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A lake in Uzboi Vallis and implications for Late Noachian–Early Hesperian climate on Mars

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ABSTRACT

Uzboi Vallis (centered at ∼28°S, 323°E) is ∼400 km long and comprises the southernmost segment of the northward-draining Uzboi–Ladon–Morava (ULM) meso-scale outflow system that emerges from Argyre basin. Bond and Holden craters blocked the valley to the south and north, respectively, forming a Late Noachian-to-Hesperian paleolake basin that exceeded 4000 km^3. Limited CRISM data suggest lake deposits in Uzboi and underlying basin floor incorporate relatively more Mg-clays and more Fe-clays, respectively. The short-lived lake overflowed and breached Holden crater's rim at an elevation of −350 m and rapidly drained into the crater. Fan deltas in Holden extend 25 km from the breach and incorporate meter-sized blocks, and longitudinal grooves along the Uzboi basin floor are hundreds of meters long and average 60 m wide, suggesting high-discharge drainage of the lake. Precipitation-derived runoff rather than regional groundwater or overflow from Argyre dominated contributions to the Uzboi lake, although the failure of most tributaries to respond to a lowering of base level indicates their incision largely ended when the lake drained. The Uzboi lake may have coincided with alluvial and/or lacustrine activity in Holden, Eberswalde, and other craters in southern Margaritifer Terra, where fluvial/lacustrine activity may have required widespread, synoptic precipitation (rain or snow), perhaps associated with an ephemeral, global hydrologic system during the Late Noachian into the Hesperian on Mars.

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1. Introduction

Uzboi Vallis (centered at ∼28°S, 323°E, Fig. 1) is the southernmost segment of the northward-draining Uzboi–Ladon–Morava (ULM) meso-scale outflow system that dominates drainage in southwest Margaritifer Terra (Grant, 1987; Grant and Parker, 2002; Parker, 1985; Saunders, 1979). The ULM system consists of deeply incised, 15–20 km-wide trunk segments that are separated from one another by depositional plains that partially fill the 300 km and 470 km-diameter inner massif rings of the Early to Middle Noachian Holden and Ladon multi-ringed impact basins, respectively (Frey et al., 2003; Saunders, 1979; Schultz et al., 1982).

Uzboi Vallis is ∼400 km long (Figs. 1 and 2) and emerges from Argyre basin before traversing northward along the southwestern flank of the "Chryse trough" (Baker, 1982; Parker, 1985; Phillips et al., 2001; Saunders, 1979). Hale (125 × 150 km in diameter) and Bond (111 km in diameter) craters on the northern margin of Argyre largely buried the basin outlet, but Uzboi originates at nearly full width and has only a few, much smaller tributaries, supporting the contention that it was fed by overflow from Argyre basin (Grant and Parker, 2002; Parker, 1985). Several large valley systems originating south of Argyre likely fed the ULM drainage (Parker, 1985, 1994), resulting in a total watershed potentially covering more than ∼11 × 10^6 km^2, or about 9% of Mars (Banerdt, 2000; Phillips et al., 2001).

Holden crater (154 km in diameter) blocked the northern end of Uzboi (Figs. 1 and 2) in the Late Noachian or Early Hesperian Epoch (Grant et al., 2008; Pondrelli et al., 2005; Scott and Tanaka, 1986). The eventual overtopping and breaching of Holden's rim (Grant et al., 2008; Pondrelli et al., 2005) demonstrates that water was present in Uzboi, possibly episodically, until at least the Late Noachian Epoch and perhaps into the Hesperian. The confinement of Uzboi between Bond crater to the south and Holden crater to the north effectively created an enclosed drainage basin and set the stage for the formation of a large lake (Grant et al., 2010a).

The broad valley forming Uzboi Vallis (Fig. 2) is nearly 2 km deep in places and descends 700–800 m from just north of Bond crater northward to the point where Holden crater interrupts its thalweg at an elevation of −1275 m (relative to the Mars Orbiter

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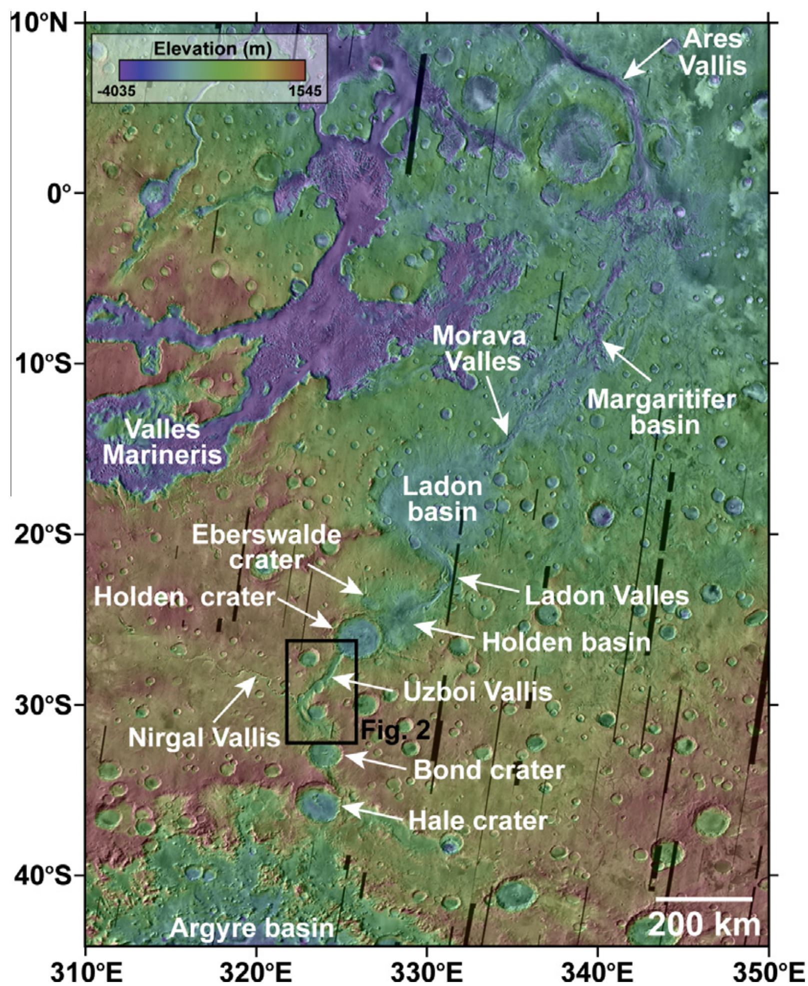

Fig. 1. Margaritifer Terra with place names referenced throughout text. The region discussed in this paper lies to the north of Argyre basin and to the southeast of Valles Marineris. Drainage in the region is defined by the once through-flowing Uzboi–Ladon–Morava (ULM) meso-scale outflow system that was interrupted by the formation of Holden, Bond, and Hale craters. MOLA topography over subframe of global THEMIS daytime IR mosaic. Black box shows the location of Fig. 2. North is towards the top.

Laser Altimeter (MOLA) datum). The north rim of Bond crater is at 120 m elevation and is well above the confluence of the Nirgal Vallis tributary into Uzboi Vallis, which is located more than halfway between Argyre and Holden basins at an approximate elevation of −760 m (Irwin and Grant, 2009).

Holden's rim rises to an elevation of −350 m, approximately 900 m above the adjacent floor of Uzboi. Hence, substantial flooding within Uzboi was required to overtop the crater rim, creating a lake exceeding 4000 km^3, which was probably contemporaneous with a lake in Holden crater (Grant et al., 2010a). Once Holden's rim was breached by Uzboi Vallis, the crater floor became the terminal basin for Uzboi Vallis drainage and was flooded to form a lake on Holden's floor (Grant and Parker, 2002; Grant et al., 2008; Irwin and Grant, 2009; Irwin et al., 2005a; Pondrelli et al., 2005). The lake in Holden created by the drainage of Uzboi was short-lived, as Nirgal Vallis and other Uzboi tributaries do not incise continuously across the drained floor of Uzboi Vallis into Holden as expected if there was a lengthy period of discharge following incision of the breach (Grant et al., 2008). Moreover, the fans and deposits associated with the drainage of Uzboi into Holden crater exhibit mafic compositions and a paucity of phyllosilicate signatures, consistent with rocks and sediment derived from the breach that had limited subsequent contact with water (Grant et al., 2008). The absence of any outlet from Holden crater indicates that it marked the northern limit of late drainage from the south and that the lake must have lost water via infiltration and evaporation and may have persisted for only hundreds of years (Grant et al., 2008)

2. Geologic setting and history

The availability of data from the High Resolution Imaging Science Experiment (HiRISE) (McEwen et al., 2007), Context Camera (CTX) (Malin et al., 2007), and the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) (Murchie et al., 2007) on the Mars Reconnaissance Orbiter (MRO) spacecraft details the 10-m to sub-meter morphology and sedimentary stratigraphy exposed in Uzboi Vallis. These data, particularly HiRISE images of ∼26–52 cm/pixel-scales, provides evidence for water impoundment along the length of Uzboi Vallis. The Late Noachian to Early Hesperian stratigraphy associated with the flooding of Uzboi Vallis records an important chapter in the aqueous history of Mars, when conditions conducive to widespread valley formation and an active hydrologic cycle were ending (e.g., Carr, 2006; Fassett and Head, 2008; Grant, 2000; Grant and Parker, 2002; Grant et al., 2009; Howard et al., 2005). As such, understanding the context of deposits related to flooding in Uzboi may assist in evaluating whether habitable conditions occurred near the end of an early, wetter period on Mars (Bibring et al., 2006).

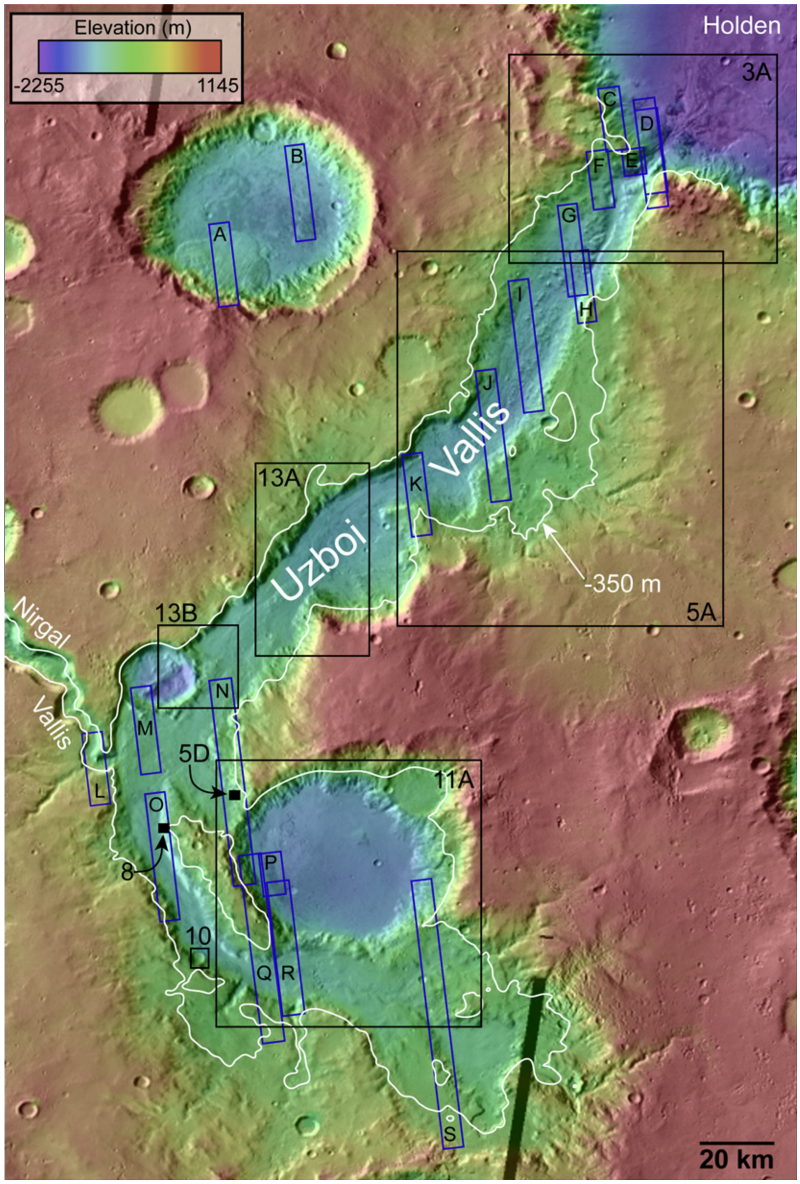

Fig. 2. Uzboi Vallis south of Holden crater (see Fig. 1 for context). The −350 m contour (white line, relative to MOLA datum) represents the approximate maximum level of the lake that formed within Uzboi Vallis after the formation of Holden crater blocked the once through-flowing ULM system. The lake in Uzboi filled until it overtopped and then breached the 900 m high dam formed by the rim of Holden and drained into the crater. Location of Figs. 3A, 5A, 5D, 8, 10, 11A, 13A and 13B indicated. Blue boxes show all currently released HiRISE images: (A) PSP_005477_1520 (26 cm pixel-scale), (B) ESP_017054_1525 (52 cm pixel-scale), (C) PSP_004277_1530 (26 cm pixel-scale), (D) PSP_003710_1530, PSP_003710_1530 (both at 26 cm pixel-scale), (E) ESP_012953_1525 (26 cm pixel-scale), (F) ESP_011608_1525 (52 cm pixel-scale), (G) PSP_010329_1525 (52 cm pixel-scale), PSP_008338_1525 (26 cm pixel-scale), (H) PSP_003499_1520 (26 cm pixel-scale), (I) ESP_012030_1520 (52 cm pixel-scale), (J) ESP_012887_1515 (52 cm pixel-scale), (K) PSP_006189_1510 (26 cm pixel-scale), (L) ESP_016553_1495 (26 cm pixel-scale), (M) PSP_003565_1495 (26 cm pixel-scale), (N) ESP_016487_1495 (52 cm pixel-scale), ESP_017120_1495 (52 cm pixel-scale), (O) ESP_013652_1495 (52 cm pixel-scale), (P) ESP_017476_1490 (52 cm pixel-scale), (Q) ESP_016909_1490 (52 cm pixel-scale), (R) ESP_013586_1490 (52 cm pixel-scale), (S) ESP_015920_1485 (52 cm pixel-scale). MOLA topography over subframe of global THEMIS daytime IR mosaic. North is towards the top of the image.

Geological mapping in Margaritifer Terra constrains the general timing of activity along the ULM outflow system with respect to regional geomorphic events (Grant, 1987, 2000; Grant and Parker, 2002; Grant et al., 2008, 2009; Parker, 1985, 1994; Pondrelli et al., 2005; Saunders, 1979; Scott and Tanaka, 1986). This mapping includes crater counting and assessment of cross-cutting relationships to establish the relative age of various features.

As summarized by Grant (1987) and Grant et al. (2009), the Early Noachian, degraded Holden and Ladon basin multi-ringed impact structures (Schultz and Glicken, 1979; Schultz et al., 1982) are the oldest features crossed by the ULM meso-scale outflow system. These ancient basins imparted considerable structural and topographic influence on the course of the ULM drainage, with incised segments turning to become radial to depositional basin centers (Fig. 1). Formation of the impact basins was followed by evolution of the diverse cratered upland surface that included three general resurfacing events occurring between the Early and Late Noachian and into the Hesperian Epochs. Surfaces created during all three resurfacing events are mostly incised by the ULM system and its tributaries. By contrast, a fourth, more localized resurfacing event of Hesperian age is hypothesized, emplacing materials that embay most ULM tributaries (Grant, 1987). Hence, major incision of the ULM system and its tributaries, including the evolution of the valley encompassing Uzboi, occurred by the

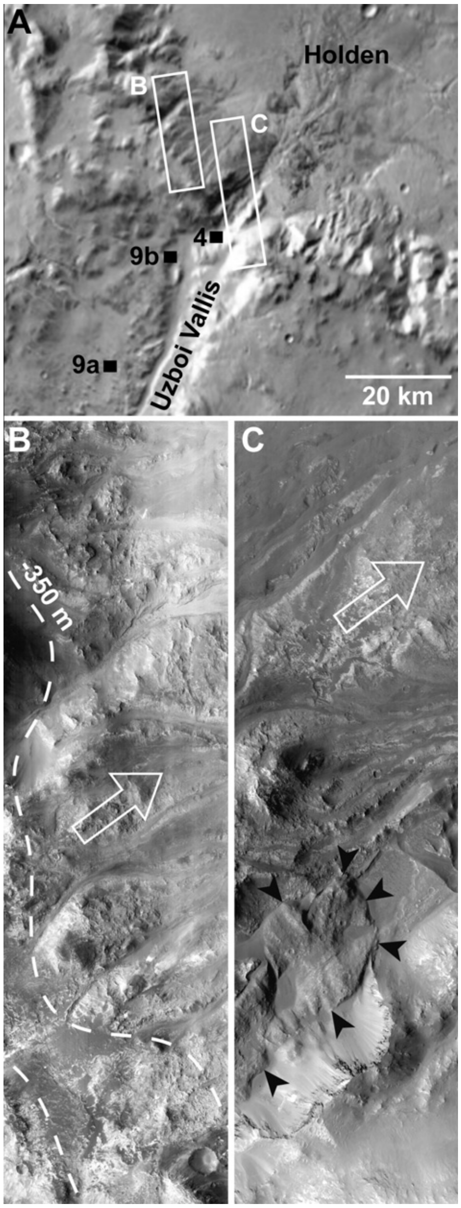

Fig. 3. (A) The formation of Holden crater and its bounding rim created a 900 m high dam across Uzboi Vallis, blocking the previously through-flowing ULM drainage system. Water draining into Uzboi Vallis during the Late Noachian to Early Hesperian resulted in flooding that eventually overtopped and incised through the southwest rim of Holden causing drainage into the crater. Location of Figs. 4, 9a and 9b indicated. Subframe of global THEMIS daytime IR mosaic. (B) Channels incised into Holden's rim when water impounded in the Uzboi lake reached −350 m (approximated from MOLA topography, white dashed line). These channels, located west of the main breach, were eventually abandoned. HiRISE PSP_004277_1530 (26 cm pixel-scale, image 6 km across). (C) Drainage consolidated forming the ~1 km deep main Uzboi breach though Holden crater's rim that has been modified by slumping (black arrow heads outline slump block that slid off east wall of the breach). HiRISE PSP_003710_1530 (26 cm pixel-scale, 6 km across). White hollow arrows point down slope and north is towards the top of each image.

Late Noachian Epoch, but flow may have persisted into the Hesperian (Irwin and Grant, 2009).

Incision of the ULM system likely occurred during multiple large discharge events (Irwin and Grant, 2009). Evidence supporting this history includes anabranching outlet valleys, that likely resulted from filling and overflowing the large intervening basins, with a discharge so large that the pre-valley topography could not confine it into a single channel. The hanging relationships between side channels and the main stem suggests that multiple

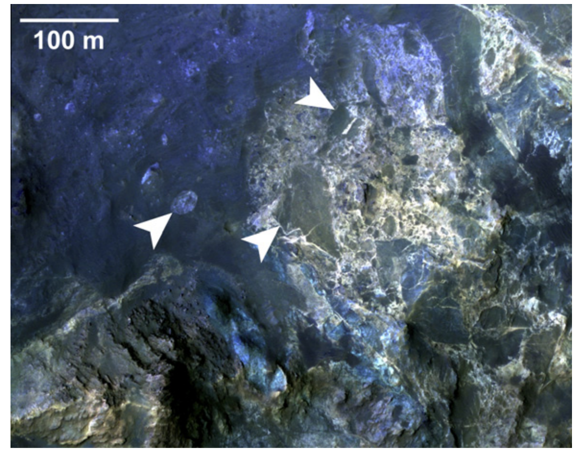

Fig. 4. Megabreccia created during the formation of Holden crater and outcropping along the main breach cut by Uzboi Vallis through the crater rim (see Fig. 3 for context). Arrow heads indicate examples of individual megabreccia blocks. Subframe of HiRISE image ESP_012953_1525_RGB (26 cm pixel-scale) with north towards the top of the image.

overflow points remained active until the central one was incised deeply enough to confine the entire flow. In support of this interpretation, a number of possible terraces are found along Uzboi Vallis, and at least five distinct terraces occur along Ladon Valles (Boothroyd, 1983; Grant, 1987; Grant and Parker, 2002; Parker, 1985). Discharge estimates during incision of the ULM are uncertain, but the elevation of terraces along Ladon Valles combined with information on channel cross-section and gradient suggest discharge rates between 150,000 $m^3\ s^{-1}$ and 450,000 $m^3\ s^{-1}$ (Grant and Parker, 2002). Such rates are 5–10 times higher than that of the Mississippi River (Komar, 1979) and on the lower end of discharge rates from the Channeled Scabland (Baker, 1982; Baker and Nummedal, 1978). If these estimates are accurate, significant discharge rates associated with evolution of the ULM are required.

3. Morphologic evidence for a lake in Uzboi Vallis

3.1. The overtopping of Holden crater's rim

Once blocked by Holden and Bond craters to the north and south, respectively, Uzboi Vallis became an enclosed basin that was flooded by water transported across adjacent contributing surfaces. The most compelling evidence supporting the occurrence of a large lake within Uzboi Vallis is a series of abandoned channels and a large breach that crosses the rim of Holden crater where it intersects the valley (Fig. 3). These channels begin at the rim crest of Holden crater, and their incision requires flooding within Uzboi Vallis/basin to −350 m to enable overtopping of the crater rim. A series of at least seven abandoned channels cross the crater rim at an elevation of −350 m, and all are located to the west of the main breach cutting through the rim (Fig. 3). These channels eroded the interior wall of the crater and coalesce into several shallow channels near the crater floor. The overflow channels to the west were eventually abandoned as the easternmost channel apparently incised more rapidly and became dominant. Eventually, this eastern channel created a wholesale breach, cutting nearly a kilometer into Holden's rim. Rocks exposed within the breach walls are locally fractured by what appear to be dikes filled by light-toned material and are sometimes characterized by mostly angular blocks up to 30 m across (Fig. 4). Analogous to similar exposures on the interior wall of Holden (Grant et al., 2008), these deposits are likely impact-fragmented megabreccia (Grieve et al.,

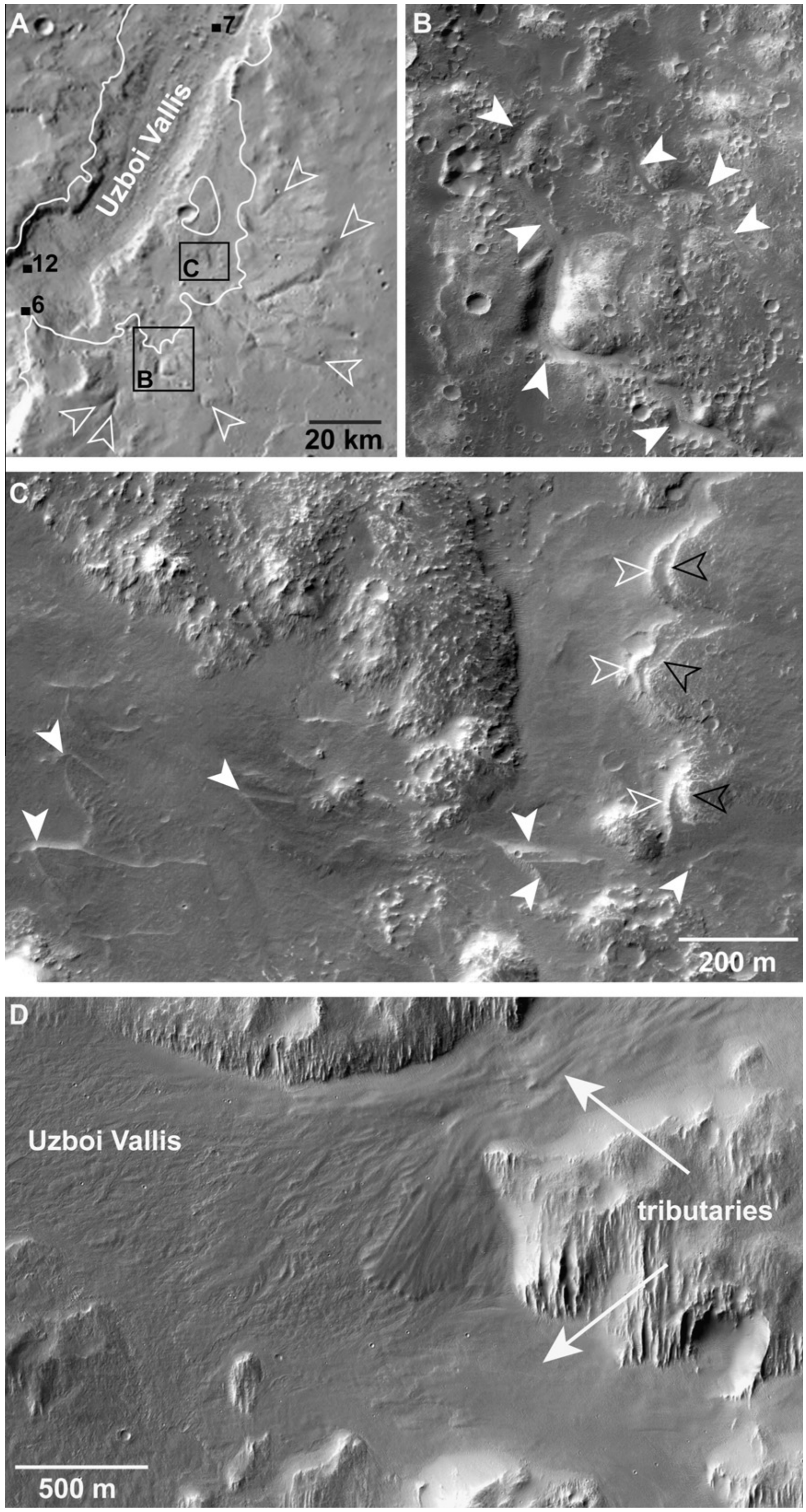

Fig. 5. (A) Tributary valleys, originating upslope of Uzboi, terminate near the −350 m contour (white line, relative to MOLA datum) correlating to the approximate maximum level of flooding in Uzboi before the Holden rim was breached. Most surfaces below −350 m are largely unincised and appear relatively smooth compared to surfaces at ∼−350 m. Hollow arrow heads point down slope and indicate the approximate location of valley heads. Subframe of global THEMIS daytime IR mosaic; see Fig. 2 for context. Location of Figs. 6, 7 and 12 indicated. (B) Many of the valleys are filled with light-toned transverse eolian ridges and terminate near the −350 m contour, showing little connection to occasional valley segments occurring further down the valley walls. White arrow heads indicate valley margins. Subframe of CTX image P17_007547_1525 (6 m pixel-scale). Image is approximately 16.5 km wide. (C) Lobate, steep fronted (down slope) features found below −350 m (bounded by white and black hollow arrow heads) may be rare examples of deposits associated with the valleys. Additional small, superposing depositional forms on the valley floor at lower elevations (solid white arrow heads) may be related to deposition of sediment transported by the valleys, and suggests emplacement occurred during falling water levels. Subframe of CTX image P17_007547_1525 with (6 m pixel-scale). (D) Late stage deposits draining onto the floor of Uzboi Valles appear laden with debris and are consistent with limited water and wet, unstable slopes that may have characterized waning drainage as locally elevated water tables were drawn down after the lake drained. Subframe of HiRISE ESP_016487_1495 (52 cm pixel-scale; see Figs. 2 and 11A for context). North is toward the top of each image.

1977) associated with the formation of Holden crater and seen elsewhere on Mars (McEwen et al., 2008).

A large slump blocking the breach post-dates its incision and the drainage of water from Uzboi into Holden (Fig. 3), suggesting that additional slumps may have occurred during down cutting of the channel. As discharge from the breach entered Holden and became less confined, material eroded from the breach and perhaps further upstream in Uzboi created a series of radiating fans of varying size and distance from the outlet into the crater (Grant et al., 2008). The fans exhibit mafic compositions and weak phyllosilicate signatures (Glotch, 2006; Grant et al., 2008; Milliken et al., 2007), consistent with sourcing primarily from the Uzboi breach and little weathering during or after transport. Several additional landforms and deposits within Uzboi Vallis, discussed below, also support the presence of a large lake.

3.2. Tributary valleys

Nirgal Vallis is the largest tributary to Uzboi Vallis, entering along the medial section from the west (Fig. 1). The estimated discharge from Nirgal is on order of 4800 $m^3\ s^{-1}$ (Irwin et al., 2005b) and could have flooded Uzboi in as little as 20–30 years. The valley is graded approximately to the floor of Uzboi and emerges onto the floor $\sim$400 m below the high stand of the lake at -350 m, thereby suggesting incision of at least the lower reach occurred prior to formation of the lake. There is an inner channel on the floor of Nirgal, but it is unclear whether its origin is fluvial or tectonic in nature, as it appears bounded by faults whose orientation mimics that of major wall segments. A small channel segment is also observed downstream of where Nirgal enters Uzboi that appears to incise the lake sediments/Holden ejecta and post-date the lake, but does not extend all the way to the breach through Holden's rim (Grant et al., 2008). Finally, obvious depositional forms associated with back flooding into Nirgal are lacking, but might be expected if the valley was forming during flooding of the lake. Hence, there is little clear evidence demonstrating that discharge from Nirgal contributed to the lake in Uzboi and the valley may have existed in something close to its present form prior to filling and draining of the Uzboi basin. Nevertheless, because Nirgal Vallis is much larger than any of the other tributary valleys along Uzboi, it remains a good candidate for some, and perhaps much, of the water responsible for creating the Uzboi lake.

Most of the smaller tributary valleys entering Uzboi from surrounding upland surfaces terminate close to or a little above an elevation of -350 m (Fig. 5), thereby implying flow through them was minor and/or short-lived or that the lake filled rapidly enough relative to their incision to provide base level control. In either case, these properties imply the valleys may not have been the major supplier of water for the lake, perhaps strengthening the argument that much of the water came from Nirgal Vallis.

The smaller tributary valleys also display little in the way of depositional forms near their terminuses in Uzboi, though some small, pointed, steep fronted features as well as lobate forms are observed near and below the terminus of one contributing valley (Fig. 5). The paucity of depositional features associated with the valleys where they debouched into the lake, even along the shallow, eastern, middle margin, implies they may have carried a limited sediment load, that the lake level was unstable and only achieved its high stand for a geologically brief interval, or that any depositional forms were since eroded. The latter case seems less likely, given the relatively fresh appearance of the valleys and a fairly abrupt transition from more rugged uplands to smoother, apparently mantled surfaces near the valley termini near and just below -350 m.

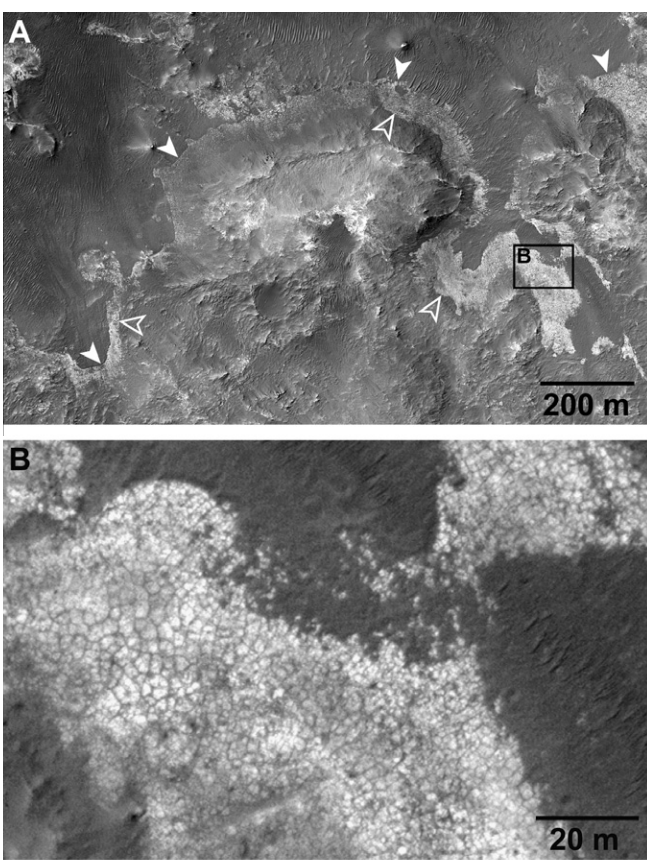

Fig. 6. (A) The transition from relatively rough, higher-relief surfaces to a smoother light-toned and polygonally fractured surface (hollow white arrow heads) and then to a smoother dark-toned surface/deposit (solid white arrow heads) occurs near -350 m (see Fig. 5A for context). The smoother light-toned and dark-toned deposits may represent deposits emplaced near the limit of flooding in Uzboi lake and/or modification of surfaces affected by flooding (light-toned surfaces) or more recent drift (dark-toned deposits). (B) Detail of polygonal pattern in light-toned material. Subframes of HiRISE PSP_006189_1510 (26 cm pixel-scale) with north towards the top of the image.

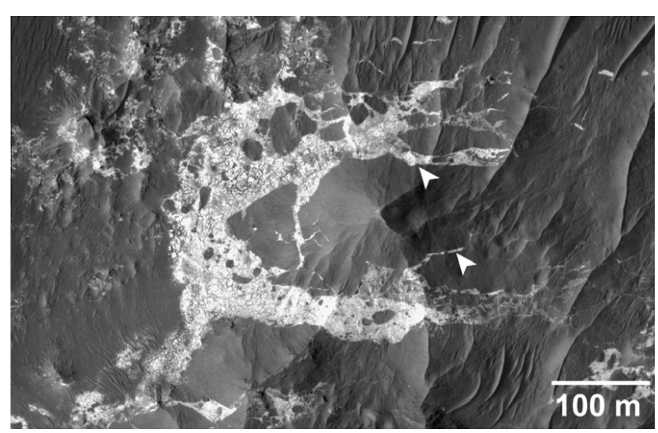

Fig. 7. Erosion of the dark smoother material may be facilitated in some places by the location of fractures in the underlying polygonally fractured light-toned material that may translate up through the dark material. If this is the case, it may relate to flexure or contraction of the underlying light-toned material, though the mechanism remains uncertain. If this interpretation is correct, the erosional pattern of the dark-toned material could produce exposures of the light-toned material along thin stringers (solid white arrow heads), with isolated remnants of dark material remaining in local lows. The result could appear somewhat similar to dikes and/or outcrops of megabreccia that occur closer to the rim of Holden crater, but are produced by erosion (see Fig. 4). See Fig. 5A for context. Subframe of HiRISE PSP_003499_1520 (25 cm pixel-scale). North towards the top of the image.

3.3. Possible alluvium and/or lacustrine deposits

In several locations, but best expressed on the eastern side of Uzboi Vallis where upper valley walls are generally less steep, a fairly abrupt transition from lower relief, smoother, surfaces below −350 m to higher-relief, rougher, lighter-toned surfaces at higher elevations is accompanied by a transition from darker-toned to lighter-toned materials (Fig. 6). A distinct edge to the lower, darker material, which appears similar in tone to relatively young drift and other non-aqueous sedimentary deposits within and near Uzboi (Fassett and Head, 2008; Grant, 1987; McDowell and Hamilton, 2007), indicates a thickness of meters and suggests that the material possesses some limited strength.

In some places, the transition from a lower darker to higher lighter surface is separated by an intervening, narrow, even lighter band of material that is characterized by numerous, meter-scale polygonal fractures (Fig. 6). This brighter material is beneath the darker deposits and is not expressed as a discrete layer, but instead appears to abruptly merge laterally with the underlying surfaces, thereby implying it offers limited resistance to erosion or represents a change in substrate properties. There are locations at lower elevations (i.e., farther from the upper limit of flooding) where the expression of these darker and brighter deposits creates a pattern of dark blocks in a bright matrix (Fig. 7). In such locales, there is little obvious relief along the contact with the darker-toned deposits, which are apparently sculpted to conform to local relief by eolian processes based on nearby occurrences of eolian bedforms. Where observed, the upper limit of the dark-toned material and the underlying, polygonally fractured bright material is near or below −350 m (within about 50–100 m certainty based on available MOLA data), which is close to the elevation defined by the outlet channels crossing the rim of Holden to the north (Fig. 3).

The apparent association of both the darker and polygonally fractured brighter units with the −350 m contour suggests that their distribution may be related to the high stand of the lake and we interpret them to be alluvium and/or lacustrine deposits draping portions of the valley. Although the darker deposits closely resemble younger eolian drift, their apparent topographic confinement may contradict such an interpretation. Deposits emplaced near the margin of the lake would be thinnest, and their eroded appearance suggests they may have been stripped back from their original extent and are now best preserved at slightly lower elevations where they may have been thicker.

It remains possible that the darker material is younger drift and its occurrence is tied to the lighter material for some unknown reason. Further, it is also possible that the brighter, polygonally fractured material could reflect exposure and/or modification of weathered surfaces to the limit of flooding within Uzboi. Such a scenario would be consistent with the difficulty in establishing thickness along the edge of the unit where it abuts higher-relief surfaces above the limit of flooding, but may be more difficult to reconcile along the lower margin of the unit.

The absence of vertical outcrops within the lighter unit that would enable detection or characterization of layering or structure, and a paucity of CRISM data that could reveal compositional information, further complicates confirmation of its origin as well as that of the overlying darker material. The correlation between the limit of flooding and the deposits, however, implies they are related. It is difficult to envision how eolian deposition or emplacement of impact ejecta would create a deposit that is topographically confined below a fairly uniform elevation, and there is no evidence for flooding by volcanic materials, which

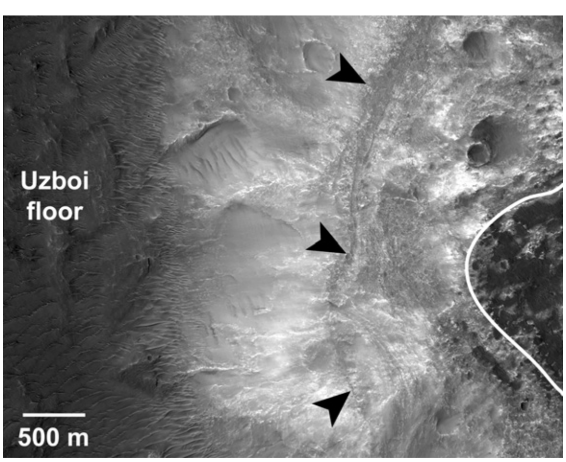

Fig. 8. Obvious examples of relict shorelines are not found around the limit of flooding in Uzboi Vallis. However, there is one possible shoreline along the eastern mid-wall and below −350 m (white line) where a narrow set of crudely linear features (indicated by black arrow heads) appears to follow topography and could reflect a bench cut during temporary stabilization of water level after initial overtopping of Holden's rim. Such features are not expected to be preserved, as they are small and among first to be destroyed via slope processes occurring after the lake drained. The features could be faults or other structures, but this interpretation also seems unlikely because they appear to roughly parallel the contour associated with the high stand of the lake. Subframe of HiRISE ESP_013652_1495 (52 cm pixel-scale, see Fig. 2 for context). North towards the top of the image.

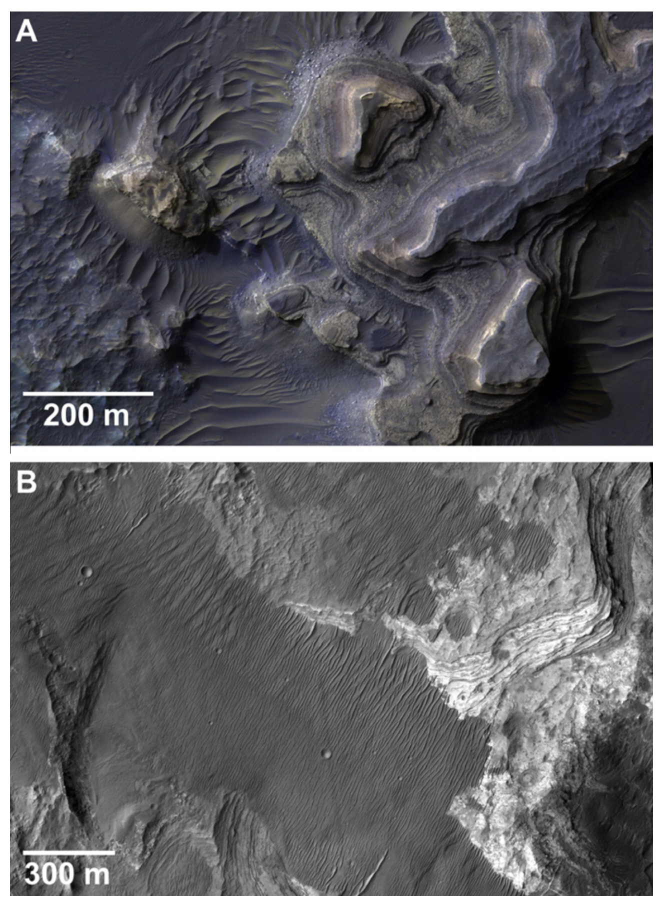

Fig. 9. Examples of bedded deposits in Uzboi Vallis that sometimes occur in alcoves along the valley and/or below the termination of tributaries to the valley. These deposits are possible lake deposits that remain preserved where they were not eroded during drainage of the lake or by later geomorphic activity (see Fig. 3 for context). Where there is CRISM data, the possible lake deposits appear to incorporate more Mg-rich phyllosilicates relative to more Fe-rich phyllosilicates occurring in the valley floor. (A) Subframe of HiRISE image PSP_010329_1525_RGB (52 cm pixel-scale). (B) Subframe of HiRISE ESP_011608_1525 (52 cm pixel-scale). North is towards the top of both images.

would not tend to be light-toned. Preferential erosion of an eolian or volcanic deposit to a uniform elevation is also unlikely. Because the transition appears to follow topography and is close to the elevation of the spillway over Holden's rim, it may somehow reflect the high stand of a lake in Uzboi (e.g., limit of deposition or alteration of submerged surfaces). The lake may have temporarily stabilized at −350 m after initially overtopping Holden's rim but before the deeper incisement of the main breach through the crater rim occurred, resulting in the lowering of water levels.

Whatever the origin, exposure of the lighter, polygonally fractured material appears controlled by partial stripping of the darker deposits (Fig. 6). In some locations, the edge of the two materials appears to correspond and follow fractures within the lighter deposits, which may arise from differential properties that assist in breakage. Slightly stronger, darker material can be sculpted by the wind, and erosion is focused where it has broken along fractures developed in the underlying, weaker, lighter deposits. The resultant morphology may resemble the megabreccia exposures within the Uzboi breach in Holden's rim (Fig. 4) and the rim and walls of Holden crater (Grant et al., 2008), but is more likely created by differential erosion of the deposits. This conclusion is supported by the observation that in some cases where the darker and lighter materials are juxtaposed in this way, they are up to a crater diameter beyond the rim of Holden and well outside of other craters, where megabreccia is less likely. Elsewhere in Uzboi, breakage along polygonal fractures within the brighter polygonal material may assist in disruption and locally enhanced erosion of overlying darker deposits along narrow outcrops. In some locales, the edge of the darker material may correspond to the margins of the polygonal fractures in the underlying lighter material. Hence, what appear to be "dike-like" outcrops of lighter material in some locations may be due to local erosion of the darker material to expose thin outcrops of the underlying brighter material and may not be related to igneous intrusion (Fig. 7).

3.4. Possible shoreline features

There are no obvious candidates for shoreline features along the −350 m contour that might correspond to a high stand of the lake within Uzboi. However, such features are often relatively subtle on Earth and, in the case of depositional forms, would likely be easily eroded or masked by younger drift. There is one location along the wall of the mid-eastern portion of the valley where a series of curvilinear features runs below, but somewhat parallel to the −350 m contour (Fig. 8). Because the expression of faults and other structural features is not likely to correspond to topography, it is possible that these features are benches created as decreasing lake levels temporarily stabilized. Their limited occurrence and poor correlation with the proposed high stand of the lake, however, makes any shoreline interpretation questionable.

3.5. Layered deposits

A variety of bedded deposits occur below −350 m on mostly lower sections of the basin, typically within alcoves down slope from where tributaries enter the basin (Fig. 9), and along the floor where exposed in craters (Fig. 10). These often light-toned beds are observed mostly in medial and distal sections of the basin, but are not observed where the largest tributary, Nirgal Vallis, enters Uzboi basin (Fig. 2). Limited CRISM data (FRT0000ABB5) from one well-bedded deposit (Fig. 9A) reveals Mg-smectites (possibly saponite or hectorite), whereas nearby phyllosilicate-bearing outcrops show less obviously bedded material that may be relatively enriched in iron (possibly a nontronite–saponite mixture).

Although some of these beds, which occur below where tributaries enter the basin, imply a genetic relationship, their eroded form and bedding orientation (where observable) may not necessarily require emplacement in a deltaic setting. Other outcrops displaying less obvious bedding are not as clearly linked to deposition within the lake. While it is possible that these less obviously bedded deposits are lacustrine in origin, an origin related to the original, pre-flooded floor and sides of Uzboi Vallis is consistent with their distribution. If the latter, these deposits could correlate with the light-toned polygonally fractured material (Fig. 6) higher in the basin and closer to the −350 m contour, possibly representing an ancient weathering surface that formed as Uzboi Vallis was down-cut and valley walls retreated via slope processes. The observed iron-enrichment of phyllosilicates in the less bedded deposits could reflect either the weathering regime during valley incision and/or the effects of later inundation when a lake occupied the valley. The Mg-enriched phyllosilicates in the well-bedded deposits below tributaries may be related to transport from a regional layer to the west covering much of northwest Noachis and consisting of phyllosilicate-rich sediments (Buczkowski et al., 2010).

3.6. Deposits in unnamed crater adjacent to Uzboi Vallis

The southern and western rims of a ∼55 km-diameter unnamed crater near the southern end of Uzboi (30.2°S, 323.3°E, Fig. 11) drop below −350 m elevation, and they would have been overtopped during flooding of Uzboi. A bench located near −350 m extends around much of the eastern wall of the crater, and there is a posi-

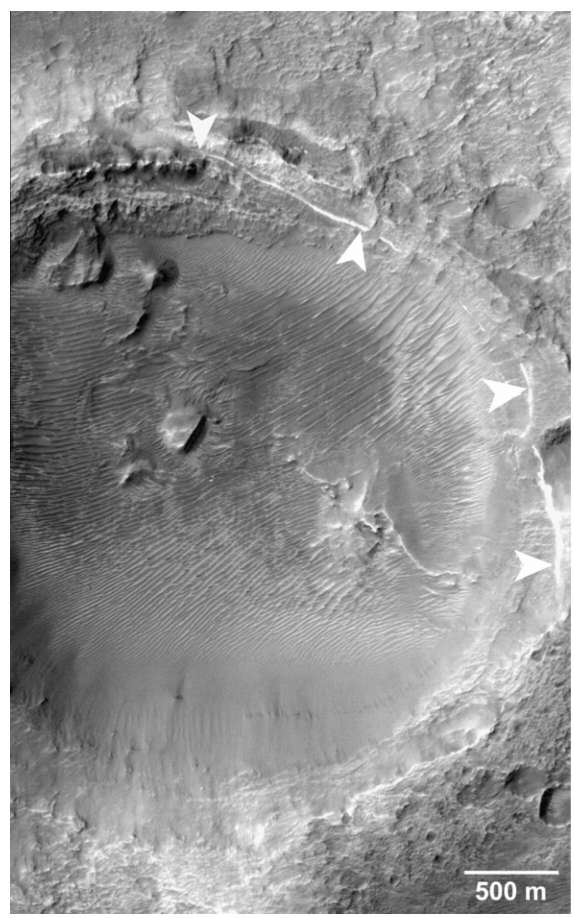

Fig. 10. Light-toned beds exposed in the wall of an impact crater that excavated the western floor of Uzboi Vallis (see Fig. 2 for context). The light-toned beds in this location (e.g., white arrow heads) appear to unconformably overly lower beds and may be deposits emplaced while a lake occupied Uzboi Vallis. Subframe of MOC image M0401181 (5.6 m pixel-scale). North is towards the top of the image.

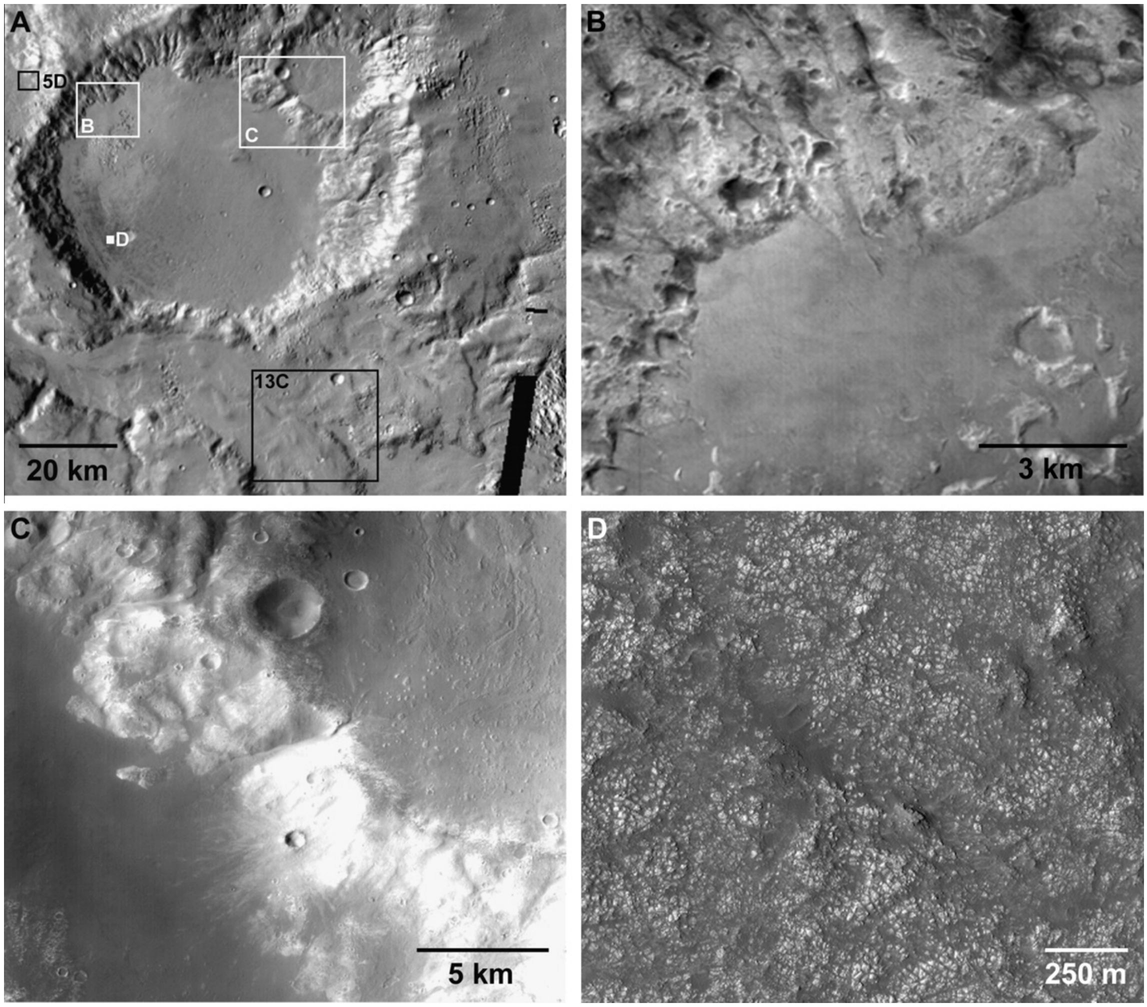

Fig. 11. (A) Unnamed crater near the southern end of Uzboi Vallis (see Fig. 2 for context). The rim along the west and south sides of the crater are below −350 m and would have been overtopped by the lake within Uzboi. Subframe of global THEMIS daytime IR mosaic. Location of Fig. 5D indicated. (B) Deposits on the floor of the crater embay the lower walls and lack obvious volcanic attributes and sources and may be related to deposition when the crater was inundated. Subframe of CTX P11_005477_1505 (6 m pixel-scale). (C) Valley connection between tributary crater basin (upper right) and floor of unnamed crater that formed as water levels dropped. Material along the floor of the unnamed crater appears to be conformable with valley and embays the unnamed crater walls. Subframe of CTX P06_003354_1477 (6 m pixel-scale). (D) Detail of polygonal fractures characterizing portions of the layered deposits on the floor of the unnamed crater. Subframe of HiRISE ESP_013586_1490 (52 cm pixel-scale). North is towards the top of all four images.

tion along the northeastern wall where a small, superposed crater created a tributary basin that drained into the larger crater (Fig. 11). Lower down, the walls of the craters are incised by valleys, and the floor appears unconformably mantled in most locations by crudely bedded, sometimes polygonally fractured, and variably light-toned material.

The crater floor deposits were likely deposited during flooding of the crater. There is no evidence of flow fronts or other morphologic features suggestive of a volcanic origin. Since there is no outlet from the unnamed crater, once flooded, water would have pooled and only slowly drained via infiltration and evaporation following the initial drawdown of the lake to the level of the rim. The longer duration of standing water in the crater may have enabled significant charging of local aquifers whose subsequent drainage could have enhanced incision along the higher, eastern wall of the crater. The more numerous, larger valleys reaching lower elevations (relative to outside of the crater) along the higher, eastern crater wall and entering from the tributary crater basin could reflect a combination of orographically induced precipitation and groundwater drainage as water levels dropped.

3.7. Summary of morphologic evidence supporting a lake in Uzboi Vallis

The suite of morphologic features in Uzboi lends strong evidence for a lake within the valley during the Late Noachian or Early Hesperian, but the high stand of the lake at −350 m is only directly related to the channels that cross the rim of Holden crater at that elevation. Because these channels head at the rim of Holden crater and are located adjacent to Uzboi Vallis, there is no collection surface that could have contributed to their incision other than flow from water impounded within Uzboi. More indirect, supporting evidence for a lake comes from (1) the transition from valley-incised and locally higher-relief surfaces above the hypothesized limit of flooding to smoother dark-toned and underlying lighter-toned, polygonally fractured deposits below and (2) other bedded, phyllosilicate-bearing deposits below −350 m. The morphology and elevation restriction of these deposits and other features makes an origin related to volcanic, impact, mass wasting, eolian, or even simple fluvial processes difficult to reconcile. Additional support for a paleolake comes from ridges and associated features

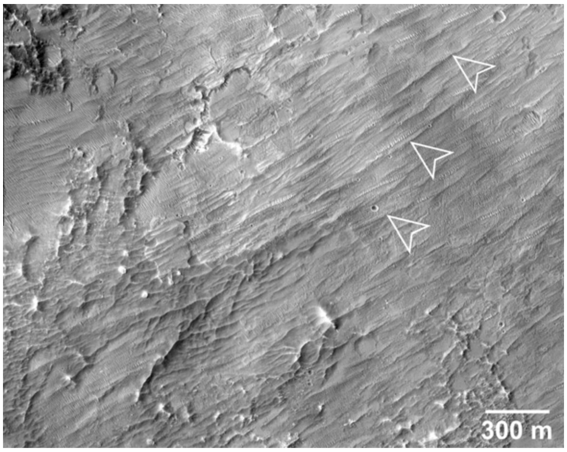

Fig. 12. Longitudinal grooves and ridges (e.g., white arrow heads) in the middle floor of Uzboi Vallis (see Fig. 5A for context). Analysis of 153 grooves/ridges reveals they are hundreds of meters long and average 60 m in width (standard deviation of 30 m). The grooves are associated with possible potholes and other features and may be analogous to grooves associated with large floods on the Earth. If correct, this interpretation indicates that at least the final stage of lake drainage was characterized by high discharge. Subframe of HiRISE PSP_006189_1510 (26 cm pixel-scale). North towards the top of the image.

along the floor of Uzboi that were likely formed during and shortly after the lake drained.

4. Draining the lake in Uzboi

Once filled, the lake in Uzboi did not persist for a geologically long period. Evidence for this short-lived high-stand comes from the general paucity of deposits at the foot of most tributaries where they debouche near −350 m and the dearth of deposits near the mouth and up to the limit of back flooding into Nirgal Vallis. These observations indicate that water levels in the lake were probably not stable at any elevation for a long period, as deposition of just the sediment required for valley incision should lead to substantial accumulations over time, especially where valleys terminate into relatively shallow portions of the basin. While a precise quantitative estimate of how long the lake in Uzboi persisted is not possible, these observations suggest the lifetime of the lake may have been less than a million years. Additional evidence indicates that drainage of the lake was characterized by high-magnitude discharge.

When the lake in Uzboi Vallis overtopped the rim of Holden crater at an elevation of −350 m (Fig. 3), initially dispersed drainage at multiple locations coalesced into a dominant breach that became incised hundreds of meters. As the Uzboi lake drained into Holden, fan deltas formed on the crater floor, reaching more than 25 km from the breach (Grant et al., 2008). Cross-cutting relationships between the fans in Holden show that the orientation and distance reached by discharge through the main breach shifted generally from northerly to northeast and then easterly over time. Varying discharge due to periodic blocking of the rim breach by collapse (Fig. 3) and/or breach cross-section and orientation as down cutting progressed may have influenced the changing nature and position of the fan deltas. Nevertheless, emplacement of the meter-sized blocks exposed in some low-gradient fans requires high-magnitude discharge (Grant et al., 2008).

Additional evidence for rapid, high-discharge drainage of the lake comes from the mid-basin of Uzboi, where a series of longitudinal grooves and ridges is preserved on the floor (Fig. 12). The grooves are formed into Holden ejecta (post-dating pre-Holden crater drainage along the ULM system), are hundreds of meters long, oriented with their long axis along the valley, and 60 m wide on average (standard deviation is 30 m). On Earth, morphologically similar features of comparable scale are associated with very large floods. In the Channeled Scabland, Iceland, and the English Channel, for example, grooves are typically 50 m or more in width and are commonly associated with grooves, potholes, and other erosional bedforms (Alho et al., 2005; Baker, 2001, 2002, 2009; Baker et al., 1988; Gupta et al., 2007) that resemble those found in association with the Uzboi features. On Earth, such features are formed by cavitation or macroturbulence in flows at least meters in depth and reflect discharge rates of 10^5–10^6 m^3 s^{-1} (Alho et al., 2005; Baker, 2001, 2002, 2009; Baker et al., 1988; Gupta et al., 2007). If the features in Uzboi (Fig. 12) were formed by a similar process, they imply rapid draining during the final stages of the Uzboi lake.

The complete drainage of water (~4000 km^3) from Uzboi into Holden crater during a single event would result in flooding within the crater to an elevation of about −1800 m. Trim lines along alluvial fans in the crater suggest, however, that water did not rise higher than about −2060 m (Grant et al., 2008; Pondrelli et al., 2005), or 260 m lower than expected for a single lake-draining event. The changing orientation, location, and scale of the fan deltas in Holden support the occurrence of multiple drainage events. Therefore, incision of the crater rim was likely pulsed, perhaps due to varying discharge into Uzboi lake, differing resistance of bedrock encountered as the breach down cut, or failure of the walls of the breach during down cutting that resulted in temporary damming. A mass wasting deposit presently partially blocks the breach, see Fig. 3, and it seems plausible that others occurring during down cutting may have temporarily blocked or slowed drainage of the lake in Uzboi, thereby keeping water levels in the crater from rising above −2060 m.

As the lake in Uzboi drained, a breachway channel eroded headward up the Uzboi valley, but it only reached about 40 km above the head of the breach. There are no well established upstream connections to other channels, and much of the floor of Uzboi remains largely unincised except for shallow and poorly integrated channels crossing mostly medial and proximal portions of the valley and below the entry of Nirgal Vallis (Fig. 13). Topography along the floor of Uzboi (Fig. 2) defines only two small enclosed depressions that provide opportunities for residual ponding after initial and essentially complete drainage of the lake: immediately above the head of the breachway channel (27.58°S, 323.76°E) and an even smaller area a little further upstream (28.18°S, 324.39°E) The limited extent and integration of the medial and proximal valley floor channels, coupled with limited opportunity for residual ponding in Uzboi and the unincised nature of the downstream deposits in Holden crater, indicates limited ponding and/or through drainage into Holden once the lake drained. Limited late drainage, if any, was probably related to final drawdown of tributary basins and discharge from elevated water tables around the sides of the flooded valley. Negligible incision of tributary valleys below −350 m (Fig. 5) also indicates minimal drainage from Uzboi into Holden following drainage of the lake, although some small, lobate, steep-fronted forms immediately below at least one tributary suggest there may have been some depositional construction shortly after lake lowering (Fig. 5). Nevertheless, the relatively small deposits that are recognizable along the lower wall and floor of the valley are dominated by what appear to be lobes of debris (Fig. 5), perhaps from debris flows shed from steep surfaces into valleys during waning activity associated with the drawdown of the water table.

5. Source of the water for the lake in Uzboi Vallis

Flooding of Uzboi Vallis likely occurred between the Late Noachian and Early Hesperian. The timing of the lake is constrained

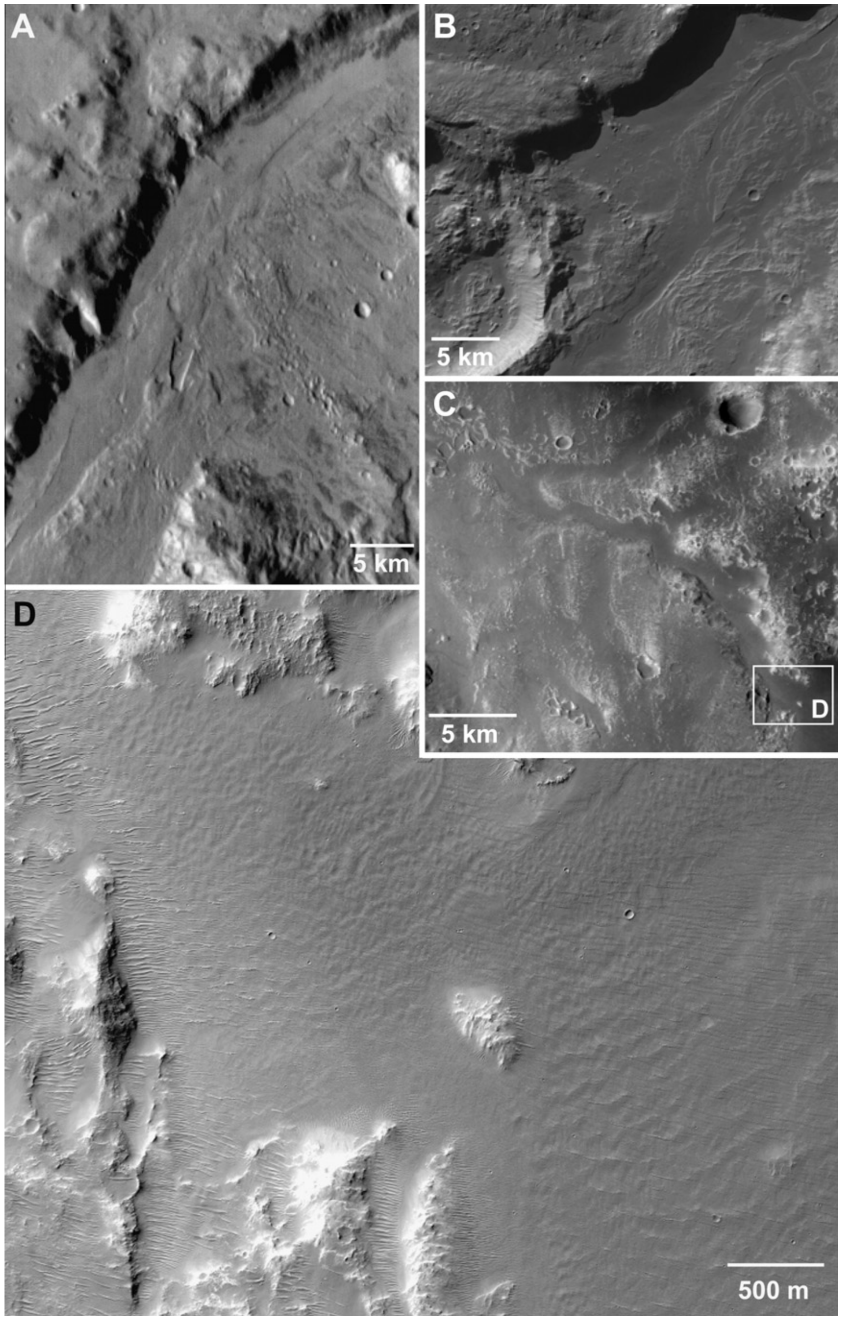

Fig. 13. Shallow, poorly integrated, post-lake channels on the floor of Uzboi Vallis. The disorganized and poorly integrated nature of these channels suggests limited through drainage along Uzboi Vallis following drainage of the lake. (A) Short channel and apparent deposits extending a short distance downstream of the outlet of Nirgal Vallis implies little through drainage from Nirgal along Uzboi after the lake drained. Subframe of THEMIS VIS I08503003 (see Fig. 2 for context). (B) Example of shallow, poorly integrated and incised, post-lake channels crossing the floor of Uzboi. Subframe of CTX P20_008694_1480 (6 m pixel-scale, see Fig. 2 for context). (C) Outlet channel from a tributary basin at the south end of Uzboi just north of where the valley is blocked by Bond crater. The valley likely formed as water in the tributary basin drained onto the floor of Uzboi and is one of the best incised examples of a post-lake channel on the valley floor. Subframe of CTX P06_03354_1477 (6 m pixel-scale, see Fig. 11A for context). (D) Possible bedforms near the outlet of the tributary basin shown in (C). If subaqueous in origin, these bedforms suggest appreciable discharge was associated with drawdown of water in the tributary basin. Subframe of HiRISE ESP_015920_1485 (52 cm pixel-scale). North is towards the top of all images.

by the formation of Late Noachian-to-Early Hesperian-aged Holden crater that blocked the system (Pondrelli et al., 2005; Scott and Tanaka, 1986), and subsequent drainage of the lake into Holden that superposed lacustrine and alluvial deposits (Grant et al., 2008; Moore and Howard, 2005). It is therefore possible that the lake in Uzboi was present during at least a portion of the time that a lake occupied the floor of Holden crater (Grant et al., 2008). It is also possible that Uzboi may even have contributed to the Holden lake via pre-breach groundwater discharge through the crater rim. There are also alluvial fans within a number of nearby craters in southern Margaritifer Terra (Grant et al., 2010b; Kraal et al., 2008; Moore and Howard, 2005) that may have been forming at about the same time (Moore and Howard, 2005), thereby suggesting the formation of a lake in Uzboi Vallis was part of an at least a regional-scale, relatively wet period.

Sources of water for Uzboi lake include surface runoff from Argyre, groundwater, and precipitation-fed runoff within the watershed. Surface water from Argyre was not possible due to blockage by Bond crater and a lack of features suggesting flow through, around, or over the rim of Bond crater. It is possible that a rising regional water table enabled groundwater to contribute to flooding, but several nearby craters suggest that the water table remained below −1275 m, the lowest point on the floor of Uzboi. For example, Holden crater is immediately to the north of Uzboi and represents the lowest surface within nearly 700 km. The crater may have held a lake, but surfaces above −1960 m appear to lack evidence for inundation (Grant et al., 2008; Pondrelli et al., 2005). Extensive fans in Ostrov crater, ~200 km to the east of Holden, grade to an elevation of −1500 m, but there is only limited evidence for temporary ponding in the deepest portions of the crater (Irwin et al., 2010a). The lower walls of an unnamed crater approximately 40 km west of Uzboi and southwest of Holden are also fringed by alluvial fans that drain to what may have been a shallow lake or playa at an elevation of −1415 m. All three of these craters imply a water table lying below the deepest point in Uzboi Vallis. Although the elevation of the regional water table may have varied considerably from location to location, the fact that none of these craters displays evidence for standing water near or above the deepest point in Uzboi implies that groundwater contributions to the lake from outside its direct watershed were minor.

The most likely source of water for the lake in Uzboi was precipitation and runoff from contributing basin surfaces in the absence of significant contributions from overflow of Argyre and groundwater. As noted earlier, the major tributary to Uzboi, Nirgal Vallis, may have been active in flooding of the valley. Despite the absence of obvious depositional features near the mouth or upstream to the limit of back flooding which would imply significant discharge while the lake was filling, the multiple overflow channels across Holden's rim suggest Uzboi filled rapidly and that discharge into the lake was sufficient to occupy more than one overflow channel. The sheer scale of Nirgal Vallis coupled with the nature of the other, much smaller tributaries (e.g., apparent base level control, minimal incision below −350 m contour, few depositional forms), implicates it as a major source of water. Minimal connection between Nirgal and the Uzboi breach through Holden's rim, however, indicates that any discharge largely ended by the time the lake drained.

Most other Uzboi basin tributaries show poor connections to small valley segments lower in the basin that were likely reactivated or wholly formed during lake draining and subsequent drawdown of the local water table. Because tributaries above −350 m did not respond meaningfully to lake draining and a dramatic lowering of base level (hundreds of meters), their incision must also have ended when the lake drained. The nature of the relatively small deposits that may be associated with the tributaries (Fig. 5) provides additional evidence that the valleys became largely inactive at about the time the lake drained. Collectively, the evidence for minimal post-lake discharge into Uzboi indicates an abrupt climate change and end to precipitation-fed runoff.

6. The lake in Uzboi Vallis and implications for Late Noachian/Early Hesperian climate

The evolution of a large lake in Uzboi Vallis that likely coincided with or just followed Late Noachian-to-Hesperian alluvial and/or lacustrine activity in and nearby Holden crater indicates that formation of fluvial and lacustrine sequences were not limited to one drainage basin in the region. Moreover, drainage from Argyre and groundwater contributions to the Uzboi lake were probably minimal, thereby pointing to precipitation and runoff from regional surfaces as the primary source of water responsible for ponding. The absence of abrupt relief (outside of craters) or regional slopes that might induce widespread orographic precipitation in Uzboi's direct watershed implies that precipitation was not only related to orographic forcing, but was more likely associated with broader, synoptic systems capable of delivering water to surfaces in multiple basins covering a wide range in relief.

The possibility of synoptic precipitation and similarities in the morphology of nearby deposits suggests that formation of the Uzboi lake may be simultaneous with alluvial and lacustrine deposition in Holden crater (Grant et al., 2008), formation of a lake in Eberswalde crater just to the north of Holden crater (Malin and Edgett, 2003; Moore et al., 2003), and may have coincided with emplacement of alluvial fans and possible playa or lacustrine deposits in many of the larger craters (>20 km in diameter) in southern Margaritifer Terra (Grant et al., 2010b; Irwin et al., 2010a; Kraal et al., 2008; Moore and Howard, 2005). These observations point to a short-lived, abruptly ending, globally active hydrologic system in the Late Noachian (Fassett and Head, 2008; Howard et al., 2005; Irwin et al., 2005b; Moore and Howard, 2005; Wray et al., 2009), perhaps extending into the Hesperian, that may have been the last widespread period when water was available across broad areas of Mars (Bibring et al., 2006). Conditions during this period may have been relatively dry by terrestrial standards (Irwin et al., 2010b), with systems being transport-limited, but capable of producing runoff sourcing a wide range of alluvial and lacustrine systems.

The catalyst for a brief wet period in the Late Noachian into the Early Hesperian when the climate on Mars supported at least occasional precipitation as part of an active hydrologic cycle is unclear, as is whether the form of the precipitation was frozen or liquid. Although steep topography could concentrate snow accumulation in the bottom of alcoves for later seasonal melting and sourcing of alluvial systems in Holden and other craters (Moore and Howard, 2005), any means of concentrating snow on the broader, lower-relief surfaces sourcing Uzboi is less obvious. Moreover, snowmelt on steep, bedrock alcove walls may favor runoff as compared to flatter surfaces capped by regolith that may possess higher infiltration capacities, thereby limiting runoff (Grant, 2000). Although runoff of snow melt from regolith could be facilitated if the ground were frozen, there is little evidence for periglacial mass wasting around Uzboi.

Alluvial fan surfaces within craters in southern Margaritifer Terra are often characterized by ridges (up to a few tens of meters high in Holden) that radiate from source alcoves and are likely the inverted expression of fan distributaries (Grant et al., 2010b; Moore and Howard, 2005). A paucity of large blocks exposed in the walls of craters excavating the fan materials coupled with the fans' ability to be deflated up to tens of meters while preserving subtle details of fan channels implies relatively efficient eolian erosion of fine-grained material. Although the slopes on some fans imply a gravel component to the distributary channel sediment (Moore and Howard, 2005), and images of alluvium exposed in small craters in Holden crater fans do reveal some large blocks, the ability to remove substantial sediment via deflation indicates a significant component of sand and perhaps even finer material. Whether this fine component is produced via weathering in source alcoves and/or in situ via weathering of gravels on the fans is uncertain, but it may point to more clear-water discharge rather than sediment-laden debris flow discharge onto the fans (Moore and Howard, 2005). Therefore, less flashy precipitation, either in the form of rain or melting snow, was a possible source of the water for the lake in Uzboi and any associated alluvial/lacustrine systems elsewhere in southern Margaritifer Terra.

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