Dynamic river channels suggest a long-lived Noachian crater lake on Mars

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[1] Recent images of the Noachian-age Holden Northeast Crater show spectacular meandering channels that form a complex 150 meter thick lacustrine river delta deposit confined to the northwest margin of the crater. We identify 11 major avulsion events in the topmost layer and suggest an avulsion frequency of a few hundred years. The meandering nature of the channels and numerous avulsions is incompatible with deposition on an alluvial fan and clearly reflects a complex history of multiple sustained flows. Assuming an average sedimentation rate of 1mm/year, we suggest that Holden NE Crater contained a lake that persisted for at least 150,000 years. Our analysis is incompatible with this feature being the result of a major bolide impact that would have released a catastrophic flood by groundwater sapping and supports the hypothesis that early Mars was both warmer and wetter during the Noachian. **Citation:** Bhattacharya, J. P., T. H. D. Payenberg, S. C. Lang, and M. Bourke (2005), Dynamic river channels suggest a long-lived Noachian crater lake on Mars, *Geophys. Res. Lett.*, *32*, L10201, doi:10.1029/2005GL022747.

1. Early Mars: Wet or Dry?

[2] There remains significant debate as to whether there were persistent water flows, significant precipitation and standing water bodies during the Noachian history of Mars (i.e. 4.8–3.5 Ga) [*Squyres and Kasting*, 1994; *Craddock and Howard*, 2002; *Head et al.*, 2003; *Jerolmack et al.*, 2004]. The presence of free water on early Mars, such as might have characterized ancient crater lakes, has important implications in identifying possible habitats that may contain fossilized evidence for extinct life. Recent Mars Global Surveyor (MGS) Mars Orbiter Camera (MOC) images (Figures 1 and 2) of a Noachian-age, possible lacustrine delta that partially filled the northwestern margin of Holden NE Crater show spectacular evidence for meandering streams in the topmost exposed layers and suggest persistent water flows [*Malin and Edgett*, 2003; *Moore et al.*, 2003]. Recent work uses channel width and meander wavelength measurements to estimate that the fluvial discharge required to build these channels was on the order of 700 m^3/s [*Moore et al.*, 2003], which would be a reasonably large river by terrestrial standards [*Milliman and Syvitsky*, 1992]. Stereoscopic analysis of the underlying 150 m of strata shows variable dips and lateral-impersistence of layers [*Lewis and Aharonson*, 2004] consistent with the complex facies architecture of deltas [*Bhattacharya and Walker*, 1992].

[3] We present the first detailed geomorphological mapping of the associated channels and channel belts in the youngest layers. The nature and history of channel migration and avulsion allows estimation of the length of time required to accumulate the topmost layer [*Bridge*, 2003] and can be extrapolated to estimate the total amount of time required to deposit the underlying 150 m of strata. The images of the Crater fill and associated drainage basin as well as MOLA contour data are publicly available on NASA website: http://www.msss.com/mars_images/moc/2003/11/13/index.html.

2. Drainage Network

[4] The contributing drainage basin (Figure 1) covers an area of about 4800km^2 and has been interpreted to represent fluvial erosion and degradation of a Noachian-age crater [*Malin and Edgett*, 2003; *Moore et al.*, 2003]. The drainage network shows at least 5 orders of tributive branching, although the smallest 1st-order branches may be associated with a yet smaller network not resolvable with the available images. Aeolian deflation may also have smoothed or eroded the finer structure of the drainage network [*Malin and Edgett*, 2003]. *Moore et al.* [2003] suggest three potential runoff sources; impact-induced climate optima, longer-term rainfall-runoff or groundwater discharge. *Jerolmack et al.* [2004] suggest that water may have been derived as groundwater discharge from the impact related to the formation of the larger Holden Crater to the southwest [*Pondrelli et al.*, 2004]. Because the delta fills a presumed early-Noachian crater, it is estimated to be a late-Noachian-age feature, formed over 3.5 Ga ago and is thus younger than Holden Crater [*Moore et al.*, 2003]. There are no obvious smaller craters directly associated with the northern and western terminal branches of the drainage network that would indicate a bolide, although there is a crater in the south. The case for the rainfall-runoff hypothesis has recently been strengthened with the discovery of a series of valleys formed between 2.9–3.4 Ga in Valles Marineris [*Mangold et al.*, 2004].

3. Crater Fill

[5] The Holden NE delta comprises three lobes (Figures 2 and 3) that forms a body of sediment that measures roughly 10 km × 25 km and ranges from about 150m to about 50 m thick, representing a volume of 20–30 cubic kilometres, which is significantly greater than the 6km^3 estimated by *Malin and Edgett* [2003] and 13.2km^3 estimated by *Moore et al.* [2003]. In several places, aeolian erosion has exposed

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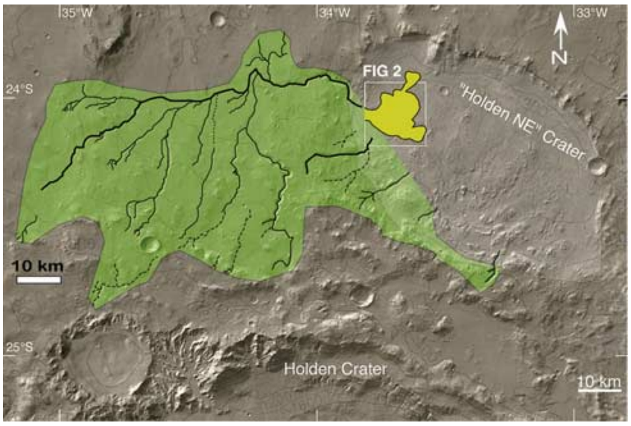

Figure 1. Holden NE Crater drainage basin showing 5th-order tributive network, typical of a fluvial drainage network. Note deeply incised (up to 200m) meandering valley network. Yellow area shows outline of delta feature that filled the northwest margin of the crater (see Figure 2).

older, typically straight, channels [*Malin and Edgett*, 2003; *Moore et al.*, 2003], and it is thus possible to determine the evolution of channel pattern, migration, and avulsion history through time. The most deeply eroded layers form a flat piedmont surface and lack any evidence of channels and show several more reflective layers (labelled B in Figure 2). These may represent older "bottomset" layers associated with infilling of the crater lake [*Moore et al.*, 2003; *Lewis and Aharonson*, 2004].

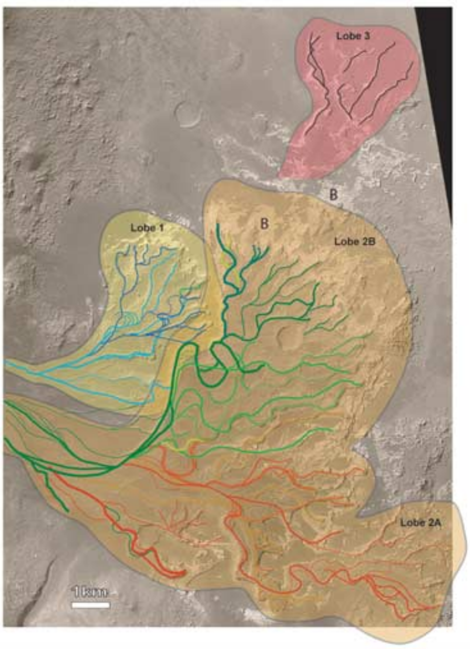

Figure 2. Map of lobes and channels at northwestern margin of Holden NE Crater fill (location in Figure 1). Reflective beds (B) in exposed bottomsets possibly represent lake-bottom evaporites. Details of channel order and number are shown in Figure 3.

[6] The topmost layer (Figure 2) shows clear evidence of meandering streams that record a complex history of migration, avulsion and bifurcation, forming a distributive pattern with up to 5 orders of branching. It was not always possible to determine whether adjacent channel are simultaneously active within the lobes, or represent an avulsion of the same channel. The best evidence for multiple active channels is the downstream decrease in channel width, and development of multiple 5th order channels in channel 11, lobe 2 (Figure 3). The oldest lobe 1 shows 5 orders of channel bifurcation, and is overlapped by Lobe 2.

[7] In lobe 2, 11 major channel complexes can be mapped (Figure 3). The 2nd and 3rd order channels migrate to form channel belts, which are presumed to be sand or gravel grade sediment [*Moore et al.*, 2003]. Cutoff relationships of the channels suggest that the channels migrated primarily to the north as the delta grew (Figure 3). Several channels in lobe 2 (Figure 3) show a distinct transition from initially straight, to highly sinuous. Channel 4 in lobe 2 (4S) starts out as straight and then becomes more sinuous (4M) building a complex channel belt. Farther north, the highly sinuous 10M channel shows increasing sinuosity of a probably initially straight channel by meander expansion followed by lateral migration (dashed lines indicate expansion of a scroll bar). A classic chute cutoff can be seen, as the 10S channel (Figure 3) avulses to the southwest. The 10S channel is much straighter than the more mature pre-avulsion 10M channel. Both 4M and 10M channels bifurcate downstream, indicating that they feed a distributive network.

[8] The most proximal 1st order and most distal 4th to 5th order channels are relatively straight, whereas the intermediate 2nd and 3rd order channel show the highest sinuosity, suggesting lower discharge than the 1st order streams and greater stability than the 5th order distributaries. Cutoff relationships show that the largest 1st order channel

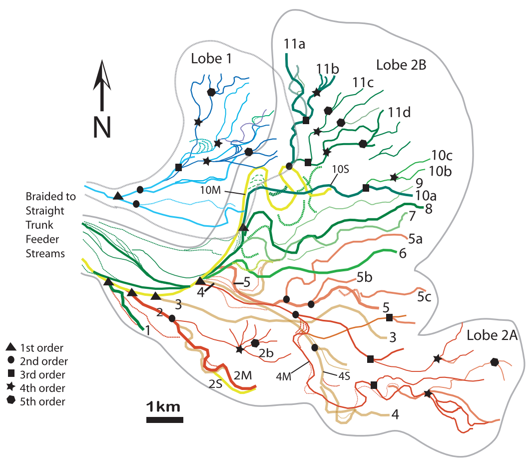

Figure 3. Details of channel patterns in lobes 1 and 2. Main channels are numbered (1–11) and subsidiary distributaries are designated with letters (11a, 11b, etc.). Channel order is determined at each bifurcation point. Meandering channels are designated with the letter M. Straight channels are designated with the letter S. Newly avulsed channels typically are straight and become more sinuous with time (e.g., 4S to 4M). See text for discussion.

in the southern lobe avulsed about 11 times, but also shows significant migration.

4. Interpretation of Environment

[9] A significant question has been raised as to whether this feature is an alluvial fan, terminal splay, or a delta [*Malin and Edgett*, 2003; *Moore et al.*, 2003]. Alluvial fans need not feed into a standing body of water, and facies models for terrestrial alluvial fans suggest that they should be dominated by shallow sheet floods and debris flows, as opposed to highly sinuous channelized flow [*Blair and McPherson*, 1994]. The Holden NE delta is remarkable for its complete lack of features that could be interpreted as debris flows or as sheetflood deposits. In addition, the channelized features that dominate the top of the feature show far more sinuous patterns, than the more braided planforms that characterize modern terrestrial alluvial fans [*Blair and McPherson*, 1994; *Bridge*, 2003].

[10] The relatively smooth, and more brightly reflective bottomset layers (B in Figure 2) may represent lacustrine fill, and we speculate could be evaporitic. The best developed channels are in the younger layers. The transition from smooth lower layers that lack channel belts, to complex bifurcating channel networks in the upper layers suggest a complex evolution consistent with a deltaic origin [*Bhattacharya and Walker*, 1992]. The high degree of sinuosity is unusual for terminal splays or alluvial fans [*Blair and McPherson*, 1994; *Payenberg and Lang*, 2003] and indicates a prolonged period of continuous flow of water within the channels, more indicative of a delta.

[11] Terminal splays are formed in arid climates where dryland rivers feed into ephemeral lakes during large floods and typically extend quite far into the lake [*Lang et al.*, 2004]. Such terminal splays superficially show many of the features of this system, however, meandering is not as well developed as in the Holden NE example. There is no evidence that this feature is an alluvial fan and a delta interpretation seems much more consistent with the data.

5. Estimate of Duration of Lake

[12] The accumulation of 150 meters of strata likely required a standing body of water rather than subsidence. However, water depth need not have been 150m. Shallow lakes can accumulate thick piles of sediment as long as the lake spill point is high. As sediment is added to a lake, it will raise water level until a spill point is reached [*Bohacs et al.*, 2000]. Examination of the contours within the crater does not reveal a clear spill point. The maximum potential accommodation is defined by the depth of the crater, and appears to be on the order of several hundred meters. Given that the thickness of the strata built by the delta is only 150m, it would appear that the crater was never filled to the brim with water, although it is hard to know how much aeolian erosion of younger layers may have occurred. Given probable channel depths of a few meters, we estimate that the minimum lake level at any one time was on this order, although it could have been significantly deeper. Detailed mapping of the underlying layers would be required to determine the actual water level. This would require high-resolution oblique images of the cliff walls, but these are currently unavailable.

[13] Holden NE Crater was probably an underfilled lake [*Bohacs et al.*, 2000], which increases the possibility for evaporites, and may have resulted in very cyclic deposition. The fact that the delta feature is confined to the northwestern margin also indicates that a semi-permanent lake several tens of meters deep. If the lake was much shallower the fluvial systems would have easily extended at least to the crater center and would not show bifurcation over as short a distance as the exposed feature suggests.

[14] *Bridge* [2003] has shown that young channels are typically straight and become sinuous with time. It may take decades to millennia for this transition to occur in moderate to large rivers, and may take much longer for meandering valleys to form, especially if they are incised into bedrock, as is seen in the drainage basin uplands to the west. Because of the lower gravity, the bedrock erosion rate on Mars is proposed to be $\sim$50% less efficient than on Earth, although transport efficiency of sand and mud is probably higher than on Earth [*Komar*, 1979; *Irwin et al.*, 2004]. Thus it may be more difficult to create sediment by fluvial erosion, but once created it may be easier to move than on Earth. Avulsion periods for terrestrial rivers are highly variable, but are typically on the order of tens of years to millennia [*Bridge*, 2003]. The Po River, in Italy, which at 300m wide is about 3 times the width of the Holden NE Delta River, has an avulsion period of about 490 years [*Bridge*, 2003]. The much larger Kosi River, which drains the Himalayas experiences much higher sedimentation rates, and is correspondingly braided; experienced avulsion on average every 28 years. Avulsion is enhanced by higher sedimentation rates [*Bridge*, 2003]. The highly meandering nature of the Holden NE rivers require relatively confined flows versus sheetfloods, and likely reflect moderate sedimentation rates. We assume that avulsion frequencies were probably more like the Po than the Kosi, although such analog comparisons must be viewed as speculative.

[15] Given that Holden NE Crater shows about 11 clear avulsion events, and several clear transitions from straight to meandering streams (and vice versa), if we assume an avulsion period of a few hundred years, we estimate that the uppermost layer probably represents deposition over a period of at least a few thousand years. The migration of meanders is also episodic, as indicated by the development of successive scroll bars (Figure 3). We assume that these were caused by smaller-scale floods on the order of years to decades.

[16] Sediment accumulation rates in terrestrial settings may be as low as mm per year to as high as 1 m per year during extreme floods [*McKee et al.*, 1967], although these high rates are very rarely sustained for extended periods. We concur with *Moore et al.* [2003] that the gradual expansion of meander loops and the uniformity of trunk channel width suggest that the flows were not especially flashy or sheet-like, as would be expected during sudden intense floods. Using a sedimentation rate of 1mm/year would mean the lake was filled over a period of about 150,000 years. Of course it is possible that there are still deeper, and as-yet, unexposed sedimentary layers, presently covered by aeolian silt and dust.

[17] If the Holden NE system was also deposited as a series of terminal splays during infrequent floods, then the time of formation would likely have to be an order of magnitude or more longer, possibly up to the order of a few millions of years, to accumulate 150m of sediment.

[18] The complex history of the delta recorded in Holden NE Crater requires significant periods of persistent water flow with numerous small floods, as opposed to the catastrophic release of groundwater that would be associated with a major bolide impact. Our analysis suggest that there were periods of rainfall over an extended time period of several thousands of years in the top layer, and 150,000 years for the underlying delta sediments.

[19] This may have implications for long term precipitation during the Noachian. If a crater lake persisted for 150,000 year, it also invites the possibility that Martian life, assuming it ever existed, may have occupied this potential habitat. Holden NE crater should thus be considered as a strong candidate in the search for fossilized habitats on Mars.

6. Conclusion

[20] A sedimentological-stratigraphic and geomorphological analysis suggests that Holden NE Crater was partially filled by three delta lobes that fed into a semi-permanent to perennial lake over a period on the order of 150,000 years. The drainage network shows a complex, multi-order tributive network that is not obviously associated with a specific bolide crater. Meandering valleys in the drainage network require multiple runoff events, as opposed to a single catastrophic flood. Mapping of channels in the upper layers of the crater fill show that initially straight channels expand to form well-developed meanders, followed by migration, and finally avulsion. The migration of meanders likely formed by small-scale floods every few years to decades. The topmost layer of the main lobe shows 11 avulsion events. Comparison with modern terrestrial analogs suggest an avulsion period of a few hundred years, indicating that the topmost layer took several thousand years to form. These avulsions were likely driven by larger 100-year floods in combination with the inherent instability experienced by meandering steams. The thickness and volume of the deposit requires an extensive history for the crater lake, supporting the hypothesis that semi-permanent bodies of water, probably fed by rainfall, existed for thousands to at least 150,000 years during early Mars history (Noachian). Given that terrestrial lacustrine systems are commonly rich hydrocarbon source rocks, the potential for finding fossilized life in NE Holden crater cannot be discounted.

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