NEW ESTIMATE OF VALLEY NETWORK VOLUME CONSISTENT WITH AN ANCIENT MARTIAN OCEAN AND A WARM AND WET CLIMATE.

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Introduction: Fluvial landforms such as valley networks (VNs), outflow channels and delta deposits found on Mars offer the best evidence for its past water activities [1, 2]. The volume of Martian valley network (VN) cavity and the amount of water needed to create the cavity by erosion are of significant importance for understanding the early Martian climate, the style and rate of hydrologic cycling, and the possibility of an ancient ocean. However, previous attempts at estimating these two quantities were based on selected valleys or at local sites using crude estimates of VN length, width, and depth [3, 4]. Here we employed an innovative progressive black top hat (PBTH) transformation method [5] to estimate them on a global scale based on the depth of each valley pixel.

Method: The PBTH method we adopted integrates techniques used in Lidar data analysis and image processing [5], which allowed us to estimate VN depth at individual pixel level [5, 6], capture the VN of different sizes with progressively increasing search window size, and derive VN volume on a global scale with greater accuracy and efficiency. Our test on simulated landforms has achieved a relative accuracy of 96% [5] and application to selected Martian VN compares well with other studies [3].

The application of the method to the whole of Mars required some special considerations. The global MOLA DEM was divided into 20°×20° tiles, processed one at a time, and results merged together. In order to automatically generate the correct VN areas around the VN lines, we started at local maxima of the VN depth grid that are near the VN line (“seeds”) and followed a standard multiple flow direction algorithm to grow the area around the “seeds” to form the VN area polygon. Crater depressions that still remain after the multiple flow direction algorithm were removed using location and diameter information from an existing database of craters [7]. Some parts of shallow valleys do not meet the depth threshold, resulting in small gaps in the valley area polygon. These gaps were connected by buffering each pixel under the VN line with a buffer size that is 10 times the depth at that location (i.e., assuming the width is about 10 times the depth [8], a conservative estimate). Finally, visual inspection and manual editing was conducted to remove any false positives not consistent with VN morphology based on THEMIS images. An example of the final VN area and VN depth is shown in Fig. 1A.

The volume of VNs was calculated by summing the volume of each pixel column (product of depth and area of each pixel) of the valley depth grid inside the VN area polygon. To avoid distortion associated with map projection for the global data, we used the spherical area of each pixel. To take advantage of higher resolution HRSC data (but with limited coverage), we took 50 random sampled areas where both HRSC and MOLA data are available and extracted VN volumes from both resolutions. A regression line was established between the values at these two resolutions (Fig. 1B) and the final MOLA DEM derived volume was scaled following the regression line as the estimate of volume under higher HRSC resolution.

Result: The global VN cavity volume estimate based on the topographically derived version of VN [10] is $(1.74\pm0.8)\times10^{14}$ m^3 and that based on the VN that integrate both the topographically derived[14] and manually digitized [10, 11] is $(2.23\pm1.0)\times10^{14}$ m^3 (Table 1). Both estimates are one order of magnitude larger than that used the Rosenberg and Head study [4].

There are several ways to convert the volume of VNs to the minimum cumulative volume of water needed to carve the VNs, e.g., using a simple water-to-sediment ratio [12, 13] or fluid/sediment flux ratio function empirically derived based on terrestrial data [4]. Since we are only interested in the global scale estimate, we derived the minimum cumulative volume of water by assuming a reasonable sediment load and density of sediment [14] as shown in Table 1. The minimum cumulative volume of water needed to erode the VNs is about 4000 times the volume of VNs (for both the topography-based VN and the combined VN), suggesting a relative high rate of water recycling involved in excavating the Martian VNs.

Discussion and Conclusion: Our estimates of the VN volume and water volume are based on the following assumptions: (1) the valley shoulder elevations did not change significantly since their formation; (2) the amount of sediments carried into the valleys from elsewhere (e.g., from hillslope by sheet flow) was negligible. Thus the estimated water volume is the minimum cumulative volume of water required to carve the VNs on Mars globally. Yet this minimum volume of water is larger than the volume of the hypothesized northern ocean (ranging from 3 m to ~2 km GEL [4, 15–17]), which suggests that the water must have cycled through the VN system many times (i.e., implying an active hydrologic cycle) and the early climate was likely wetter than suggested by some previous studies [4, 18]. As on Earth, the great amount of water recycling needed to carve VNs would likely require a large open water body (ocean) on Mars contemporaneous with the VN formation and a warm and wet climate to support the active hydrologic cycle. Without an ocean-sized open body of water, it would be hard to imagine the high rate of water cycling. The gap between the geomorphic evidence such as this study that suggests a warm and wet climate and the climate models that struggle the get temperature high enough for early Mars [20] still requires further study.

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Table 1. Global Martian VN Volume Estimates based on PBTH Method and Volume of Water Required

	Topo-derived VN [10]		Combined VN [10-11]	
	Volume (m^3)	GEL (m)†	Volume (m^3)	GEL (m)†
V_{VN} (MOLA)	$(1.74\pm0.8)\times10^{14}$	1.20	$(2.23\pm1.0)\times10^{14}$	1.54
V_{VN} (HRSC*)	**$(2.31\pm1.1)\times10^{14}$**	**1.59**	**$(2.96\pm1.4)\times10^{14}$**	**2.04**
$V_s = V_{VN} / (1-\lambda)$	$(3.55\pm1.6)\times10^{14}$	2.45	$(4.55\pm2.1)\times10^{14}$	3.14
$M_s = V_s \times \rho_s$	$(1.03\pm0.5)\times10^{18}$	7.10×10^3	$(1.32\pm0.6)\times10^{18}$	9.12×10^3
$V_w = M_s / L_s$	**$(6.86\pm3.2)\times10^{17}$**	**4.74×10^3**	**$(8.80\pm4.1)\times10^{17}$**	**6.08×10^3**

(V_{VN} = volume of VN; V_s = volume of sediment; M_s = mass of sediment; λ = porosity = 0.35; ρ_s = density of sediment = 2900 kg/m^3; V_w = volume of water; L_s = sediment load in water = 1.5 kg/m^3; *scaled based on regression line shown in Fig. 3C; †errors for GEL are all less than 10^{-6} m. Errors were estimated based on propagation of vertical error (~45 m) in gridded MOLA DEM [19]. Since the horizontal error of MOLA data (~100 m) is less than the cell size, it would not impact the estimate of the final volume estimate.)

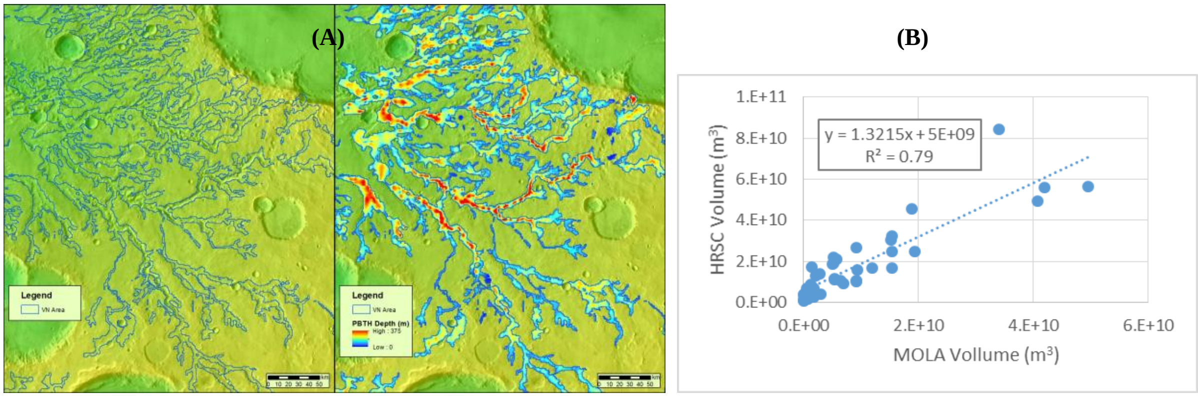

Fig. 1 (A) Example final PBTH depth (right) in comparison with MOLA DEM shaded relief (left); (B) Regression line relating volumes extracted from MOLA and HRSC data based on 50 random samples.