Flow rates and duration within Kasei Valles, Mars: Implications for the formation of a martian ocean

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Abstract. Calculated maximum discharges for the largest outflow channel system on Mars, Kasei Valles, based on elevation data from the Mars Orbiter Laser Altimeter (MOLA), are 2 to 4 orders of magnitude lower (8×10^4 – 2×10^7 m^3 s^{-1}) than estimated previously. Mars Orbiter Camera (MOC) images show morphological evidence consistent with these relatively modest flow rates. Topographic profiles of the outflow channels reveal previously unrecognized narrow, inner channels. Development of a sapping channel network between flow events suggests the system was active over a significant period of time and likely involved several separate flood events. The longer formation history and lower discharge rates may require a long fill time (>25 years) and a warmer climate to form a martian ocean.

Introduction

Outflow channels represent compelling evidence that large quantities of water once flowed over the surface of Mars. While alternate hypotheses for outflow channel formation have been proposed, it is generally accepted that outflow channels formed by catastrophic fluvial activity with peak discharges of 10^9–10^{10} m^3 s^{-1} [*Carr*, 1996]. Given these large discharges, most investigators feel catastrophic floods could occur under the current low temperature and atmospheric pressure conditions [*Carr*, 1996]. Previous studies of Kasei Valles, have implied that either multiple flood events or changes in water level within a singular flow event formed the outflow channel system [*e.g. Tanaka and Chapman*, 1992].

Examination of recently acquired Mars Observer Laser Altimeter (MOLA) and Mars Observer Camera (MOC) data sets from the Mars Global Surveyor (MGS) together with high resolution Viking images provides insight into the sequence and scope of events that formed Kasei Valles. We present evidence supporting the hypothesis that the system formed by several fluvial episodes operating over a geologically significant period of time. We discuss morphological observations and present hydrologic calculations suggesting relatively modest flows. Further, we examine the implications of such flow rates for the formation of a martian ocean.

Channel Geometry

MOLA acquires measurements of topography and surface reflectivity that have a maximum vertical resolution of ~30 cm and along-track spatial resolution of ~300 m [*Smith et* *al*., 1998]. During the first science phasing orbits (March 26, 1998 - April 30, 1998), three MOLA topographic profiles crossing the Kasei Valles region reveal new detail of the outflow channel geometry not recognized in Viking images (Figures 1 and 2). Kasei Valles splits into two narrow, eastward-flowing branches at ~20º N, Northern Kasei Vallis (NKV) and Kasei Vallis (KV), and recombine at ~63º W. Narrow, inner channels are evident within the confines of the broader banks of both branches of Kasei Valles. Within Northern Kasei Vallis, the inner channel is 6 km wide at the base of the channel and 220 km downstream it widens to 8 km (Figure 2B). The inner channel in Kasei Vallis has a base width of approximately 6 km in both MOLA profiles (orbits 233 and 252; Figure 2C). We propose that these narrow, well-defined channels record a late stage period of channel incisement. Further, a previously unrecognized channel is evident in orbit 214 across the Kasei Valles plain (Figure 2A).

A series of benches, evident in topographic profiles for both channels, may represent fluvial terraces or scarps resulting from mass wasting. Some of the benches have comparable elevations on either side of the channel (Figure 2B), an observation which suggests that they are paired fluvial terraces that formed due to differential erosion or pulses of entrenchment within the fluvial system. In Kasei Vallis, benches on the northern bank (Figures 2C and 2D) can be correlated with features in high resolution Viking images and are traceable along channel for over 40 km. The lateral continuity of these features is consistent with a fluvial terrace rather than a mass wasting interpretation. We infer that these terraces are erosional rock-cut terraces formed on the outside bend of a meander in response to floodwaters cutting laterally and simultaneously downcutting.

Chronology

The formation of the Nilus Mensa channel network was probably not related directly to the fluvial events in the Kasei Valles system. For the water to flow east over Nilus Mensa seems improbable given its dominant northward flow at that point (Figure 1). Further, the extensive tributary systems present on Nilus Mensa most likely did not form in a subfluvial environment (Figure 3). Rather, the Nilus Mensa channel network exhibits morphological characteristics of terrestrial channels formed by sapping due to seepage weathering. Seepage weathering refers to the effects of a group of processes at a site of groundwater emergence, including chemical and mechanical weathering, which disaggregates consolidated rock. Removal of the weathered products by erosive agents leads to sapping (the undermining of basal support) and scarp retreat. [*Higgins*, 1990]. Theater-shaped heads, U-shaped profiles, a relatively constant valley width from source to outlet, and the develop-ment of tributaries along regional fracture patterns are all consistent with formation by sapping [*Laity and Malin*, 1985].

Superposition relationships reveal the sequence of develop-ment for these discreet channels. Kasei Vallis clearly cross-cuts earlier longitudinal grooves formed by Northern Kasei Vallis where the two channels recombine (see Viking frame 520A27). Thus, we infer that the last flood flowing through the southern channel post-dated fluvial activity within the northern channel. Furthermore, the development of the channel network on Nilus Mensa was intermediate between floods within Northern Kasei Vallis and Kasei Vallis. The distal Nilus Mensae channel network tributaries crosscut pre-existing grooves formed by Northern Kasei Vallis; however the main channel of Nilus Mensa is breached and cut-off by Kasei Vallis. Significantly, the southern channel benches discussed above are topographically lower than the base-level of the Nilus Mensa channel network (Figure 2C). In addition, there is no debris fan at the juncture between the channel network and Kasei Vallis. We infer that the final fluvial event in Kasei Vallis that carved the presumed rock-cut terraces and removed the sapping debris occurred after the Nilus Mensa channel network formed.

Given the stratigraphic position of Nilus Mensa, we can use the channel network development time as a chronometer, albeit crude, for the Kasei Valles system. Estimates of cliff retreat by basal sapping in terrestrial settings range from 0.1 – 180 m/10^3 yr [e.g., *Higgins*, 1990]. If Mars had a cold and dry environment during Nilus Mensa channel formation, these environmental conditions would likely have retarded cliff retreat rates. To be conservative, we assume a rapid cliff retreat rate of 200 m/10^3 yr which corresponds to a lush, sub-tropical terrestrial environment. Using the longest channel length in the system (140 km), the Nilus Mensa channel network would take a minimum of 7 x 10^5 yrs to form. The length of the channel network which cross-cuts longitudinal grooves formed by Northern Kasei Vallis is estimated at 10 km. Thus, the minimum elapsed time between the final flow events in Northern Kasei Vallis and Kasei Vallis would be 5 x 10^4 yrs, indicating that fluvial activity in the Kasei Valles system occurred over a significant period of time. Further, this time gap suggests that discreet flood events are more plausible than sustained flooding.

Channel Hydraulics

The narrow, incised channels revealed by MOLA constrain parameters needed for hydraulic calculations. Further up-stream on broad plains, the channel profile is ambiguous and may be overprinted by post-channel modification (*Malin and Edgett*, 1999). Unambiguous high water marks have not been identified for martian outflow channels. [*Robinson and Tanaka* (1990) used striations on a streamlined bar, located at approximately 26.5° N, 70.5° W, as a high water mark. MOLA orbit 233, proximal to the bar, illustrates that this landform is located on the plain well outside the banks of Northern Kasei Vallis (Figure 2B).] For the purpose of this study, the elevation of the lowest bench at each site (Figures 2B and 2D) was used as proxies for water depth. Assuming these benches are fluvial terraces, then calculated discharges are upper-bound values for the most recent flows in Kasei Valles. Maximum discharge (Q) estimates were obtained for reaches of the Kasei Valles system using a modified Manning equation for steady, uniform flow to account for the lower gravitational acceleration on Mars [*Komar*, 1979]:

$$Q = A\left(\frac{g_m\ S\ R^{\frac{4}{3}}}{g_e\ n^2}\right)^{\frac{1}{2}} \qquad (1)$$

where A is the flow cross-sectional area, g_m and g_e are gravity on Mars and Earth, respectively, S is the local slope, n is the Manning roughness coefficient and R is the hydraulic radius, defined as the ratio of flow cross-sectional area to wetted perimeter. Use of this equation to determine flow discharge has been used extensively for Martian outflow channels [c.f. *Carr*, 1996]. Calculated maximum discharge values (Table 1) are on the order of calculated discharges associated with large terrestrial floods, such as the Lake Missoula Flood [*Baker*, 1973] or the Lake Bonneville Flood [*O'Conner*, 1993]. For the lower bench in Kasei Vallis, calculated discharges are within an order of magnitude of average discharge values for the Mississippi River [*Carr*, 1996]. These maximum discharge values are several orders of magnitude lower than estimates made for Northern Kasei Valles (> 1 x 10^9 m^3 s^{-1}) by *Robinson and Tanaka* [1990], who based their calculations on derived channel dimensions from high resolution Viking stereo images. Thus, the discrepancy in calculated discharges between their work and this study is attributed to their larger flow cross-sectional area, which is primarily due to their over-estimation of channel width (83 km). The relatively low upper-bound discharges obtained here, along with the tentative identification of fluvial terraces, support the hypothesis that vertical incisement within the Kasei Valles system was akin to behavior ranging from that of large terrestrial river systems up to that of large terrestrial floods ─ a far less cataclysmic scenario than previously thought.

It is important to recognize that our hydrological calculations are solely for the final fluvial event in each channel because only the channel profile associated with the last event has been preserved. What, if anything, can be stated about the magnitude of early flow events? Evidence for such catastrophic floods in Kasei Valles of magnitude 10^9 m^3 s^{-1} no longer exists in light of the MOLA data. Thus, older flood events may have been larger, but there is no evidence to substantiate such a claim in the Kasei Valles region.

Morphological observations are consistent with relatively modest discharge, short duration floods within the Kasei Valles system. MOC image 34504 (Figure 4) shows an exhumed 6 km diameter crater, once buried underneath Lunae Mensa material. This crater was partly excavated by Kasei Valles floods and subsequent scarp retreat of the mesa. To the southwest, a "moat" or trench partly encircles the crater and was formed where the turbulence of the floodwaters interacting with the obstacle presented by the crater rim eroded material in front of, and along the side, of the crater. The rim was too high for the flood to overtop, and the flood lasted too short a time for the erosion to breach the crater rim and destroy it. The close-up view provided by MOC confirms that the Kasei flooding excavation of the crater must have been gentle enough to leave the basic morphology intact.

Discussion

The sum of the evidence presented in this paper — incised channels, fluvial terraces, relatively low maximum discharge rates, the sequence and duration of fluvial activity — are not consistent with a single, large catastrophic flood. Rather, the evidence suggests an alternate hypothesis for the formation of the Kasei Valles system: Kasei Valles formed gradually as a result of multiple fluvial events involving relatively modest flows (by previous estimates) operating over a relatively long time period. These discrete flood events were no more severe than large terrestrial floods. This working model suggests that Mars once had an active hydrological cycle capable of recharging the source region for these floods over at least tens of thousands to hundreds of thousands of years. Further, the model has implications for the formation of a martian ocean.

Parker et al. [1989] hypothesized that the circum-Chyrse outflow channels were active simultaneously and emptied into standing water within Chryse Planitia forming a global ocean in the martian northern plains. This ocean may have formed episodically [*Baker et al.*, 1991] and several contact/shoreline boundaries have been identified [e.g., *Parker et al.*, 1993]. According to the hypothesis, the latest episode of flooding in the major circum-Chryse channels was simultaneous and formed the youngest and smallest martian ocean (Contact 2). Using MOLA data, a more accurate volume estimate for the martian ocean bounded by Contact 2 has been determined: 1.4×10^7 km^3 [*Head et al.*, 1999]. The Kasei Valles system would have contributed a significant proportion of water to a martian ocean. The total volume of material removed by water associated with the Kasei Valles system was 9.04×10^5 km^3 [*Carr*, 1996]. Assuming a hyperconcentrated flood containing 40% sediment by volume [*Komar*, 1980], this yields a water volume of 1.36×10^6 km^3 involved in erosion. (Decreasing the sediment load would increase the water volume.) This volume of water represents nearly 10% of the volume of a martian ocean bounded by Contact 2.

Estimated filling rates for the Contact 2 martian ocean were < 1 month based on total combined outflow channel discharge rates of 10^9-10^{10} m^3 s^{-1} [*Parker et al.*, 1989]. The upper bounds on discharge rates obtained here (Table 1), applied to all outflow channels, imply lower bounds on fill times ranging from ~25 to ~6000 years, assuming continuous filling. We argued above that the Kasei Valles system was active in possibly discrete, spatially-confined floods over an extended period of geologic time. Further, it is unlikely that all outflow channels were active simultaneously [*Carr and Clow*, 1995]. Thus, an even longer fill time would be required. Standing bodies of water (liquid or frozen) are not currently stable under current martian atmospheric conditions and certainly could not persist for the time-scales estimated here. If a martian ocean did form with the flow rates calculated here, a warmer climate (higher surface temperature and atmospheric pressure) apparently would have been required to allow flooding water to accumulate to the observed “shorelines.”

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Table 1. Hydrologic parameters for Kasei Valles and comparison with terrestrial flow conditions. Slope for each channel was determined based on the change in base-level between MOLA crossings (orbits 233 and 252). Data gaps preclude the use of orbit 252 in hydraulic calculations.

Site	Slope	Depth m	n	V $m\ s^{-1}$	Q $10^7\ m^3\ s^{-1}$
NKV[1]	0.002	93	0.01	51	2
NKV[1]	0.002	93	0.07	7	0.3
KV[1]	0.0002	22	0.01	5	0.06
KV[1]	0.0002	22	0.07	1	0.008
NKV[2]	0.001	374*	0.015	75	230
NKV[2]	0.001	374*	0.035	32	100
L. Bonneville[3]					0.1
L. Missoula[4]					2
Miss. R.[5]					0.003

[1]This study. [2]Robinson and Tanaka, 1990.
[3]O'Connor, 1993. [4]Baker, 1973.
[5]Carr, 1996. *Average depth.

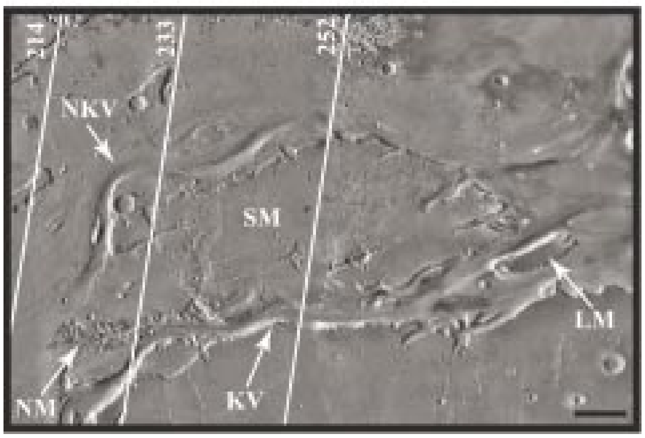

Figure 1. Regional view of Kasei Valles system. White lines are MOLA ground tracks. NKV = Northern Kasei Vallis; KV = Kasei Vallis; NM = Nilus Mensa; LM = Luna Mensa; SM = Sacra Mensa. Scale bar is 60 km.

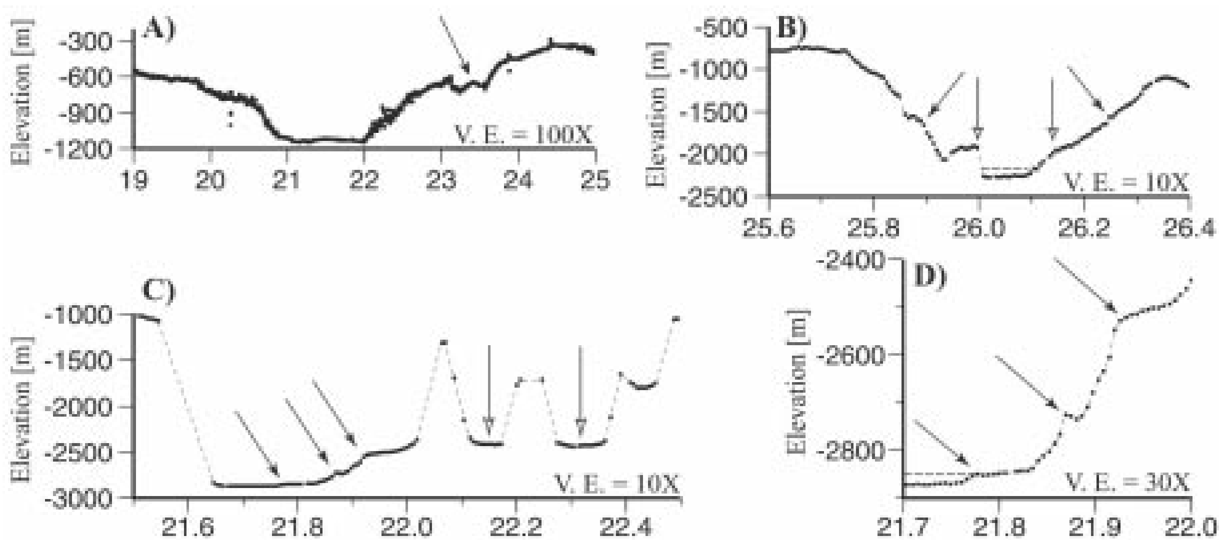

Figure 2. Topographic profiles across Northern Kasei Vallis (A and B) and Kasei Vallis (C and D). Horizontal dashed line is "bank-full" elevation used in hydraulic calculations. Thin line is a linear interpolation of topography for data gaps. One degree of latitude is approximately 60 km. A) Orbit 214 crosses previously unrecognized incised channel (arrow) on northern bank of Northern Kasei Valles head. B) Orbit 233 illustrates possible paired terraces: 1) –1561.90 m and –1557.18 m (solid arrows); 2) –1923.40 m and –1928.90 m (open arrows). C) Orbit 233 illustrates benches (solid arrows) on the northern bank and base-level of the Nilus Mensae channel network (open arrows). D) Enlargement of (C) highlighting the three topographic benches on north bank of Kasei Vallis.

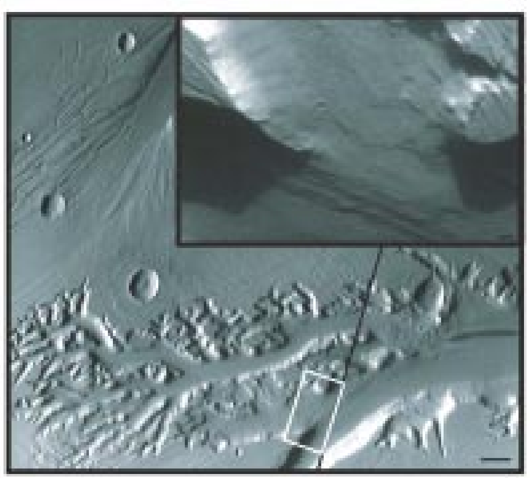

Figure 3. The Nilus Mensae channel network and Kasei Vallis in Viking image 555A06 (189 m/pix). Black line is orbit 233 ground track. Scale bar is 5 km. Inset is Viking frame 664A13 (42 m/pix) illustrating the topographic benches in (2C) and discussed in text. Scale bar for inset is 1 km.

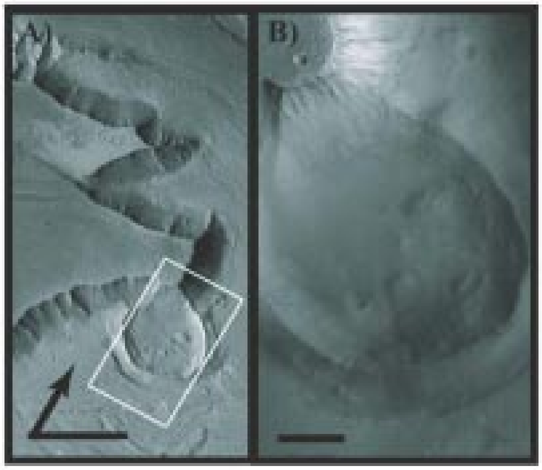

Figure 4. A) Local context Viking image 226A08 (70 m/pix) of the western portion of Lunae Mensa. Illumination is from the left. Scale bar is 10 km. B) MOC image 34504 (4.84 m/pix) of 6 km diameter exhumed crater. Illumination is from the right. Scale bar is 2 km.