Magnitude of a catastrophic flood event at Kasei Valles, Mars

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ABSTRACT

Kasei Valles compose an enormous outflow-channel system on Mars. The upper part of the channel system is typically less than 1 km deep and descends from Echus Chasma about 1 km over a distance of 1000 km; it then splits into north and south channels. On the basis of a stereomodel of Viking images, we have measured the geometry of a steep, constricted reach of the north channel that drops 900 m in only 100 km. A late-stage flood is hypothesized to have scoured the channel. If we assume that channel striations indicate water levels, then the flood had a minimum cross-sectional area of 3.12×10^7 m^2 (the putative flood had a width of 83 km, an average depth of 374 m, and maximum depth of 1280 m). These channel measurements suggest that flood velocities ranged from 32 to 75 m·s^{-1} and that discharge was greater than 1 km^3·s^{-1}, values larger than those calculated for any other flood event on Mars or Earth. The flood maintained supercritical flow and caused intense erosion in this area, scouring a 350-m-deep megapothole. The source of the flood water may have been a temporary lake in Echus Chasma, a deep canyon formed in association with tectonism at Valles Marineris.

INTRODUCTION

The Kasei Valles flood event described here has a striking terrestrial analogue in the catastrophic outburst flood of paleo–Lake Missoula and the subsequent erosion of the Channeled Scablands in eastern Washington State. This flood is the largest of its type known on Earth. Detailed studies by Bretz (1969), Baker (1973), and Baker and Milton (1974) have established the events and processes that shaped the Channeled Scablands during the Lake Missoula flood. The Channeled Scablands and Kasei Valles contain analogous features such as streamlined bars, cataracts, and linear grooves interpreted to be formed during catastrophic floods (Baker and Kochel, 1979), though such features have been interpreted by others (Lucchitta et al., 1981) to be the result of ice erosion. Additionally, the late-stage flood at Kasei Valles probably dissected a series of layered volcanic rocks similar to the flood basalts that were cut to form the Channeled Scablands.

A major impediment in the study of outflow-channel hydraulics on Mars has been the lack of high-resolution elevation data from which to determine channel geometry. Previous studies have attempted to calculate the paleohydrology of Martian channels on the basis of crude estimates of channel geometry (Carr, 1979; Komar, 1979; Baker, 1988), resulting in calculated flood-discharge rates that have large ranges of uncertainty. To obtain more precise results, we have analyzed the upper reach of the north channel of Kasei Valles (Fig. 1), where (1) the channel is clearly exposed, (2) the limits of the flow depth of a late-stage flood event can be defined, and (3) topography can be determined by a stereopair of Viking images having excellent viewing geometries. Channel geometry of Kasei Valles can help define the magnitude of maximum flood discharges on Mars, because the Kasei Valles form the largest of the Martian outflow channels. The stereopair has a ground resolution of about 200 m per pixel, and height measurements from the stereomodel have a maximum error of about 100 m, confirmed by comparisons with photoclinometric and shadow measurements along selected profiles of channel scarps. We base our model of the dynamics of the flood event on the measured channel geometry and then make speculations regarding the origin of the flood.

GEOLOGIC SETTING

Although Mars now has an arid climate, its outflow channels record the most voluminous catastrophic floods known anywhere in the Solar System. The Kasei Valles system emanates from Echus Chasma, a broad, deep canyon in northwestern Valles Marineris. The Kasei system traverses 3200 km of western and northern Lunae Planum (Fig. 1) and locally reaches depths of more than 3 km below the adjacent plateaus. Nearly halfway to its mouth in Chryse Planitia, the system turns from northeast to east and splits into two main channels, which partly merge to the east before entering Chryse. Streamlined channel bars and terraces cut by the channels resemble features in the Channeled Scablands in eastern Washington State (Baker, 1982, p. 139).

Two major rock units appear to be cut by Kasei Valles, according to stratigraphic and morphologic relations (Robinson and Tanaka, 1988). The upper unit is about 1 km thick (De Hon, 1982; Robinson and Tanaka, 1988) and is made up of relatively friable material capped by ridged-plains material of early Hesperian age (Tanaka, 1986), which forms a relatively pristine surface. Ridged-plains material is generally interpreted to be made of up lavas. Where cut by channels and fractures along Kasei Valles, the

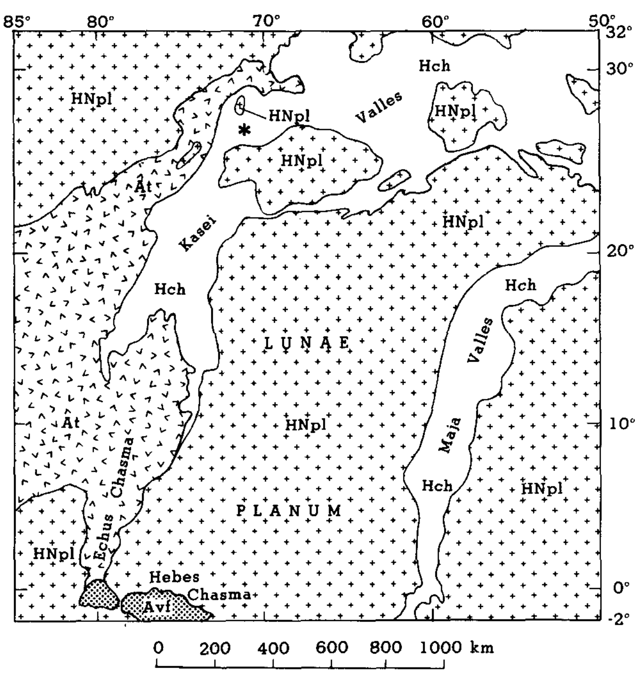

Figure 1. Geologic map of Kasei Valles region of Mars, simplified from Scott and Tanaka (1986). Martian geologic periods: N = Noachian, H = Hesperian, A = Amazonian. HNpl = plateau material, Hch = channel material, At = Tharsis lava flows, Avf = canyon-floor material. Asterisk shows location of center of Figure 3 (study area).

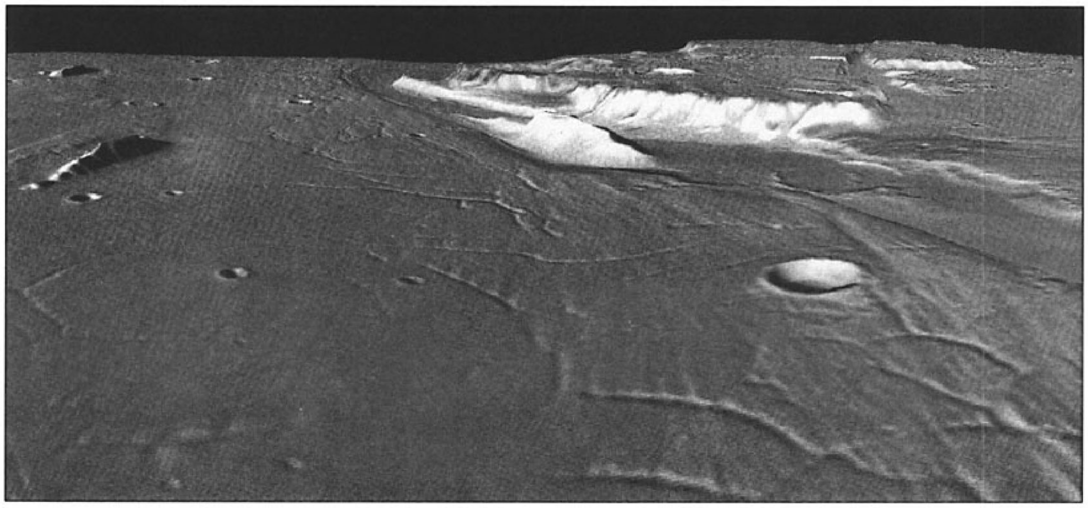

Figure 2. Perspective view of Kasei Valles from digital elevation model created in this study and from Viking Orbiter images 519A08 and 51910. View to northeast simulates perspective from 5000 m above surface; total viewing angle is 80°. Main north Kasei channel drops sharply into megapothole up channel from constricted easterly bend.

upper unit has been eroded by the sapping of ground water or ground ice to form fretted, U-shaped valleys, debris aprons, and chaotic terrain (Sharp, 1973); some shallow outflow channels are preserved on the plateau surface. The friable part of the unit may be loosely consolidated, fragmented material produced by impact bombardment. In contrast, the lower unit was eroded mainly by outflow channeling; only minor mass-wasting of the unit has occurred. The lower unit is found at depths of as much as 3 km below the ridged-plains materials, and it is much lower in stratigraphic position than most exposed materials on Mars. The lower unit may correspond to lower Noachian basement rocks that elsewhere form isolated massifs or the rims of ancient, large impact basins (Tanaka, 1986).

Streamlined forms occur at all levels in the rocks cut by Kasei Valles. The superposition of these forms and the crosscutting relations of grooves cut in the channel floor suggested to Neukum and Hiller (1981) that a series of floods produced Kasei Valles. Crater densities and stratigraphic relations indicate that the floods occurred during the late Hesperian (Scott and Tanaka, 1986).

CHANNEL GEOMETRY

The geometry of the upper reaches of Kasei Valles is poorly known because of the absence of detailed stereophotogrammetric measurements and the local postflood burial of the channel by lava flows (Scott and Tanaka, 1986; see Fig. 1). About 500 km south of the study area (Fig. 1), shadow measurements indicate depths of 500 to 1000 m for troughs that appear to have depths similar to that of the channel. In this southern area, the channel is as much as 300 km across. Regional topography indicates that the upper Kasei Valles drop about 1 km over a distance of about 1000 km (U.S. Geological Survey, 1989). The channel system then turns east and splits into two branches, of which the north branch is the wider. Stereophotogrammetry indicates that this northern channel deepens and its bed slope steepens as it enters the study area.

Our stereomodel includes the upper part of the northern channel, where it narrows and bends from northeast to east (Fig. 1). Stereophotogrammetric profiles were taken along the channel bottom and perpendicular to the channel to determine cross-sectional areas and channel-bottom slope. The resulting topographic data show that the channel drops about 900 m over a distance of 100 km (Fig. 2). Then, as the channel turns northeast and broadens, the floor rises more than 350 m over a distance of about 50 km (Fig. 3A; A–A′).

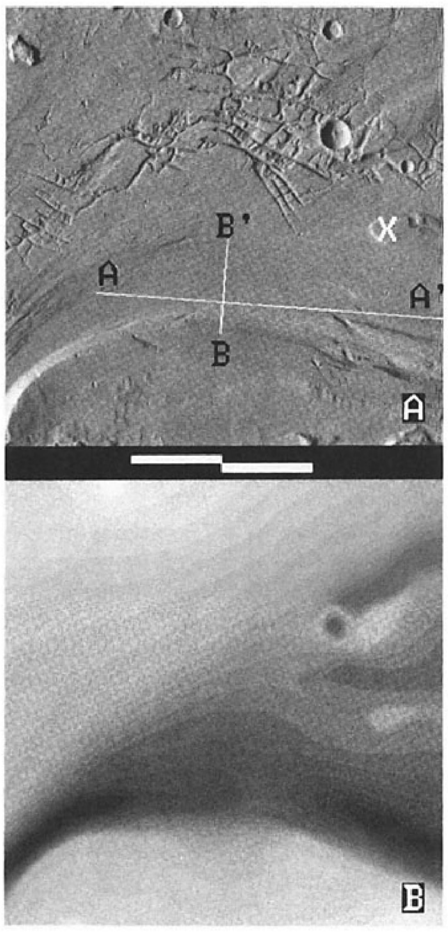

Figure 3. A: Part of Kasei Valles north channel showing area of reverse gradient in channel floor. Profiles indicate stereogrammetric measurements plotted in Figure 5. Streamlined bar marked with X is seen at high resolution in Figure 4. B: Elevation map corresponding to image data in A. Each gray level represents change in elevation of 100 m. Total length of scale bar represents 40 km; north is at top.

Distinct striations veer out from the main channel where its floor begins to rise, and they are deflected by several bars (Figs. 3A and 4). The striations are not cut by later channeling in the lower reaches of the channels; thus we infer that the striations record high-water marks of a late-stage flow event. High-resolution images of one of the bars (Fig. 4) show its top to be devoid of streamlined features, indicating that the flow did not overtop the bar for very long. A conservative estimate for the high-water level is the midpoint height of the bar. We calculated this height by averaging stereomeasurements across the bar, because the relief of the bar is near the resolution of the stereophotogrammetric data; the height of the bar is about 250 m. Given this high-water level, we determined the minimum cross-sectional area of the flood by using the cross-channel bottom profile at its highest point (profile B–B′: Figs. 3A and 5). We derived an average flow depth of 374 m across a channel 83 km wide with a maximum depth of 1280 m.

FLOW CHARACTERISTICS

Given this geometry of the north channel, we calculated the average flow velocity and the discharge for the flood event by using the Manning equation as described in Sellin (1969, p. 6) and as modified by Komar (1979) to account for the lower gravity on Mars. The average flow velocity, u, is defined by

$$u = \left(\frac{g_{\mathrm{m}} h s}{C_{\mathrm{f}}}\right)^{1/2}, \qquad (1)$$

where g_{m} is the Martian gravitational acceleration, h is the hydraulic radius (a ratio of channel

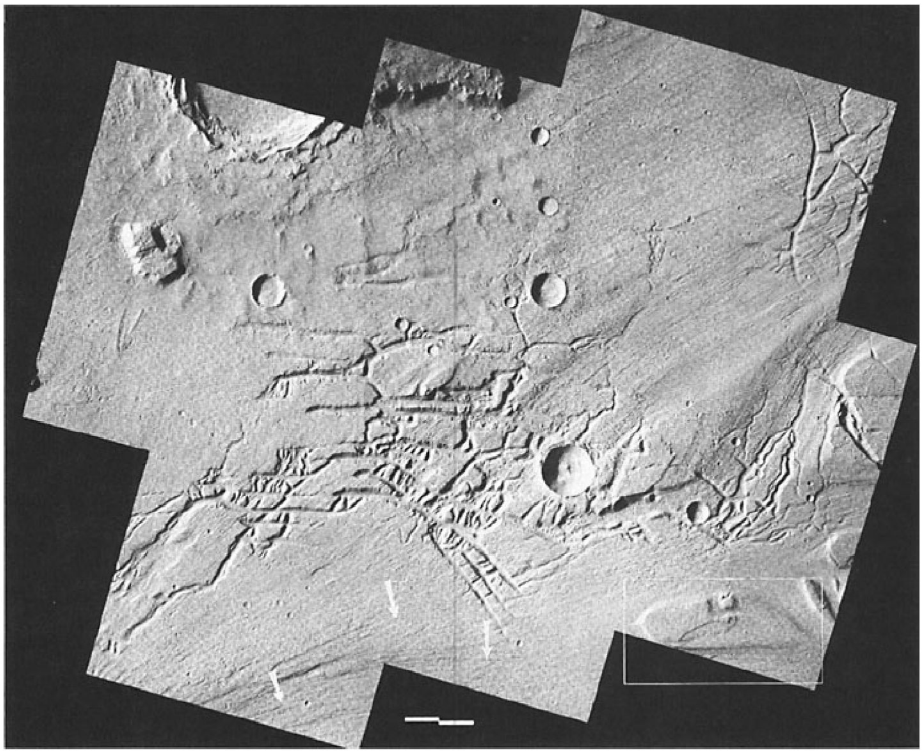

Figure 4. High-resolution digital mosaic (images from Viking 1, orbit 665A) of northern Kasei Valles (refer to Fig. 3 to locate mosaic). Box encloses streamlined bar used in model to determine upper limits of flooding (see text). Arrows indicate striations etched in channel floor that cross unusual rise in channel. Total length of scale bar represents 9 km; north is at top.

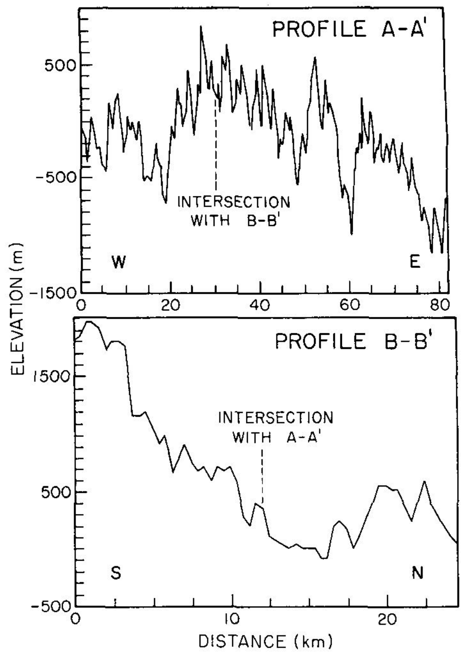

Figure 5. Stereogrammetric profiles that indicate channel geometry across reverse gradient in northern Kasei Valles. Profile A-A' roughly parallels channel, and profile B-B' cuts perpendicularly across channel. Profile locations shown in Figure 3A.

cross-sectional area over wetted perimeter), and s is the sine of the channel-bed slope. The dimensionless drag coefficient, C_f, allows for the gravity correction and is given by

$$C_f = g_e \left(\frac{n^2}{h^{1/3}}\right), \tag{2}$$

where n is the Manning roughness coefficient (n has units of s·m$^{-1/3}$) and g_e is the gravitational acceleration on Earth. The value for n is empirically derived from observations of terrestrial channel flows, but its value for a large-scale flow event on Mars is uncertain. Therefore, we calculated velocities for a range of n values based on empirical values for different channel conditions on Earth and estimates used in previous studies of catastrophic flows on Mars. As a result, calculated mean flow velocities range from 32 to 75 m·s^{-1} (Table 1). The discharge, Q, is the product of the average flow velocity, u, and the cross-sectional area. Discharges range from 0.9 to 2.3 × 10^9 m^3·s^{-1} (Table 1). Because of the uncertainty inherent in our elevation measurements, Q conservatively ranges (for n = 0.025, u = 45 m·s^{-1}) from 0.9 to 1.4 × 10^9 m^3·s^{-1} (Table 2) as peak-flow elevation is lowered to account for possible errors of as much as 100 m each for water level and channel profile. Even with the maximum error in the stereomeasurements, peak discharge of the north-channel flood appears to have been extremely high—nearly two orders of magnitude greater than that calculated for the Lake Missoula flood on Earth (Baker, 1973). Discharge of the Kasei south channel (not estimated) would have added to the total magnitude of the flood.

The tremendous discharge of the north channel had a correspondingly high ability to erode and transport sediments. An indication of this ability is the power of the flow, ω, which is given by

$$\omega = \tau_0 u. \tag{3}$$

The bottom shear stress, τ_0, is defined as

$$\tau_0 = \rho C_f u^2, \tag{4}$$

where ρ is the mean density of the fluid (Komar, 1979). For water (ρ = 1 g·cm^{-3}), τ_0 for the north-channel flood (with u = 45 m·s^{-1}, n = 0.025) was about 1.8 × 10^4 dynes·cm^{-2} (1.8 × 10^3 N·m^{-2}), and ω was about 7.9 × 10^7 ergs ·cm^{-2}·s^{-1} (7.9 × 10^4 W·m^{-2}; C_f = 0.0009). The density and power of the flood were probably greater because of entrained sediment load.

For comparison, calculated values for the Lake Missoula flood are 2 × 10^4 dynes·cm^{-2} for the shear stress and 5 × 10^7 ergs·cm^{-2}·s^{-1} for the power of the flow. Despite the much larger discharge of the Kasei event, the values for τ_0 and ω are comparable with those of the Missoula flood. This similarity is due to τ_0 and ω having their dependence on u and h rather than on the total discharge. The upper limits for the value of u for the Missoula flood are comparable with our average value of 45 m·s^{-1} for the Kasei north-channel event. The north-channel flood was distributed over a greater channel width, and its average depth (374 m) was only somewhat greater than the range of depths for the Missoula flood (50 to 200 m). Counteracting the greater depth of the Kasei flood is the lower gravity of Mars (40% of that on Earth).

Additionally, the erosive power of a flood is dependent on its ability to transfer stream energy

TABLE 1. PARAMETERS FOR A LATE-STAGE FLOOD, NORTH KASEI CHANNEL, MARS

n	u (m/s)	Q (10^9 m^3/s)
0.015	75	2.3
0.020	56	1.8
0.025	45	1.4
0.030	37	1.2
0.035	32	1.0

Note: u is flow velocity, Q is discharge, both functions of Manning roughness coefficient, n.

TABLE 2. CHANGE IN DISCHARGE AS A FUNCTION OF DECREASING WATER DEPTH FOR THE NORTH KASEI CHANNEL, MARS

ΔD* (m)	Q† (10^9 m^3/s)
0	1.4
-50	1.2
-100	1.0
-150	1.0
-200	0.9

* Decrease in water depth (D) from peak estimated depth.

†Discharge (Q) is product of average flow velocity and cross-sectional area.

into the channel bed and to provide lift. Such action is greatly enhanced when supercritical flow is attained (resulting in hydraulic jumps), particularly where a channel bends, becomes constricted, or changes bed slope (Koloseus, 1971; Baker, 1982, p. 162). All three of these conditions were met by the Kasei north channel. Supercritical flow occurs when the Froude number exceeds 1 (Chow, 1959, p. 43). The Froude number, F, is given by

$$F = u\,(gD)^{-1/2}, \tag{5}$$

where D is the average depth of the flow (Barnes, 1956). For the north Kasei flood, F was about 1.2 for the measured profile (profile A–A′, Figs. 3A and 5).

Cavitation is another process that can enhance erosion in a catastrophic flood (Baker, 1981). Although poorly understood, cavitation apparently occurs when vapor bubbles collapse in a fluid because of dynamic pressure variations (Baker, 1979). The critical velocity for the onset of cavitation, V_c, is determined by

$$V_c = 1.6D^{1/2}. \tag{6}$$

For the average depth of the Kasei flood (374 m), the critical cavitation velocity would have been 31 $m \cdot s^{-1}$, well within our range of calculated velocities. Therefore cavitation may have contributed to the erosion of the megapothole. Baker has cautioned that this critical cavitation approximation does not account for (1) increased atmospheric pressure, which may or may not have existed in the Martian past; (2) large sediment load, which would increase the effective density of the water; or (3) formation of an ice layer on top of the flood. Therefore it is quite difficult to determine what the cavitation velocity would have been with our limited knowledge of these conditions. But it is apparent that cavitation may have played an important role in forming the outflow channels on Mars.

DISCUSSION

The published reconstructions of the Missoula flood and our measurements of the geometry of the Kasei north channel allow us to speculate on the overall hydraulic character of the flood event that carved the channel. As the flow left the Echus region, the channel's upper reaches were broad and its bed slope was very low, indicating shallow depth and low flow rate. As the channel narrowed and the gradient steepened, flow velocity increased (north of lat 22.5°N), and the flow became supercritical. Stream energy was dissipated through hydraulic jumps that may have imparted strong uplift forces on the channel bottom, dramatically increasing erosion. This intense erosion may have been responsible for the 350-m-deep megapothole in the channel (Fig. 2).

A problem in explaining the Kasei flood is the source of the water. The likely arid climate of Mars during outflow-channel development generally prohibited precipitation and long-term preservation of bodies of water or ice in the equatorial region; thus water for the flood most likely originated in the Martian crust. If a very porous and permeable, confined aquifer has a high hydraulic head and a thickness of 1 to 3 km, breakouts of ground water from zones as large as 60 km in diameter may have yielded discharges of 10^5 to 10^7 $m^3 \cdot s^{-1}$ (Carr, 1979). The north Kasei discharge alone was more than two orders of magnitude higher than this estimate. Therefore, breakouts of confined aquifers, although perhaps contributing to the flood, probably were not its main source. An alternative explanation is that the water was temporarily ponded (Lucchitta and Ferguson, 1983). Echus Chasma, at the head of Kasei Valles, has a volume of about 5×10^5 km^3 (Carr et al., 1987), and it may previously have been dammed or enclosed, as is neighboring Hebes Chasma. Water may have collected in Echus through drainage of an aquifer system in the northern Valles Marineris region, perhaps along east-striking faults or tension cracks (Tanaka and Golombek, 1989). If half the volume of Echus Chasma was available for a catastrophic outburst flood, a discharge of 1.4×10^9 $m^3 \cdot s^{-1}$ could have been sustained for over 49 h. The size of such an event could have important implications for evaluating the planet-wide water inventory of Mars, which is currently estimated to range from 1.4×10^5 km^3 to 1.44×10^8 km^3 (Carr, 1986).

REFERENCES CITED

Baker, V.R., 1973, Paleohydrology and sedimentology of Lake Missoula flooding in eastern Washington: Geological Society of America Special Paper 144, 80 p.

——1979, Erosional processes in channelized water flows on Mars: Journal of Geophysical Research, v. 84, p. 7985–7993.

——1981, Erosional forms and processes for the catastrophic Pleistocene Missoula floods in eastern Washington, *in* Morisawa, M., ed., Fluvial geomorphology: London, George Allen and Unwin, p. 123–148.

——1982, The channels of Mars: Austin, University of Texas Press, 198 p.

——1988, Flow modeling of cataclysmic flood discharges, *in* Howard, A.D., Kochel, R.C., and Holt, H.E., eds., Sapping features of the Colorado Plateau: National Aeronautics and Space Administration Special Publication 491, p. 98–99.

Baker, V.R., and Kochel, R.C., 1979, Martian channel morphology: Maja and Kasei Valles: Journal of Geophysical Research, v. 84, p. 7961–7983.

Baker, V.R., and Milton, D.J., 1974, Erosion by catastrophic floods on Mars and Earth: Icarus, v. 23, p. 27–41.

Barnes, H.L., 1956, Cavitation as a geologic agent: American Journal of Science, v. 254, p. 493–505.

Bretz, JH., 1969, The Lake Missoula floods and the Channeled Scablands: Journal of Geology, v. 77 p. 505–543.

Carr, M.H., 1979, Formation of Martian flood features by release of water from confined aquifers: Journal of Geophysical Research, v. 84, p. 2995–3007.

——1986, Mars: A water-rich planet?: Icarus, v. 86, p. 187–216.

Carr, M.H., Wu, S.S.C., Jordan, R., and Schafer, F.J., 1987, Volumes of channels, canyons, and chaos in the circum-Chryse region of Mars [abs.], *in* Abstracts, 18th Lunar and Planetary Science Conference: Houston, Texas, Lunar and Planetary Institute, p. 155–156.

Chow, V.T., 1959, Open channel hydraulics: New York, McGraw-Hill, 680 p.

De Hon, R.A., 1982, Martian volcanic materials: Preliminary thickness estimates in the eastern Tharsis region: Journal of Geophysical Research, v. 87, p. 9821–9828.

Koloseus, H.J., 1971, Rigid boundary hydraulics for steady flow, *in* Shen, H.W., eds., River mechanics: Fort Collins, Colorado, H. W. Shen, p. 3-1–3-51.

Komar, P.D., 1979, Comparisons of the hydraulics of water flows in Martian outflow channels with flows of similar scale on Earth: Icarus, v. 37, p. 156–181.

Lucchitta, B.K., and Ferguson, H.M., 1983, Chryse basin channels: Low gradients and ponded flows: Journal of Geophysical Research, v. 88, p. A553–A568.

Lucchitta, B.K., Anderson, D.M., and Shoji, H., 1981, Did ice streams carve Martian outflow channels?: Nature, v. 290, p. 759–763.

Neukum, G., and Hiller, K., 1981, Martian ages: Journal of Geophysical Research, v. 86, p. 3097–3121.

Robinson, M.S., and Tanaka, K.L., 1988, Stratigraphy of the Kasei Valles region, Mars: Lunar and Planetary Institute Technical Report 88-05, p. 106–108.

Scott, D.H., and Tanaka, K.L., 1986, Geologic map of the western equatorial region of Mars: U.S. Geological Survey Miscellaneous Investigations Map I-1802-A, scale 1:15,000,000.

Sellin, R.H.J., 1969, Flow in channels: London, Macmillan, 149 p.

Sharp, R.P., 1973, Mars: Fretted and chaotic terrain: Journal of Geophysical Research, v. 78, p. 4073–4083.

Tanaka, K.L., 1986, The stratigraphy of Mars: Journal of Geophysical Research, v. 91, p. E139–E158.

Tanaka, K.L., and Golombek, M.P., 1989, Martian tension fractures and the formation of grabens and collapse features at Valles Marineris: Proceedings, 19th Lunar and Planetary Science Conference: Houston, Texas, Lunar and Planetary Institute, p. 383–396.

U.S. Geological Survey, 1989, Topographic map of western equatorial region of Mars: U.S. Geological Survey Miscellaneous Investigations Map I-2030, scale 1:15,000,000.

ACKNOWLEDGMENTS

We thank J. Simpson for stereophotogrammetric measurements, P. A. Davis for photoclinometric assistance (both U.S. Geological Survey), and P. D. Komar (Oregon State University), A. S. McEwen, M. H. Carr (both U.S. Geological Survey), and V. R. Baker (University of Arizona) for helpful reviews. The Alaska Data Visualization and Analysis Laboratory of the University of Alaska, Fairbanks, provided the computer facilities for much of this project.

Manuscript received December 14, 1989
Revised manusript received April 19, 1990
Manuscript accepted April 27, 1990