Interior channels in Martian valley networks: Discharge and runoff production

Rossman P. Irwin III Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, 6th Street and Independence Avenue SW, Washington, DC 20013-7012, USA, and Department of Environmental Sciences, University of Virginia, Charlottesville, Virginia 22904, USA
Robert A. Craddock Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, 6th Street and Independence Avenue SW, Washington, DC 20013-7012, USA
Alan D. Howard Department of Environmental Sciences, University of Virginia, Charlottesville, Virginia 22904, USA

ABSTRACT

The highland valley networks are perhaps the most compelling evidence for widespread fluvial activity on Mars >3.5 Ga. However, determining the hydrology of these features has been difficult owing to poor image resolution and the lack of available topographic data. New orbital imaging reveals 21 late-stage channels within valley networks, which we use to estimate formative discharges and to evaluate water supply mechanisms. We find that channel width and associated formative discharge are comparable to terrestrial valley networks of similar area and relief. For 15 narrow channels in basin-filling networks, likely episodic runoff production rates up to centimeters per day and first-order formative discharges of ~300–3000 m^3/s are similar to terrestrial floods supplied by precipitation. Geothermal melting of ground ice would produce discharges ~100 times smaller per unit area and would require pulsed outbursts to form the channels. In four large valleys with few tributaries, wider channels may represent large subsurface outflows or paleolake overflows, as these four channels originate at breached basin divides and/or near source regions for the catastrophic outflow channels.

Keywords: Mars, channels, discharge, runoff, Noachian Period.

INTRODUCTION

Most Martian valley networks date to the Noachian Period, generally inferred to be >3.7 Ga, when both impact cratering and erosion rates were higher than at present (Craddock et al., 1997; Carr, 1996; Hartmann and Neukum, 2001). Fluvial erosion is thought to be responsible for the branching valley networks, with water supplied by groundwater springs (Pieri, 1980; Gulick, 2001) or precipitation (Craddock and Howard, 2002). Support for past precipitation on Mars comes from tributaries that commonly head near sharp ridge crests where groundwater sources are unlikely (Fig. 1) (Milton, 1973; Masursky et al., 1977; Irwin and Howard, 2002), ubiquitous Noachian impact craters in the equatorial highlands that appear degraded by fluvial processes (Craddock et al., 1997; Forsberg-Taylor et al., 2004), and the need for recharge to support the erosion of valley network volumes (Howard, 1988; Goldspiel and Squyres, 1991; Grant, 2000; Gulick, 2001; Craddock and Howard, 2002). Martian valley networks are immature if formed by runoff, with numerous enclosed drainage basins, headcuts, or knickpoints along their longitudinal profiles (Baker and Partridge, 1986; Aharonson et al., 2002; Irwin and Howard, 2002), and relatively sparse tributary development on intervalley surfaces (Carr, 1996; Malin and Carr, 1999). The low abundance of chemical weathering products (Bandfield et al., 2000) and difficulty in modeling a warm atmospheric greenhouse (e.g., Haberle, 1998) are counterarguments to the concept of a warmer, wetter early Mars.

Mariner 9 (1971–1972), Viking Orbiter (1976–1980), and Mars Global Surveyor (1997–present) imaging suggested that channels are extremely rare on valley floors, even where resolution was not a limiting factor (Pieri, 1980; Carr, 1996; Malin and Edgett, 2001). Here we use new and recent observations of interior channels to evaluate the water sources for valley networks. Channel dimensions provide the first empirical indication of formative discharge Q (m^3/s) and runoff production rate P ($P = Q/A$) for Martian drainage basins as a function of drainage area, A. Results indicate that valley networks commonly formed in likely runoff-dominated but immature drainage basins, as well as by late-stage paleolake overflows and possible large subsurface outflows.

MARTIAN CHANNELS

At least eight exposed channel segments were identified within small valleys prior to this study, and we have identified 13 additional examples (Table 1; Fig. 2). This low occurrence may be largely due to more than 3.5 b.y. of evident eolian infilling and impact gardening (Hartmann et al., 2001) after fluvial activity ceased. Several other possible channels were identified in Mars Odyssey (2001–present) Thermal Emission Imaging System (THEMIS) visible (17–35 m/pixel) and infrared (100 m/pixel) imaging, but preservation or resolution prevented their use in this study.

Features identified herein as channels are elongated, flat-floored troughs that dissect the otherwise flat floors of larger branching valley networks (Fig. 2). In the few examples where we observe the confluence of a trunk and major tributary channel, the tributary channel dissects the valley floor to the level of trunk channel floor, suggesting contemporary activity. In contrast, short tributaries originating on

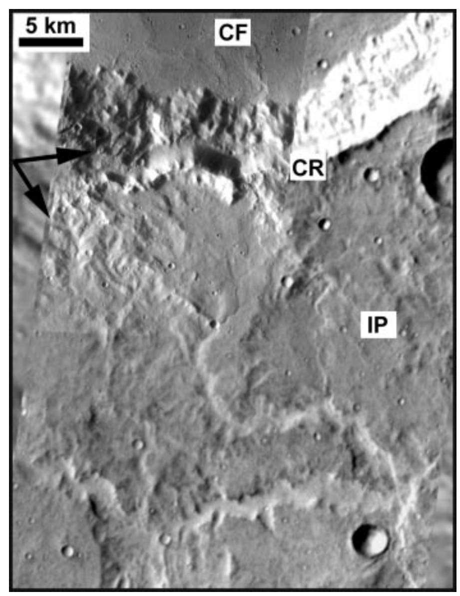

Figure 1. Typical Martian valley networks in headwater region for Al-Qahira Vallis, centered at 20.6°S, 158.3°E. Crater floor (CF, depositional surface) is undissected, steep crater interior wall is densely dissected, and intercrater plains (IP) to south contain more typical valley networks with poorly dissected interfluves. On both sides of steep crater rim (CR), gullies or valley networks begin near drainage divide (arrows). Overlay of Thermal Emission Imaging System (THEMIS) daytime infrared image I01281002, THEMIS visible image V06474003, and Mars Digital Image Mosaic 2.1.

TABLE 1. CHANNEL DATA AND REFERENCES FOR DISCHARGE AND RUNOFF PRODUCTION

Valley, quadrangle	Location (reference image)	Channel width (m) (contributing area (km²))	Discharge (m³/s) (production (cm/d))	Channel identified by
Samara Vallis, Margaritifer Sinus	31.51°S, 347.00°E (Viking 084A10)	400 (62,000)	2200 (0.3)	Pieri (1980)
Unnamed, Memnonia	12.00°S, 198.22°E (Viking 443S13)	1000 m (*)	6,600 (†*)	Carr (1996)
Al-Qahira Vallis, Aeolis	19.79°S, 161.30°E (THEMIS V06399003)	§ (§)	§ (§)	Carr (1996)
Nanedi Vallis, Luonae Palus	7.74°N, 312.26°E (THEMIS V05207009)	530 (#)	3,000 (†#)	Malin and Edgett (2001)
Nirgal Vallis, Margaritifer Sinus	29.24°S, 321.63°E (THEMIS V01837003)	770 (#)	4,800 (#)	Malin and Edgett (2001), this paper
Licus Vallis, Mare Tyrrhenum	2.95°S, 126.35°E (THEMIS V05876001)	380 (60,000)	2000 (0.3)	Irwin and Howard (2002)
Unnamed, Mare Tyrrhenum	6.63°S, 134.74°E (MOC E02-00129)	90 (550)	350 (5.5)	Irwin and Howard (2002)
"Eberswalde" Crater, Margaritifer Sinus	24.1°S, 326.1°E (MOC E18-00401)	130 (4800)	550 (1.0)	Malin and Edgett (2003), data from Moore et al. (2003)
Unnamed, Memnonia	12.00°S, 187.54°E (THEMIS V01305003)	180 (8,000)	800 (0.9)	This paper
Unnamed, Memnonia	11.61°S, 182.15°E (THEMIS V06261002)	140 (15,000)	600 (0.3)	This paper
Unnamed, Memnonia	11.59°S, 184.45°E (THEMIS V06573001)	140 (7100)	600 (0.7)	This paper
Unnamed, Memnonia	13.46°S, 186.44°E (THEMIS V09943003)	130 (2800)	550 (1.7)	This paper
Durius Vallis, Aeolis	17.19°S, 172.09°E (THEMIS V07984005)	460 (13,000)	2600 (1.7)	This paper
Unnamed, Eridania	33.33°S, 138.52°E (THEMIS V07673003)	140** (930)	** **	This paper
Unnamed, Syrtis Major	0.63°N, 80.83°E (THEMIS V08161024)	200 (9300)	900 (0.9)	This paper
Unnamed, Arabia/Sinus Sabaeus	0.26°N, 36.55°E (THEMIS V06340025)	480 (438,000)	2700 (0.1)	This paper
Unnamed, Sinus Sabaeus	0.26°S, 29.93°E (THEMIS V05404013)	360 (286,000)	1900 (0.1)	This paper
Unnamed, Margaritifer Sinus	22.57°S, 357.51°E (THEMIS V01686002)	110 (1900)	450 (2.0)	This paper
Paranà Valles, Margaritifer Sinus	24.06°S, 350.23°E (THEMIS V07079004)	180 (6200)	800 (1.1)	This paper
Unnamed, Margaritifer Sinus	9.6°S, 345.4°E (THEMIS V06143001)	700 (†)	4,300 (†)	This paper
Unnamed, Margaritifer Sinus	23.58°S, 347.97°E (THEMIS V09538003)	310 (52,500)	1600 (0.3)	This paper

*Significant structural modification of the drainage basin, possible supply from Memnonia Fossae.
†The channel originates at a breached basin divide, so discharge may reflect paleolake overflow.
§The channel appears too heavily modified for a reliable width or discharge calculation.
#The valley has short, theater-headed tributaries that are not connected to networks on nearby slopes, contributing area is poorly defined, likely dominant supply by groundwater.
**Resolution is inadequate for a reliable channel width measurement. Not included in Figure 3.

individual valley sidewalls generally did not incise the channel banks, suggesting flow in the channel during or after activity of the valley wall gullies. The nearly constant width, sinuosity, branching planform with distributed source points, topographic control of trough orientation, and lack of observed local volcanic landforms support interpretation as fluvial channels rather than volcanic rilles, grabens, or sites of eolian deflation. In four examples with entrenched or exhumed meanders, the channels exhibit the same relationship between width W and bend wavelength λ that is observed in terrestrial rivers:

$$\lambda = K_\lambda W, \tag{1}$$

where $K_\lambda = 7–14$ (Knighton, 1998). Otherwise, the channel segments have low sinuosity, as do the valley networks they occupy. The observed channels drained northward and most are located within the more heavily dissected regions on Mars, e.g., Margaritifer Sinus, Terra Cimmeria, and Terra Sirenum.

DISCHARGE AND RUNOFF PRODUCTION

Discharge was estimated in 19 of the 21 channels identified to date, using an empirical function that relates channel width W to discharge Q_2 (a flood with a recurrence interval of 2 yr) in alluvial channels of the Missouri River basin (Osterkamp and Hedman, 1982):

$$Q_2 = 1.9W^{1.22}. \tag{2}$$

Bankfull floods with recurrence intervals of 1–2 yr appear to control alluvial channel dimensions in many terrestrial humid regions, but limitations to this relationship are noted (Knighton, 1998, p. 162–167), and we imply no particular recurrence interval for the Martian channels. Equation 2 is most applicable to sand-bed channels with sand or silt banks, which have greater width per unit discharge than do channels that are confined by clay-rich or bedrock banks (Osterkamp and Hedman, 1982; Montgomery and Gran, 2001). We also measured width at relatively narrow, straight channel segments, and we used the channel floor rather than the bank-to-bank width, as the channels could be somewhat entrenched or the banks may have been laid back by subsequent mass wasting. Our discharge estimates are therefore conservative. To scale this empirical equation to Martian gravity, we use a combination of the unit-balanced continuity equation and empirical Manning equation, which is applicable to channels that are much wider than they are deep:

$$Q = HWV = H^{5/3}S^{1/2}g^{1/2}Wn^{-1}. \tag{3}$$

In equation 3, H is mean flow depth, V is mean velocity, S is slope, g is relative gravity (0.38), and n is the Manning roughness coef-

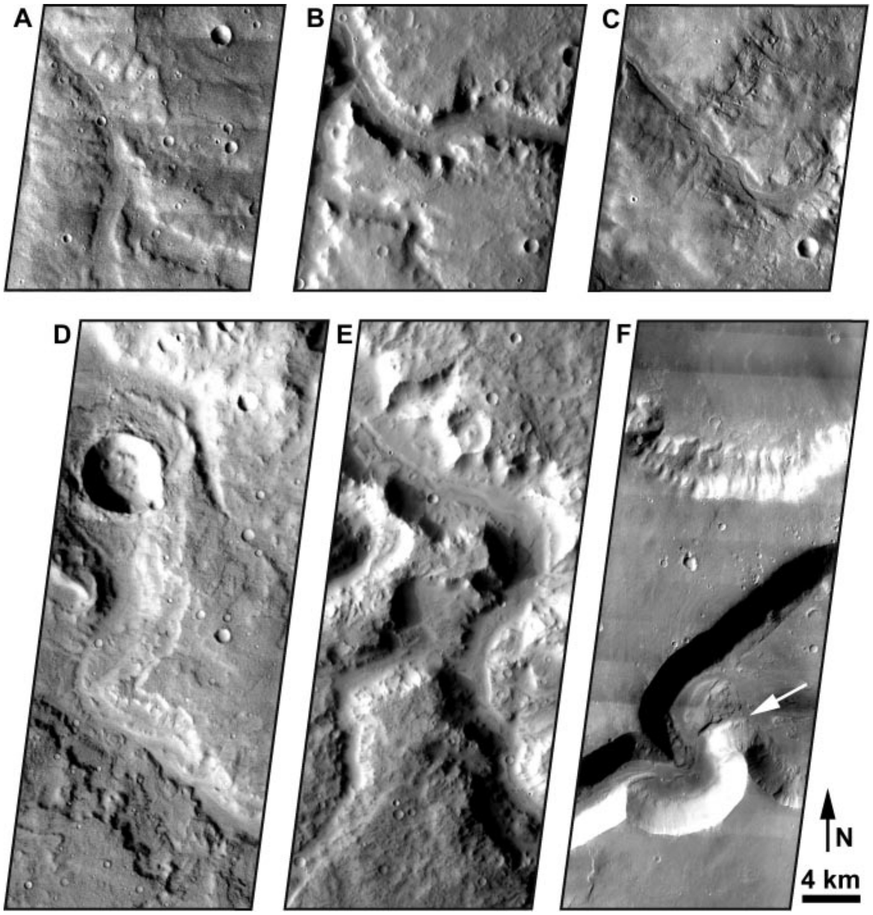

Figure 2. Channels on floors of Martian valley networks, using THEMIS (see Fig. 1) visible reference images listed in Table 1. A: Parana Vallis. B: Dawes-Mamers drainage basin. C: Samara Vallis. D: Durius Vallis. E: Licus Vallis. F: Cutoff meander loop (white arrow) and interior channel in Nirgal Vallis. Locations given in Table 1.

ficient. As S and n are not varied in the model between Earth and Mars, increased W and H are necessary to compensate lower velocity on Mars given the same discharge (Moore et al., 2003). Empirical data suggest that $H \propto W^{0.69}$ (Williams, 1988), so Martian channels should have a depth, width, and velocity of 1.17, 1.25, and 0.69 times that of their terrestrial counterparts per unit discharge, respectively. We multiply Q in equation 2 by a factor of 0.76 ($1.25^{-1.22}$) to correct for the greater width of Martian channels.

Local variability in channel width and the potential for widening by postfluvial degradation introduce potential errors of a factor of ~2 into the discharge estimates. Possible errors of a factor of ~3 are also inherent to the empirical equation 2, as the coefficient and exponent vary with other factors, including the unknown cohesion of the channel banks. The results are conservative, however, and they are likely precise within an order of magnitude.

Runoff production rate includes all water discharged by a river, regardless of whether it may have moved across part of a drainage basin in the subsurface. Some of the larger topographically defined drainage basins incorporate large plains surfaces and enclosed, degraded impact craters that may have contributed runoff or groundwater to the channel discharge. However, errors in the remaining area measurements (Table 1) are likely smaller, because these regions are heavily dissected and the drainage basins are sharply defined, with narrow undissected divides separating them from neighboring basins.

RESULTS AND CONCLUSIONS

Channel width, contributing area, formative discharge, and runoff production rates are given in Table 1. Channel width varies from ~100 to ~1000 m. Channels <90 m wide were not observed, consistent with results from Mars Orbiter Camera studies (Malin and Carr, 1999), which may reflect the effectiveness of postfluvial impact gardening and eolian processes in eradicating or burying landforms of that size (Craddock and Howard, 2002). For 15 Martian valley networks that extend to topographic basin divides, our estimates of Q range from ~300 to ~3000 m^3/s and increase with contributing area (Fig. 3). Estimated runoff production rates for these 15 valley networks are 0.1–6 cm/d and decline with increasing area, as they do in terrestrial valley networks. Three larger valleys that originate at breached basin divides, including Nanedi Vallis, had formative discharges of ~3000–7000 m^3/s. The interior channel in Nirgal Vallis is similarly wide, but its tributaries do not extend to topographic divides, so its contributing area was not available for a runoff production rate. These four large channels may reflect drawdown of paleolakes and/or subsurface outflows rather than the primary production of runoff from drainage basins.

Figure 3 shows the Martian Q and A results plotted against similar measured discharges with a 2 or 2.33 yr recurrence interval from diverse regions in the United States. Our data suggest that $W \propto A^{0.27}$ ($R^2 = 0.75$) and $Q \propto A^{0.33}$ ($R^2 = 0.75$) on Mars. These exponents are somewhat lower than is observed in terrestrial regions, where $W \propto A^{0.3–0.5}$ and $Q \propto A^{0.7–0.75}$ (Leopold et al., 1964; Montgomery and Gran, 2001). The discharge-area relationship for Mars partially reflects the Missouri River basin on which it is based, but the

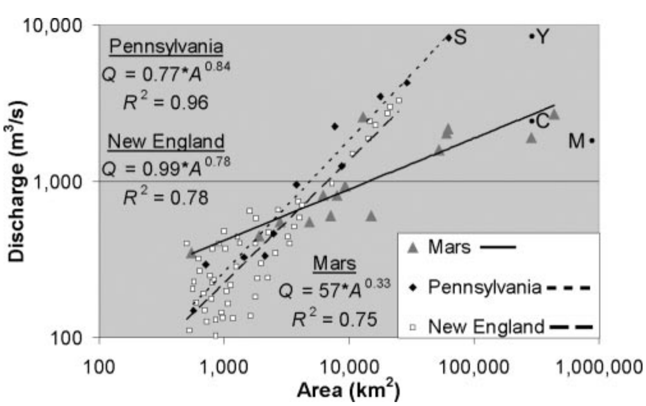

Figure 3. Comparison of discharge-area relationship between valley networks on Mars and drainage basins of similar area and relief in United States. S is Susquehanna River at Harrisburg, Pennsylvania; Y is Yukon River at Eagle, Alaska; C is Colorado River at Lee's Ferry, Arizona; M is Missouri River at Omaha, Nebraska (Brush, 1961; Benson, 1962; Howard and Dolan, 1981; Osterkamp and Hedman, 1982; Kane and Janowicz, 1989). Discharge (*Q*) is shown for floods with recurrence interval of 2.0–2.33 yr, although no particular recurrence interval is implied for Mars. Regression equations are given for trend lines. Slope of Mars trend line and *Q* estimates would increase with greater assumed bank resistance.

width-area relationship also suggests that Martian drainage basins produced runoff inefficiently. This may reflect the low drainage density, the occurrence of level surfaces within the drainage basins, or the small size of Martian storm cells relative to contributing area. These empirical relationships for Mars could change with the introduction of more data.

Although both runoff and groundwater discharges should increase with contributing area, the discharges reported here are inconsistent with runoff production rates that are possible through ambient geothermal heat flux, such as melting of ground ice (Gulick, 2001) or basal melting of a thick snow pack (Carr and Head, 2003). Contemporary geothermal heat fluxes on Mars are thought to have been 0.05–0.15 W/m^2 (Schubert et al., 1992; Spohn et al., 2001), which, if the energy could be applied entirely to melting water ice, could produce as much as 14 kg/m^2 of water per terrestrial year or $\sim$1.4 cm/yr of runoff from the drainage basin. To account for estimated runoff production of $\sim$1 cm/d, locally greater heat fluxes or some mechanism for suddenly releasing area-dependent water volumes would be required. These channels represent flows toward the end of fluvial activity on Mars and may or may not be representative of conditions earlier in the Noachian Period. The preservation and low sinuosity of these wide channels suggest an abrupt decline in conditions that supported fluvial activity.

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