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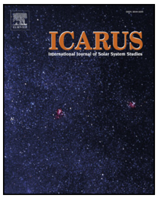

The volume of water required to carve the martian valley networks: Improved constraints using updated methods

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ABSTRACT

The martian valley networks are a key piece of evidence for the presence of liquid water on early Mars, and understanding their formation conditions can provide valuable insight into the nature of the early climate. Previous studies have used various methods to estimate the volume of water required to carve the valley networks, with results ranging from 3–5000 m Global Equivalent Layer (GEL). In comparison, other workers have found that the surface/near-surface water inventory was likely to have been ~24 m GEL at the Noachian-Hesperian boundary. Thus, 3 m GEL may be consistent with recycling in a cold and icy Late Noachian-Early Hesperian climate, while 5000 m GEL may require continuous warm and wet conditions. In this study, we use updated methods and datasets to better constrain the necessary volume of water, finding a conservative lower limit of 640 m GEL. Based on valley network formation timescales, we find that our results do not preclude a cold and icy Late Noachian-Early Hesperian climate. Thus, this updated estimate of the minimum volume of water required to carve the valley networks is consistent with both formation in a cold and icy and warm and wet climate.

1. Introduction

Late Noachian surfaces on Mars contain widespread and abundant valley networks (VNs) (Fassett and Head, 2008; Carr, 1995; Hynek et al., 2010), fluvial features that were formed by flowing liquid water. These VNs demonstrate that the climate of Mars was different in the Late Noachian than it is today, but the nature of the early climate of Mars is a matter of dispute. The VNs are often cited as evidence that the climate of Mars was once warm and Earth-like, with mean annual temperature (MAT) ≥ 273 K, regular rainfall, and a vertically integrated hydrological system (Luo et al., 2017; Craddock and Howard, 2002). However, recent 3-dimensional climate models predict a cold and icy early Mars (Wordsworth et al., 2013, 2015; Forget et al., 2013), in which water is preferentially deposited in the highlands as snow and ice and MAT is ~ 225 K, well below the melting point of water (Wordsworth et al., 2015; Head and Marchant, 2014). In this model, punctuated events, such as volcanic eruptions (e.g., Halevy and Head, 2014), impact events (e.g., Segura et al., 2008; Palumbo and Head, 2017), melting during the warmest hours of the summer season (e.g., Palumbo et al., 2018a), or the introduction of greenhouse gases into a transient reducing atmosphere (e.g., Wordsworth et al., 2017), have been proposed as mechanisms to melt the surface ice (Fastook and Head, 2015), leading to surface runoff and formation of the VNs.

In this work, we test the plausibility of the proposed cold and icy early Mars climate scenario by estimating the volume of water required to carve the VNs and determining whether the volume of water could be accounted for by transient/punctuated ice melting and fluvial activity, as proposed to be the formation mechanism of these features in a cold and icy climate, or whether the estimated volume of water requires a sustained vertically integrated hydrological cycle, continuous warm and wet/arid climate, and (at least) seasonal rainfall (e.g., Craddock and Howard, 2002; Ramirez, 2017; Luo et al., 2017; Ramirez and Craddock, 2018).

Rosenberg and Head (2015) produced a preliminary estimate of the water volume required to carve the VNs. First, Rosenberg and Head (2015) utilized the valley network distribution data compiled by Williams and Phillips (2001) (derived from MOLA data, horizontal resolution 460 m/pixel) and the volumes of eight large VNs (Hoke et al., 2011) to estimate the volume of sediment removed to carve the VNs. Next, they used an empirically derived fluid:sediment flux ratio and the total volume of sediment removed from the VNs to estimate the minimum volume of water required to carve the VNs. They estimated

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the required volume of water to be a global equivalent layer (GEL) of 3–100 m. This volume of water does not preclude formation through transient fluvial activity in a cold and icy climate scenario. In a more recent analysis, Luo et al. (2017) implemented methods based on those of Rosenberg and Head (2015) and performed a global evaluation of the volume of sediment removed from all martian VNs in order to determine the volume of water required to carve all of the VNs. After applying several fluid:sediment volume ratios, to convert the sediment volume to a water volume, Luo et al. (2017) reported that an ~5000 m GEL volume of water was required to have carved the VNs. Because this volume of water could not reasonably have been introduced to the surface through transient fluvial activity in a predominantly cold and icy climate when considering reasonable water inventory constraints (Carr and Head, 2015), Luo et al. (2017) claim that this updated water volume estimate is evidence for a warm and wet early Mars and that this volume of water also requires the presence of a Noachian ocean in the northern lowlands.

Here, we revisit the estimates of Rosenberg and Head (2015) and Luo et al. (2017), but implement both a more inclusive estimate of the VN cavity volume and an improved estimate of the fluid:sediment flux ratio based on a terrestrial dataset that is more applicable to the martian VNs. By taking these steps, we provide improved estimates of the minimum amount of water required to carve the VNs.

We use the updated VN cavity volume from Luo et al. (2017) which employed a progressive black top hat (PBTH) transformation method to calculate the cavity volume of the VNs based on an earlier automated VN mapping (Luo and Stepinski, 2009) and on the VN mapping by Hynek et al. (2010). This new cavity volume includes all VNs, not just the eight measured by Hoke et al. (2011), and thus represents an improvement over the cavity volume used by Rosenberg and Head (2015). Additionally, we use an empirically derived distribution of fluid:sediment flux ratios (median 3900; displayed in Fig. 3), rigorous error analysis, and we correct errors in previous analyses. For comparison, Luo et al. (2017) used a fixed fluid:sediment flux ratio of ~4000.

We then apply our updated methods to the VNs studied by Hoke et al. (2011) to estimate the volume of water required to form each of the eight VNs included in that study as well as provide updated timescales of formation. Next, we apply our updated water volume estimates and test whether the VNs could have formed in a cold and icy climate through several mechanisms, and assess in more detail a specific formation mechanism: seasonal melting during the warmest hours of the summer season (e.g., Palumbo et al., 2018a). We conclude with a discussion of the implications of our results for the nature and evolution of the early martian climate.

2. Methods and discussion

2.1. Sediment volume

The first step in estimating the volume of water that was required to erode the VNs is to estimate the volume of sediment that was removed from the VN cavity. The volume of sediment removed is related to the total present-day cavity volume (ignoring subsequent infilling) by

$$\text{cavity volume} = \text{sediment volume} + \text{pore space between packed sediment grains}. \qquad (1)$$

Let V_c denote the cavity volume, V_s denote the sediment volume, and $\lambda = \frac{V_c - V_s}{V_c}$ denote the fraction of the total cavity volume that was pore space prior to erosion, i.e., the porosity. It follows that the sediment volume is related to the cavity volume by

$$V_s = V_c(1 - \lambda). \qquad (2)$$

The porosity of martian regolith is estimated to range between ~ 0.2 – 0.4 (Kleinhans, 2005; Clifford, 1993). It is important to note that Luo et al. (2017) erroneously calculated sediment volume as $V_s = V_c/(1 - \lambda)$, which does not represent the desired physical quantity and overestimates the sediment volume by a factor of $(1 - \lambda)^{-2}$, which is equivalent to overestimation by a factor of 1.6 – 2.8 for our preferred range of λ.

Table 1

5th percentile required water volumes, with specified assumptions, in addition to the assumptions specified earlier about grain size, flow depth, and other variables. “Single mapping” and “combined mapping” refer to the two different cavity volumes reported by Luo et al. (2017). “Field data” and “experimental data” refer to the two different datasets compiled by Brownlie (1981).

Field data, automated mapping				
Porosity	0.2	0.3	0.35	0.4
5th percentile V_w (10^{16} m^3)	7.15	6.14	5.81	5.36
5th percentile GEL (m)	494	424	401	370
Field data, combined mapping				
Porosity	0.2	0.3	0.35	0.4
5th percentile V_w (10^{16} m^3)	9.21	8.06	7.48	6.90
5th percentile GEL (m)	636	556	517	477
Laboratory data, automated mapping				
Porosity	0.2	0.3	0.35	0.4
5th percentile V_w (10^{16} m^3)	10.7	9.37	8.70	8.03
5th percentile GEL (m)	740	647	601	555
Laboratory data, combined mapping				
Porosity	0.2	0.3	0.35	0.4
5th percentile V_w (10^{16} m^3)	13.79	12.07	11.21	10.35
5th percentile GEL (m)	953	834	774	714

As previously mentioned, in our implementation of Eq. (2) we use the updated VN cavity volume from Luo et al. (2017). Using MOLA data and automated PBTH methods, Luo et al. (2017) measure the total cavity volume of the VNs to be $(1.74 \pm 0.8) \times 10^{14}$ m^3 based on the VN mapping of Luo and Stepinski (2009) (referred to here as “automated mapping”), or $(2.23 \pm 1.0) \times 10^{14} m^3$ based on the combined VN mappings of Luo and Stepinski (2009) and Hynek et al. (2010) (referred to here as “combined mapping”). We perform calculations for both cavity volumes, as shown in Table 1, but use the automated mapping to state the main results of the paper in order to draw a more conservative, or lower limit, conclusion.

In the work of Luo et al. (2017), the authors scale the estimated cavity volumes to account for additional cavity volume that is typically observed in the higher-resolution HRSC DEMs, but is below the resolution of the data used in the automated mapping and combined mapping efforts. However, Luo et al. (2017) incorrectly scale an observed cavity volume of zero to a scaled cavity volume of 5×10^9 m^3 (this is the y-intercept of the regression line in their Fig. 3). Thus, if the scaling were consistently applied to individual VNs, it would artificially inflate the cavity volume; there are many locations on the martian surface where VNs are not observed in even the highest resolution data. For this reason and to provide a lower bound on the VN cavity volume, we do not adopt the methods of Luo et al. (2017) to scale our results and directly implement the cavity volume estimates from the automated mapping and combined mapping efforts. If included, the scaling used by Luo et al. (2017) would increase our estimates by a factor of ~1.3, the slope of the regression line in Fig. 3d of Luo et al. (2017) and the factor by which their volumes increased after scaling.

Substituting the VN cavity volume from Luo et al. (2017) into Eq. (2), the sediment volume derived from the automated mapping is $V_s = \left(1.13^{+0.90}_{-0.57}\right) \times 10^{14}$ m^3, where we have used a preferred porosity of 0.35, following Luo et al. (2017), but have also considered other values that span the range 0.2–0.4. The sediment volume resulting from the combined mapping is, by the same logic, $V_s = \left(1.45^{+1.13}_{-0.71}\right) \times 10^{14}$ m^3. To increase the accuracy of our estimate, we perform a more careful error analysis in Section 2.3, treating the cavity volume and the porosity as random variables and convolving them in order to obtain a 95% confidence interval.