Insights into surface runoff on early Mars from paleolake basin morphology and stratigraphy

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ABSTRACT

We present observations on the morphology and stratigraphy of more than 400 paleolake basins on Mars. We show that there are two distinct classes of Martian paleolake basins: (1) paleolakes fed by regionally integrated valley networks (N = 251), and (2) paleolakes fed by isolated inlet valleys not integrated into broader regional drainage systems (N = 174). We conclude that valley network–fed paleolakes primarily formed prior to approximately the Noachian-Hesperian boundary, ca. 3.7 Ga, while isolated inlet valley paleolakes primarily formed later in Martian history. All 174 isolated inlet valley paleolakes are closed-basin lakes; however, there are surprisingly few (31) valley network–fed closed-basin lakes compared to a large number (220) of valley network–fed open-basin lakes. This observation is consistent with declining levels of fluvial activity over time on the Martian surface. Our results imply that during the era of valley network formation, ~90% of topographic basins breached by an inlet valley had sufficiently high ratios of water influx to losses to fill, overtop, and form an outlet valley. This conclusion provides an important constraint on the balance between surface runoff production and water losses on early Mars that must be satisfied by any model of the early Martian climate and hydrologic cycle.

INTRODUCTION

The southern highlands of Mars contain abundant geomorphic evidence for fluvial activity, largely associated with valley network formation that primarily ceased around the Noachian-Hesperian boundary, ca. 3.7 Ga (e.g., Carr, 1996; Howard et al., 2005; Irwin et al., 2005; Fassett and Head, 2008a; Hynek et al., 2010; Mangold et al., 2012). Paleolake basins are key features that indicate past fluvial activity (e.g., Forsythe and Blackwelder, 1998; Cabrol and Grin, 1999, 2010; Irwin et al., 2005; Fassett and Head, 2008b; Goudge et al., 2012, 2015). Catalogs of Martian paleolakes have been made for both hydrologically closed and hydrologically open basins (Fassett and Head, 2008b; Goudge et al., 2012, 2015).

Closed-basin lakes in the Goudge et al. (2015) catalog have an inlet valley breaching the basin-confining topography, but no outlet valley (Figs. 1A and 1B). These features are best referred to as candidate paleolakes, as the presence of a valley flowing into a basin does not require the formation of a lake; however, the formation of an inlet valley requires fluvial incision and transport of water into the basin, so for simplicity we refer to these basins as closed-basin lakes. Open-basin lakes are typically fed by inlet valleys and have an outlet valley that breaches the basin-confining topography (Fig. 1C), which requires that the basin was once filled with water prior to incising an outlet breach (Fassett and Head, 2008b).

While both closed- and open-basin lakes have been widely documented on Mars (Cabrol and Grin, 1999, 2010; Fassett and Head, 2008b; Goudge et al., 2012, 2015), the relationship between these two sets of features is unclear. Did closed- and open-basin lakes form during the same era of Martian history? Did they involve similar levels of fluvial activity? What can these basins tell us about the surface environment of early Mars? Here we analyze the morphology and stratigraphy of a catalog of more than 400 paleolakes to provide insight into these questions.

DATA SETS AND METHODS

We studied the morphology, degradation state, and stratigraphy of 205 closed-basin lakes (e.g., Figs. 1A and 1B; Goudge et al., 2015) and 220 open-basin lakes (e.g., Fig. 1C; Fassett and Head, 2008b; Goudge et al., 2012), along with their associated fluvial valleys, using image and topographic data. The primary image data sets include ~6 m/pixel images from the Context Camera (CTX; Malin et al., 2007), <0.5 m/pixel images from the High Resolution Stereo Camera (HRSC; Neukum et al., 2004), and the ~100 m/pixel global daytime infrared mosaic (Edwards et al., 2011) from the Thermal Emission Imaging System (THEMIS; Christensen et al., 2004). For topographic analyses, we used ~463 m/pixel global gridded topography from the Mars Orbiter Laser Altimeter (MOLA; Smith et al., 2001).

The morphology of inlet and outlet valleys associated with the catalog of paleolakes was assessed based on the level of regional fluvial integration and incision. Particular attention was paid to comparing the morphology of these valleys with the morphology of ancient valley networks, which have multiple branching tributaries and are integrated with the surrounding landscape (e.g., Howard et al., 2005; Irwin et al., 2005; Hynek et al., 2010; see the GSA Data Repository1 for additional details).

We analyzed the stratigraphy and degradation state of the basins that host the >400 paleolakes, which are largely defined by impact craters (Fassett and Head, 2008b; Goudge et al., 2012, 2015), to provide an estimate of the timing of paleolake activity (for additional details, see the Data Repository). Crater degradation is a well-studied process on Mars, and older craters tend to be more degraded than younger craters of similar diameters (e.g., Craddock et al., 1997; Craddock and Howard, 2002; Mangold et al., 2012; Robbins and Hynek, 2012). Primary effects of crater degradation include basin infilling, removal of the central peak or pit, erosion and modification of ejecta deposits, and backwasting and erosion of crater rims and walls (Craddock et al., 1997; Mangold et al., 2012).

RESULTS

Paleolake Valley Morphology

We identify 31 closed-basin lakes fed by inlet valleys with a morphology consistent with typical Martian valley networks (Howard et al., 2005; Irwin et al., 2005; Hynek et al., 2010), i.e., regionally integrated valleys with multiple branching tributaries and Strahler orders commonly ≥2 (e.g., Fig. 1B; Figs. DR1 and

1GSA Data Repository item 2016136, additional detail on methods and results, Figures DR1–DR5, and Tables DR1 and DR2, is available online at www.geosociety.org/pubs/f2016.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.
of these, 41 basins host isolated inlet valley paleolakes, which have few or no tributaries (i.e., typical Strahler orders of 1) and are poorly integrated with the surrounding landscape (e.g., Fig. 1A; Figs. DR2 and DR5A; Table DR1). All 220 open-basin lakes are associated with inlet and outlet valleys that have morphologies consistent with typical Martian valley networks (e.g., Fig. 1C; Figs. DR3 and DR5A; Table DR1; Howard et al., 2005; Irwin et al., 2005; Fassett and Head, 2008b; Hynek et al., 2010). We collectively refer to the group of 31 closed-basin lakes and 220 open-basin lakes associated with valley networks as valley network–fed paleolakes, while the remaining 174 closed-basin lakes are referred to as isolated inlet valley paleolakes.

**Paleolake Degradation State and Stratigraphy**

Valley network–fed paleolakes are typically contained within heavily degraded impact craters with eroded rims and walls and infilled crater floors (e.g., Figs. 1B and 1C; Figs. DR1, DR3, and DR5B). Many isolated inlet valley paleolakes, however, are contained within less degraded impact craters that often show terraced walls and central uplift structures (e.g., Fig. 1A; Figs. DR2 and DR5B). We also identify 44 paleolakes hosted by craters with preserved continuous ejecta deposits or with inlet valleys that incise continuous ejecta deposits from nearby craters (Figs. 2 and 3; Fig. DR4; Table DR2). Of these, 41 basins host isolated inlet valley paleolakes, and three host valley network–fed paleolakes, all of which are closed-basin lakes (Fig. 3; Table DR2). We also find two examples of isolated inlet valley closed-basin lakes hosted by impact craters with preserved continuous ejecta deposits that clearly overlie nearby valley networks (e.g., Fig. 2C).

**IMPLICATIONS FOR PALEOLAKE ACTIVITY**

**Timing of Paleolake Activity**

Based on the degradation state of the host impact craters and the morphology of the associated valleys, we conclude that the formation of valley network–fed paleolakes occurred during the era of major valley network activity, which primarily ceased ca. 3.7 Ga, around the time of the Noachian-Hesperian boundary (Howard et al., 2005; Irwin et al., 2005; Fassett and Head, 2008a, 2008b; Mangold et al., 2012). Therefore, valley network–fed paleolake basins represent the paleolake record from early Mars.

In contrast, we conclude that isolated inlet valley paleolakes primarily formed subsequent to the era of major valley network formation, based on three main observations. First, the host craters for isolated inlet valley paleolakes are morphologically fresher (e.g., Fig. 1A; Figs. DR2 and DR5B), suggesting a younger age of formation compared to the more heavily degraded craters hosting valley network–fed paleolakes (e.g., Figs. 1B and 1C; Figs. DR1, DR3, and DR5B). Second, 41 isolated inlet valley paleolakes are hosted by craters with intact continuous ejecta deposits or have inlet valleys crosscutting the continuous ejecta deposits of nearby craters (Figs. 2 and 3; Fig. DR4; Table DR2), again suggesting a geologically recent age of formation (e.g., Mangold et al., 2012). Finally, in two locations, stratigraphic relationships show that the host craters with isolated inlet valleys are superposed upon ancient valley network systems (e.g., Fig. 2C), requiring that the paleolake formed after the preexisting valley network ceased incision.

**Average Rates of Surface Runoff Production versus Water Losses**

Our results also suggest differences in the average rates of surface runoff production versus water losses (e.g., via infiltration or evaporation) associated with the formation of valley network–fed paleolakes and isolated inlet valley paleolakes. We note that the small number of valley network–fed closed-basin lakes (31) is in stark contrast to the large number of valley network–fed open-basin lakes (220). This requires that during the era of valley network formation, global average rates of surface runoff production versus water losses must have been sufficient for ~90% of craters breached by an inlet valley to fill with standing water, overtop, and incise an outlet valley to form a stable open-basin lake, as opposed to forming a hydrologically stable closed-basin lake. Isolated inlet valley paleolakes, however, are all closed-basin lakes, consistent with our conclusion that these basins formed later in Martian history, subsequent to the major period of valley network formation.
We hypothesize that these younger basins were precluded from filling and overtopping due to (1) less intense surface runoff production, (2) faster rates of water loss, and/or (3) a shorter overall time period of associated fluvial activity.

Eras of Martian Paleolake Activity

Our conclusions indicate two distinct eras of Martian paleolake formation and associated climate conditions. The first era of paleolake activity was associated with the formation of valley network–fed, primarily open-basin lakes driven by a climate with higher surface runoff production compared with water losses, and occurred during the period of major valley network formation. The second era, which occurred later in Martian history, was associated with the formation of closed-basin lakes fed by isolated inlet valleys, with a climate characterized by a lower ratio of surface runoff production to water losses and/or shorter overall periods of fluvial activity. This conclusion is consistent with a hydrologic evolution of Mars with relatively intense fluvial activity in a period that ceased at approximately the Noachian-Hesperian boundary, and only limited fluvial activity during the Hesperian and Amazonian (e.g., Howard et al., 2005; Irwin et al., 2005; Fassett and Head, 2011; Mangold et al., 2012).

SURFACE RUNOFF ON EARLY MARS

Our analysis provides an important broad constraint on Martian hydrology and climate during the period of valley network formation: time-averaged surface runoff production compared with water losses during this era must have been sufficiently large to fill and overtop ~90% of paleolake basins breached by an incised inlet valley. We note that our analyses do not consider potential paleolakes not fed by an inlet valley, such as enclosed basins with shallow lakes in their interiors fed by internal drainage, e.g., Columbus crater (Wray et al., 2011). Such paleolakes may have been prominent on the early Martian surface; however, geomorphic evidence for standing water in closed basins without external tributaries is typically lacking, which makes identification of any possible paleolakes in this class difficult.

For paleolake basins on early Mars that were breached by an inlet valley, a strong control on whether the basin filled and breached to form an outlet valley would have been the ratio of watershed area to lake area. This ratio controls the relative amount of surface runoff-derived input a basin receives compared to the amount of water the basin loses through evaporation off the lake surface. All else being equal, basins on early Mars with larger watershed area to lake area ratios would have been more likely to fill and breach an outlet valley (e.g., Fassett and Head, 2008b).

An additional controlling factor on the formation of open-basin versus closed-basin lakes on early Mars would have been basin geography, as the early Martian climate is likely to have had significant spatial variation (e.g., Urata and Toon, 2013). Certain regions of Mars are likely to have had higher (or lower) than average surface runoff production compared with water losses. We note a marked paucity of valley network–fed closed-basin lakes compared with valley network–fed open-basin lakes in the Margaritifer Sinus region, from ~60° to 0°N and ~30° to 30°E (Fig. 3). This may suggest that Margaritifer Sinus had a notably high ratio of surface runoff production to water losses, consistent with the observation that this region is one of the most densely dissected areas of Mars (e.g., Hynek and Phillips, 2001; Craddock and Howard, 2002; Grant and Parker, 2002; Howard...
et al., 2005; Barnhart et al., 2009; Hynek et al., 2010) and has a high concentration of large, integrated lake-chain systems (Fassett and Head, 2008b).

Our results indicate that the ratio of surface runoff production to water losses on the early Martian surface was both high and spatially variable; however, they do not constrain the total length of time over which valley networks were active. Both a short-lived period of valley network incision with large surface runoff fluxes and a longer lived period with lower surface runoff fluxes are consistent with our observations.

In a scenario with short-lived, perhaps catastrophic, valley network activity where surface runoff production greatly exceeds water losses, the pre-breach volumes of valley network–fed open-basin lakes provide a minimum constraint on the amount of surface runoff that must be generated from the watersheds of those basins. For open-basin lakes hypothesized in Fassett and Head (2008b) to be mostly fed by surface runoff derived from their catchment, this typically corresponds to meters to tens of meters of water spread across the entire watershed.

Alternatively, in a scenario with longer lived valley network activity and water loss rates that are comparable to surface runoff fluxes, our results require that for a typical paleolake that formed in this era, time-averaged water influx was greater than time-averaged water losses. A valley network–forming era characterized by multiple short episodes of fluvial activity insufficient to cause widespread outlet breaching and separated by long periods of drought and evaporation is inconsistent with our observations: such a scenario would have resulted in far more valley network–fed closed-basin lakes than observed.

CONCLUSIONS

Analysis of the morphology, degradation state, and stratigraphy of more than 400 paleolakes on Mars has revealed two distinct classes of basins: (1) valley network–fed paleolakes (e.g., Figs. 1B and 1C) that formed prior to ca. 3.7 Ga, and (2) isolated inlet valley paleolakes (e.g., Fig. 1A) that formed subsequently. Our observations are consistent with secular changes in the Mars environment and declining levels of fluvial activity throughout Martian history. Our analysis of the Martian paleolake record also reveals a fundamental characteristic of the hydrology of early Mars: ~90% of paleolake basins breached by well-incised inlet valleys were hydrologically open, requiring significant amounts of water influx to completely fill and overtop the vast majority of these basins. Future climate models must be able to sufficiently explain surface runoff production on early Mars that is consistent with this constraint.

ACKNOWLEDGMENTS

We thank J.L. Dickson for help with image and topographic data processing, and K.E. Scanlon for helpful discussions. We also thank R.P. Irwin, R.A. Craddock, B.M. Hynek, and an anonymous reviewer for careful reviews that greatly improved the quality of this manuscript, and J.B. Murphy for editorial handling. Goude gratefully acknowledges support for this work from the Natural Sciences and Engineering Research Council of Canada (NSERC) Postgraduate Scholarships Program (PGSD3–421594–2012). Head acknowledges support from membership on the ESA Mars Express HRSC Team through grant JPL-1488322, and the Mars Data Analysis Program through grant NNX11AI81G.

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Manuscript received 27 January 2016
Revised manuscript received 5 April 2016
Manuscript accepted 6 April 2016
Printed in USA