

a continuing inflow of water, a 200–300-m-deep lake would persist only hundreds of years.

DISCUSSION

HiRISE images confirm that Holden crater preserves impact megabreccia overlain by distal alluvial and/or lacustrine deposits emplaced during two contrasting Noachian-aged wet phases. These diverse aqueous strata in Holden crater provide the first clear context for phyllosilicates in an alluvial and/or lacustrine environment, and exposed stratigraphy represents a unique opportunity to evaluate a potentially habitable setting on Mars. The lower unit stratigraphy and incorporated phyllosilicates suggest emplacement in a relatively quiescent, distal alluvial and/or lacustrine setting that would require more clement, widespread, and stable conditions than currently occur on Mars. By contrast, the upper unit reflects deposition in a higher-energy alluvial grading to lacustrine depositional system. The lower unit rocks reflect a setting more likely to have preserved geochemical or lithological signatures consistent with habitable environments. Phyllosilicates in the lower unit may preserve subtle biogenic signatures or even adsorbing organics if present (Knoll and Grotzinger, 2006) and deposited in the low-energy aqueous setting implied by the stratigraphy. By contrast, the higher-energy and short-lived environment recorded by the upper unit suggests an environment where indicators of habitability were less likely to be preserved (Knoll et al., 2005).

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