JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 102, NO. E2, PAGES 4151-4160, FEBRUARY 25, 1997

Paleohydrology and flood geomorphology of Ares Vallis

G. Komatsu

Lunar and Planetary Laboratory, University of Arizona, Tucson

V. R. Baker

Lunar and Planetary Laboratory and Department of Geosciences, University of Arizona, Tucson

Abstract. Ares Vallis is a Martian outflow channel which is about 1500 km long and locally exceeds 100 km in width and 1000 m in depth. We estimate the channel's paleoflow capacity using paleohydraulic techniques. At a constricted and unusually deep reach, not affected by tributaries or secondary inflows, the estimated possible maximum peak discharges are of the order of 10^8-10^9 m^3/s. These values are 1 to 2 orders of magnitude larger than any known terrestrial floods. These high-discharge flows were theoretically capable of transporting boulders larger than 10 m in diameter. The downstream depositional plain, where Ares debauches into the Chryse Planitia, displays geomorphological features indicative of high erosional capacity by the flooding. In this area, site of the proposed Pathfinder landing, we expect to find a complex sequence of sediments created by varying paleoflood flow hydraulics, sediment transport characteristics, and probable secondary modification of the primary flood landforms.

Introduction

The Martian outflow channels are immense in scale and very important as evidence of a rich planetary inventory of water [*Carr*, 1996]. The channels display landform assemblages that indicate conveyance of cataclysmic floods originating from subsurface sources [*Baker and Milton*, 1974; *Baker*, 1978, 1982; *Carr*, 1979; *Mars Channel Working Group*, 1983]. Paleodischarges for selected channels have been estimated using the standard Chezy and Manning equations appropriately modified for Mars gravity [*Komar*, 1979; *Baker*, 1982; *Robinson and Tanaka*, 1990; *De Hon and Pani*, 1993]. Results indicate that paleodischarges may have been 10 to 100 times greater than the known largest prehistoric floods on Earth [*Baker*, 1982]. In recent years, new evidence of Pleistocene cataclysmic floodings has been recognized on the continental regions of Earth [*Baker et al.*, 1993; *Komatsu and Baker*, 1996], and the geological and environmental impacts of these floods are being assessed. Studying the mechanics of Martian outflow channels will contribute to the understanding of the potentially very significant paleofloods which affected Earth's landscape and, possibly human settlement in the area where the floods occurred.

The goal of the present study is to estimate the scale of flooding that was primarily responsible for the origin of Ares Vallis and to explore the consequences of that scale of flooding for deposition of large quantities of sediments in the Pathfinder landing site area. There are many limitations on making such estimates, given the present state of knowledge concerning Mars topography. There also appears to have been a complex history of deposition at the proposed landing site [*Golombek et al.*, this issue; *Rice and Edgett*, this issue; *Tanaka*, this issue; T. J. Parker, personal communication 1996]. We hope to provide guidelines for improving upon our estimates when new data are provided by the upcoming Pathfinder and Mars Global Surveyor Missions.

Paper number 96JE02564.
0148-0227/97/96JE-02564$09.00

Paleohydrology and Geomorphology

Flow Conditions

A simple estimate of paleoflow conditions may be made with the Chezy equation,

$$v = C(Rs)^{1/2}, \tag{1}$$

in which C is the Chezy coefficient, R is hydraulic radius, and s is slope. The Chezy coefficient is related to the Manning coefficient n, as follows:

$$C = 1/n(R)^{1/6}, \tag{2}$$

where C is proportional to $g^{1/2}$ (where g is gravity). Hence the Manning coefficient for Mars (n_M) can be related to the empirical terrestrial Manning coefficient (n_E), by the equation

$$n_M = n_E(g_E/g_M)^{1/2} = 1.62n_E, \tag{3}$$

where g_E is terrestrial gravity and g_M is Martian gravity. More realistically, the empirical Manning coefficient on Earth ranges over a factor of about 2, and for our application, the influence on the final result is minimal. The Manning coefficient of Mars (n_M) was assumed to be 0.032 (n_E=0.02).

There are many considerations applicable to assumptions inherent in these equations, scaling to Mars paleoflows, and sources of error. These issues are extensively discussed in the literature concerned with catastrophic flow paleohydraulics, both for Mars and Earth [*Baker*, 1973; *Komar*, 1979; *O'Connor and Baker*, 1992].

In our application to Ares Vallis we utilized the engineering hydraulic software FLOWMASTER, which was developed to determine accurately the hydraulic radius from the crosssectional area of a channel and to derive better estimates for the flow velocity and discharge rate. While this makes the hydraulic calculations quite straightforward, considerable attention must be focused on the geomorphological context in which the calculations are made.

Flood Reaches

In the paleohydrology of ancient floods, geomorphology is used to constrain paleoflow estimates. The procedure involves the mapping of the high-water marks and other preserved paleostage indicators, the reconstruction of the paleochannel geometry, and the identification of flow-produced features [*Baker*, 1973; *O'Connor and Baker*, 1992].

Ares Vallis is a channel exceeding 1500 km in length that has reaches in multiple geological settings (Figure 1). The channel originates at a source region characterized by collapsed chaotic terrains (Figure 2a). The main part of channel occurs in heavily-cratered highlands (Figure 2b), where the channel depth locally exceeds 1 km. At the highland-northern plains boundary, the channel expands and shallows (Figure 2c). At this point the floor of Ares Vallis is modified by a remarkable network of depressions with interconnected valleys, separated by sinuous and narrow ridges, which in places extend across the valley. These morphologies are hypothesized by some researchers to be thermokarst developed in a deposit that mantles the channel floor [*Costard and Kargel*, 1995]. Downstream of this unusual reach, the channel expands into the Chryse Planitia and merges with the Tiu Vallis from the west (Figure 2d). As will be shown below, massive deposition of material eroded from upstream, constricted channels likely occurred in this region. However, the floor of the Chryse Planitia has a number of features indicative of erosional processes, as described below. Thus the history of erosion and deposition, associated with cataclysmic flooding, was likely to have been complex, particularly in the downstream reaches of Ares. For our calculations, therefore, we focus on an unusually narrow, deep upstream reach to provide an upper limit on possible paleodischarges. We also consider the downstream expansion as a contrasting manifestation of the paleohydraulics.

Narrow reach. We chose an upstream reach where the channel is well-defined, unusually deep, and where it lacks tributaries (Figure 3a). For simplicity, the cross sections of

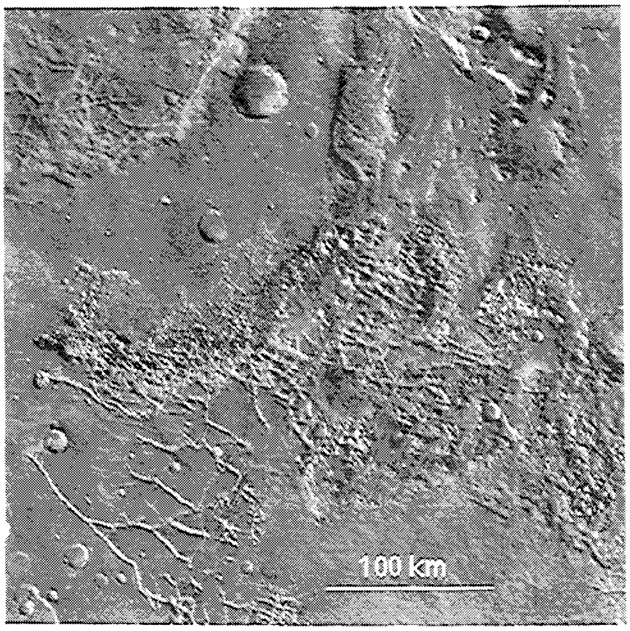

Figure 2a. Viking imagery of the source region for Ares Vallis. It consists of numerous knobs and depressions composing chaotic terrain.

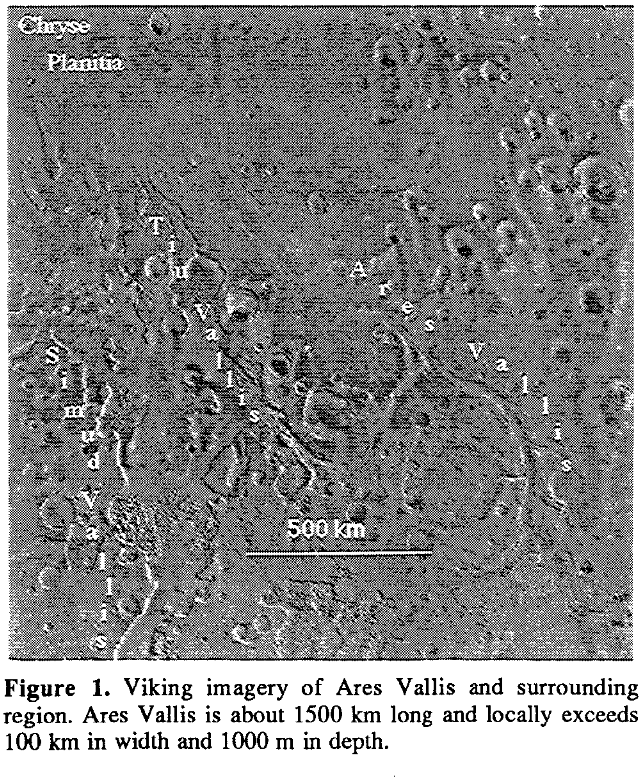

Figure 1. Viking imagery of Ares Vallis and surrounding region. Ares Vallis is about 1500 km long and locally exceeds 100 km in width and 1000 m in depth.

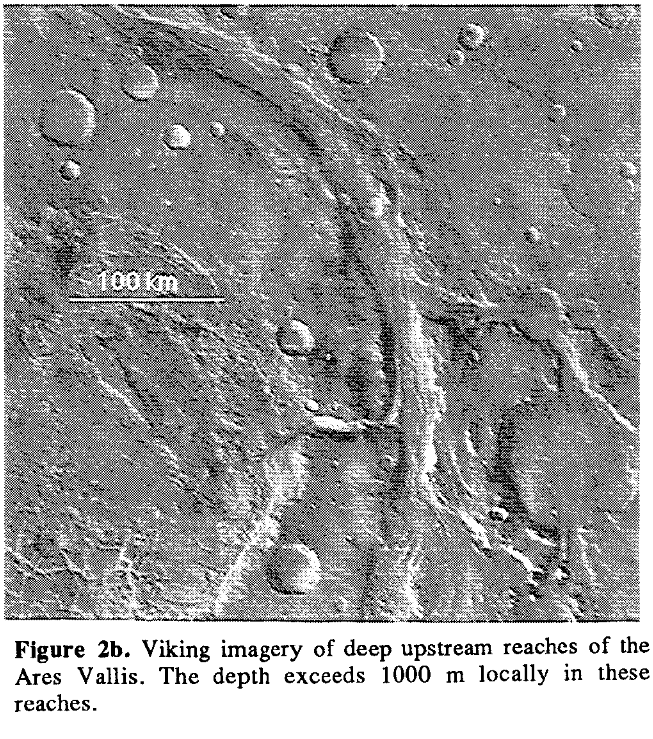

Figure 2b. Viking imagery of deep upstream reaches of the Ares Vallis. The depth exceeds 1000 m locally in these reaches.

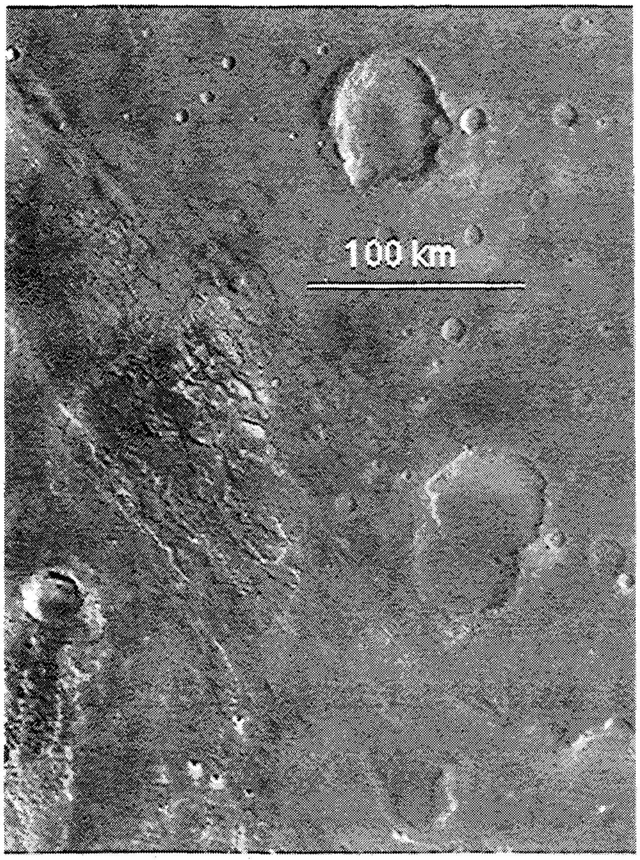

Figure 2c. Viking imagery of an expanded reach in lower Ares Vallis. In this section, the channel's floor shows irregular patterns, implying periglacial processes [*Costard and Kargel*, 1995].

the Ares Vallis (Figure 3b) are assumed to represent the paleogeometry of the channel at the time of flooding. These cross sections were derived from the U.S. Geological Survey Digital Terrain Model (DTM), which is known to have a large error as a function of latitude. As a check on the DTM cross sections, we compared the cross sections to photoclinometric measurements made by G. Ori and A. Baliva (written communication, 1995). Depths derived from the DTM were consistently lower than those indicated by the photoclinometry, but the discrepancy nowhere exceeded a factor of 2. Thus, the peak discharge estimate made using the cross sections in Figure 3b is likely to be conservative.

The depth increases from the upper to the lower part of the study reach. The DTM indicates an unusually steep bed slope for the first two cross sections, but there is essentially no bed gradient through the rest of the study reach (Figure 3c). Unfortunately, slopes of channel floors along the flow direction are not able to be compared to photoclinometric values. This is because elevation changes are very small over the 100-km study reach. Nevertheless, the local steep gradient corresponds to the narrowest part of the channel. Steep slopes in constricted reaches are what would be expected for cataclysmic flood flows in their terrestrial analogs [*Baker*, 1973; *Baker et al.*, 1993]. The channel floor in this reach appears to be smooth, although careful examination reveals grooves, which are probably erosional. This is a reach where the flood flow was constricted, deep and very fast, resulting in the deep incision. The sediment transport capacity of the flow also must have been very high, as will be discussed below.

Although the paleodischarge estimate for this reach will clearly be very crude, we wish to see if its general magnitude is consistent with landforms in the channel and downstream at the Pathfinder landing site. A discussion of the factors involved in the estimate, its geomorphological context, and its implications will be useful for future calculations when improved topographical data become available.

Expanding reach. The zone of expansion into Chryse Planitia contains a variety of flood-related features. In our interpretation, we used experience gained from terrestrial analogs: the Channeled Scabland of eastern Washington State, formed by the outbursts of the Pleistocene Lake Missoula [*Baker and Nummedal*, 1978], and flood-modified valleys in the Altay Mountains [*Baker et al.*, 1993]. These landscapes were formed by cataclysmic floods caused by the failures of glacier-dammed lakes in the Pleistocene. The scales of the terrestrial floods were probably an order of magnitude smaller than their Martian counterparts [*Baker*, 1982], but they provide the best available terrestrial comparisons.

From the western edge of the image, mottled terrains extend westward (Figure 4a). The upper strata (lower albedo) seem to be stripped away, exposing either lower strata or trapped eolian materials (higher albedo). These terrains may be scabland formed by the erosion of high-energy flows (T. J. Parker, personal communication 1996). Scabland in eastern Washington State is formed by the stripping of loess caprock, eroding into the underlying basaltic bedrock [*Baker and Nummedal*, 1978]. Basalt is considered to be the most common volcanic rock on Mars, and basalt may account for the stripped

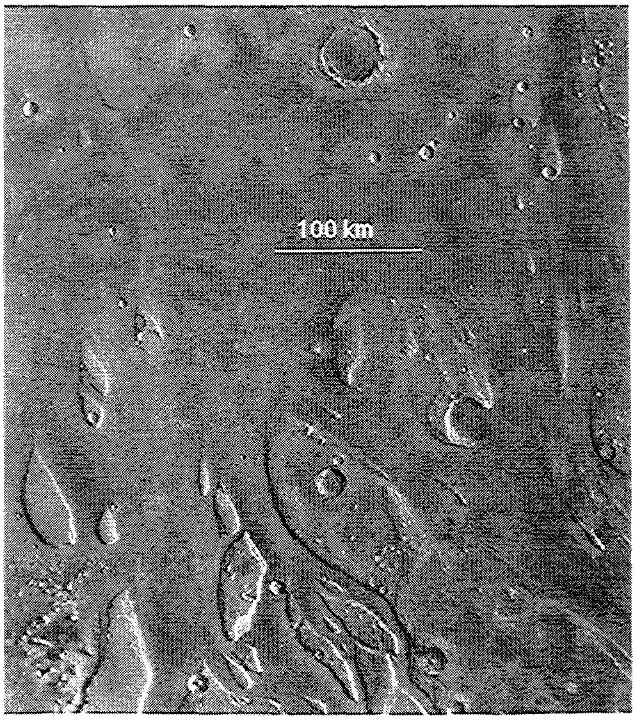

Figure 2d. Viking imagery of the Ares Vallis expansion into Chryse Planitia. This area contains the proposed Pathfinder landing site [*Golombek et al.*, this issue], which is located at the upper right corner of the image.

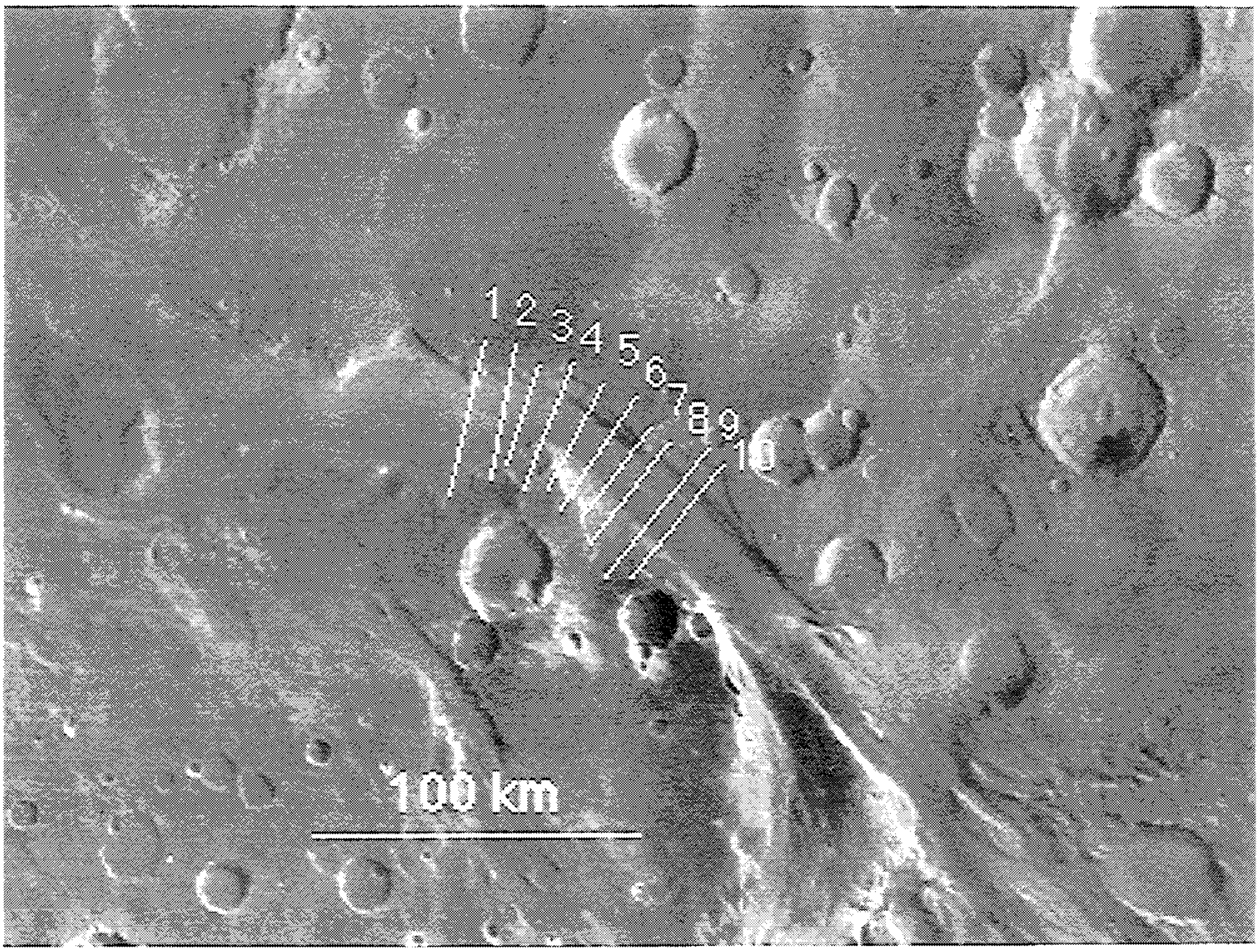

Figure 3a. A constricted reach of Ares Vallis and locations of channel cross sections along the reach.

strata. Scabland erosion of basalt would explain the very rugged terrains that are similar in texture to terrestrial scabland (Figure 4b). An alternative explanation is that this rugged terrain was scoured by the eolian processes (T. J. Parker, personal communication 1996). High-discharge flood flows can also produce longitudinal grooves [*Baker and Nummedal*, 1978] (Figures 4c and 4d). Streamlined hills are among the most predominant landforms in the region (Figure 4e). Streamlined hills are also commonly developed by terrestrial catastrophic floods [*Baker and Nummedal*, 1978] (Figure 4f). Many hills seem to be either terraced or layered, or both. This indicates either that the flood had multiple stages, or that it differentially eroded layers to make terraces.

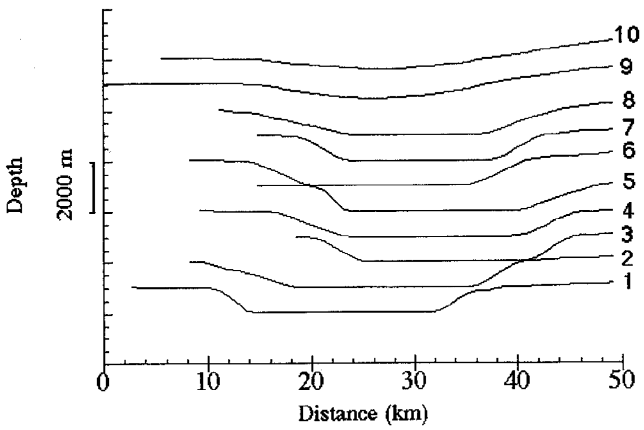

Figure 3b. Cross sections (number of each section is indicated) of Ares Vallis. Sections are numbered from upstream to downstream. Locations are shown in Figure 3a.

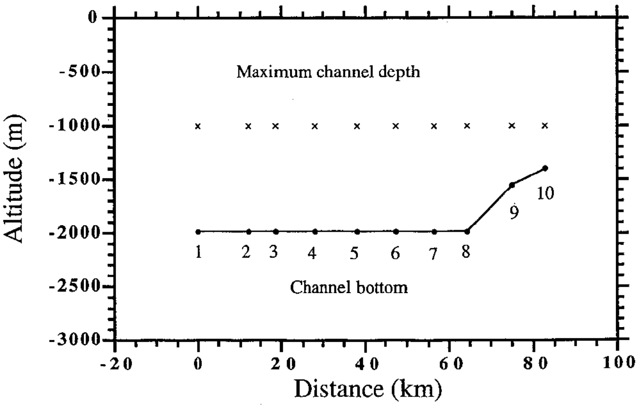

Figure 3c. Longitudinal view of the channel cross sections (number of each section is indicated). Altitude is with respect to the Martian datum. Note that, in this reach, the channel has both steep and gentle slopes.

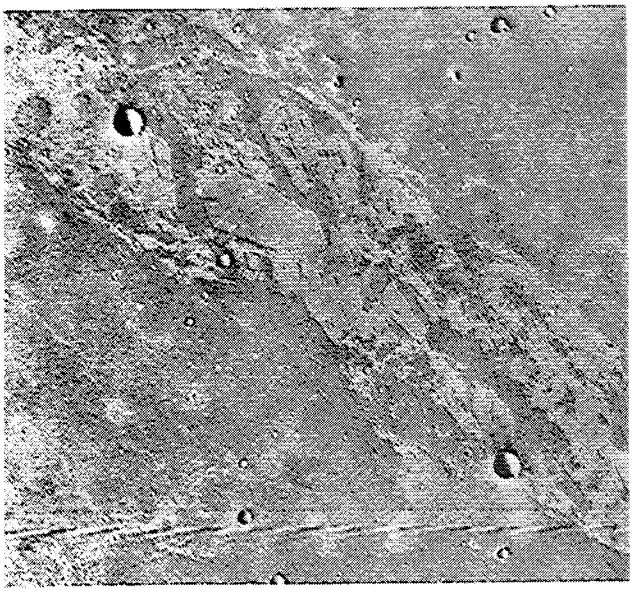

Figure 4a. Mottled terrains. The darker upper strata may have been stripped by the high discharge flow, exposing either lower lighter strata or trapped eolian materials. An alternative explanation is that the darker strata were stripped by eolian processes. Viking frame 4A37. The frame width is approximately 33 km.

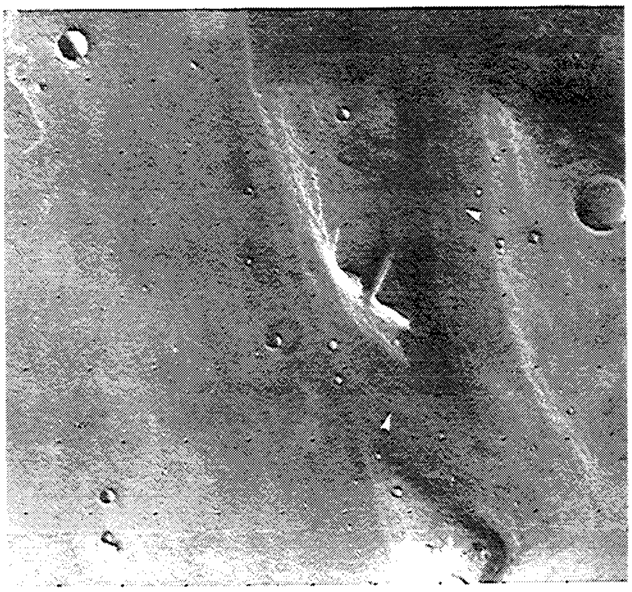

Figure 4c. Grooves (arrows) scoured by the flood flows. Viking frame 4A40. The frame width is approximately 33 km.

Boulders, 1 to 10 m in diameter transported through narrow reaches upstream, may have been deposited in this region [*Komatsu et al.*, 1995]. This scale is close to or smaller than the resolution limit of the highest resolution Viking images. Hills tens of meters to a few hundreds of meters across exist in the region (Figure 4g). Their morphologies and sizes indicate that these hills are probably the erosional remnants of the bedrock, rather than transported boulders, but this point needs more investigation. One to 10 m boulders are transported by the terrestrial catastrophic floods that were at least an order of magnitude smaller than the Ares Vallis paleoflood (Figure 4h). The Ares Vallis floods may have been capable of moving unexpectedly large size boulders by unusual modes of transportation, such as ice rafting. Depositional bars and giant current ripples are also common features observed in association with terrestrial catastrophic floods [*Baker*, 1982; *Baker et al.*, 1993], but preliminary mapping has not identified these features in the study area. Their identification may not be possible at the available resolution. Impact craters compose one of the primary landforms of the region (Figure 4i), and many craters larger than several kilometers in diameter were modified by the floods. Craters up to several kilometers in diameter which seem pristine probably postdate the flood events.

Calculation Results

Narrow reach. The slope between cross sections 1-8 (Figure 3a) could not be resolved within the accuracy of the available topography. We assumed a very low value of 0.0001.

Figure 4b. Scabland landscape along the Columbia Gorge near Blue Lake, formed by the outburst of the Pleistocene glacier Lake Missoula. See roads for scale (photograph by V.R. Baker).

Figure 4d. Longitudinal grooves above Dry Falls. See buildings for scale (photograph by V.R. Baker).

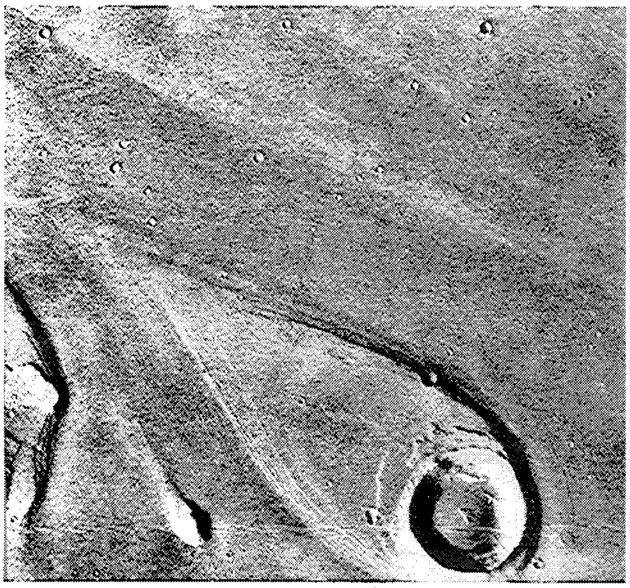

Figure 4e. Streamlined hills with possible terraces. Viking frame 4A50. The frame width is approximately 33 km.

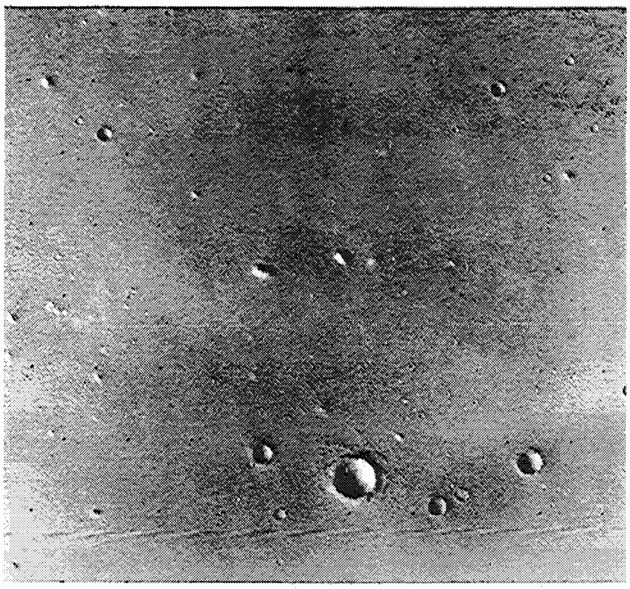

Figure 4g. Hills scattered on the outwash plain. The estimated range of boulder sizes transported in suspension by floods is tens of meters, possibly up to 100 m. This is comparable to the spatial resolution limit. The hills in this frame are larger (up to several hundreds of meters), and these are likely erosional remnants of preexisting terrains. However, the sediment transport for such immense-scale floods is not well understood, and the possibility remains that these hills are transported boulders. Viking frame 4A41. The frame width is approximately 33 km.

Figure 4f. Streamlined hill landscape (within the radar-dark reach) of eastern Washington State near Spokane (European Earth Resource Satellite 1 synthetical aperture radar (SAR) image). Image frame is approximately 50 km wide.

Because high-water marks, such as trim lines and deposits, are not apparent on the available Viking imagery, we assumed that the water surface reached the rims of the channel. We also assumed that the flood did not overflow the rims of the channel because of a lack of apparent erosional and depositional features on the surrounding plains near the channel banks. The peak discharge was calculated for each cross section, and we took the maximum peak discharges at section 1 and section

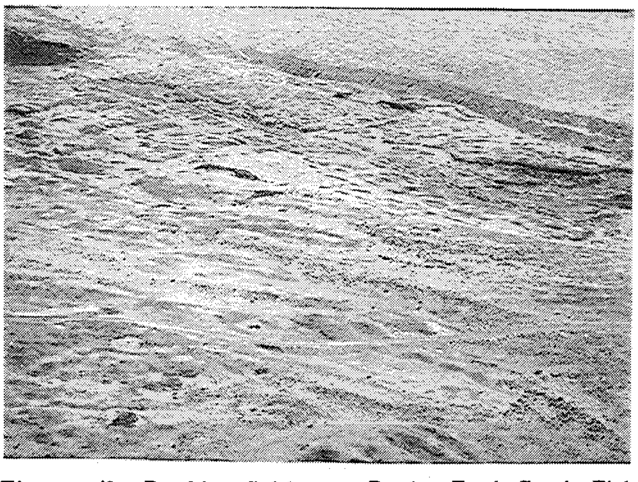

Figure 4h. Boulder field near Rocky Ford Creek Fish Hatchery in the Channeled Scabland. Size of these boulders ranges up to about 20 m (photograph by V.R. Baker).

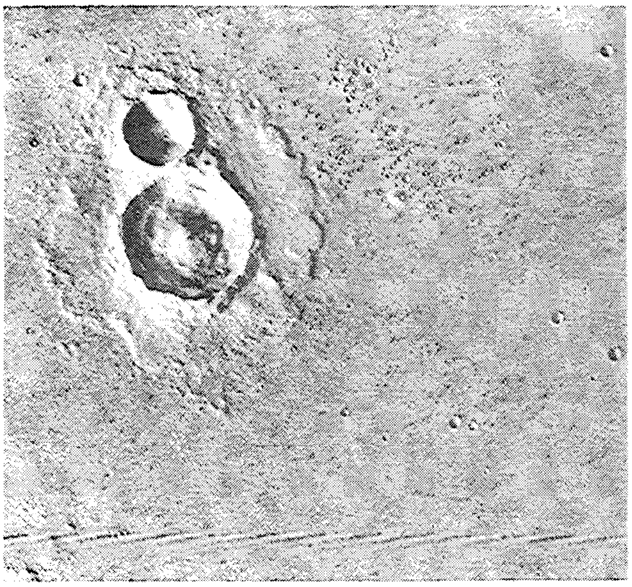

Figure 4i. An impact crater with fluidized ejecta blankets (rampart crater). The crater field (upper center), which is probably a group of secondary craters possibly postdates the flood events. Viking frame 4A47. The frame width is approximately 33 km.

Table 1. Flow Reconstruction Using Manning Equation

	Section 10	Section 1
Manning coefficient	0.032	0.032
Depth, m	398.40	985
Slope	0.02	0.0001
Velocity, m/s	148.91	25.43
Froude number	5.46	0.49
Discharge, 10^9 m^3/s	0.57	0.57

10, which represent the steep and gentle slope sections respectively (Table 1).

The resulting possible maximum peak discharge is 0.57 $x10^9$ m^3/s. This discharge rate is of the same order as the estimates for the Kasei Vallis, the largest Martian outflow channel [*Robinson and Tanaka*, 1990]. For this discharge, the flow velocity ranges from tens of meters per second to over 100 m/s. These flow velocities are also generally consistent with maximum flow velocities estimated by *Craddock and Tanaka* [1995] for the Ares Vallis. The slope they used was 0.0005 and their numbers fall in between our two flow velocities, 25.43 m/s and 148.91 m/s. Note that the slope difference causes a great difference in flow velocity estimate. Froude numbers

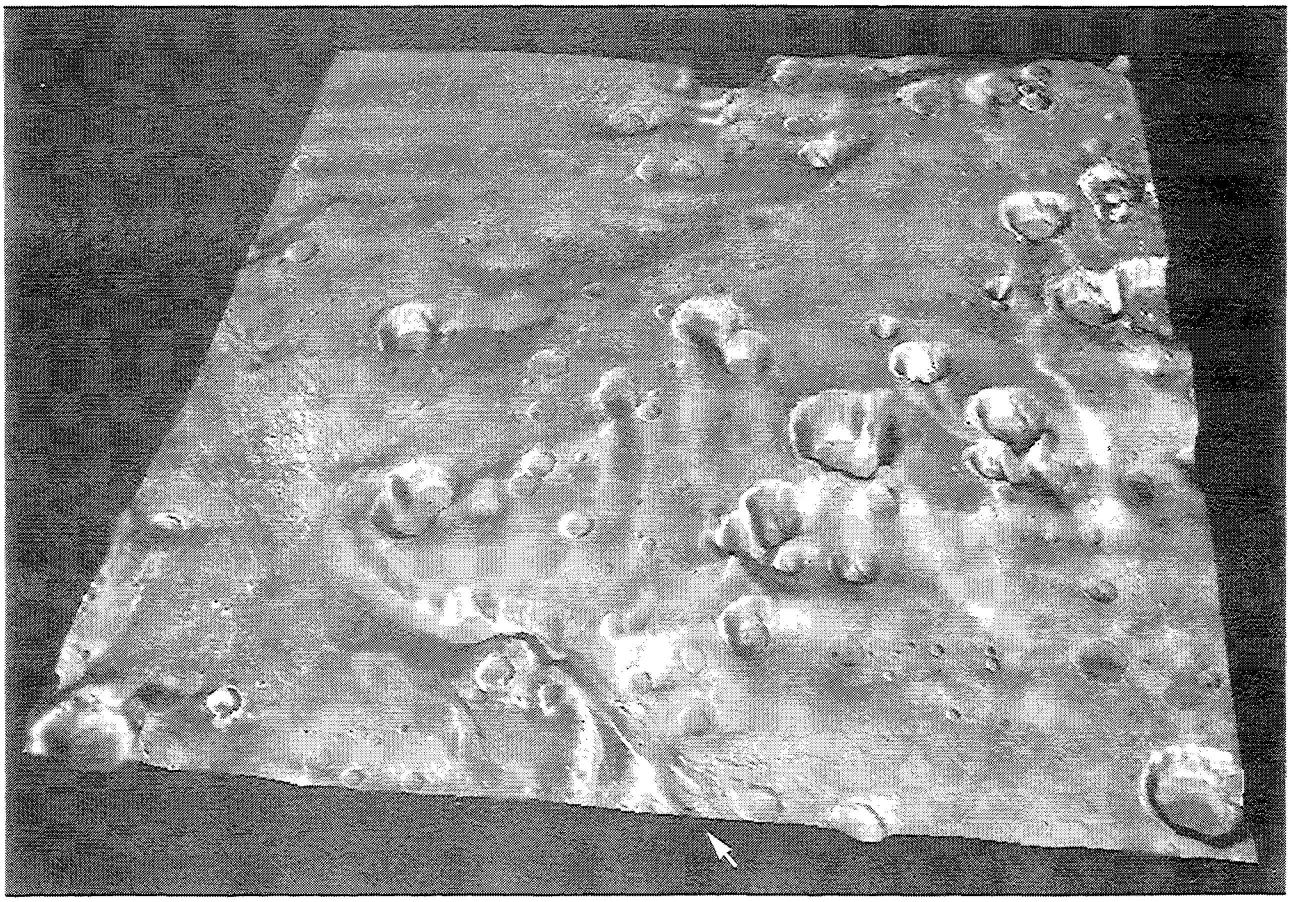

Figure 5. Three-dimensional perspective of a section of Ares Vallis and surrounding regions. This perspective illustrates a topographic barrier which caused diversion and deep incision (~ 1000 m) of Ares Vallis. An arrow indicates flow direction. The reach where the cross sections were derived (Figure 3a) is included in this section. The width of the three-dimensional image is approximately 830 km.

suggest that, at the steep section, the flow was supercritical, and at the less steep section, the flow was subcritical.

We expect that the water may have incised the channel and therefore may not have filled it to the rim. In this case, the discharge could well have been much lower than the estimated peak. Alternatively, the current channel geometry may be somewhat enlarged because of postflooding processes, such as glaciation, wind action, or mass wasting. It is unlikely that such enlargement was very great, since primary flood-erosional forms, including streamlined hills, grooves, and scabland, are all scaled consistently with the channel size, which is about an order of magnitude larger than the largest Earth cataclysmic flood channels. Thus, the extant channel scale, while not precisely limiting the cataclysmic flood paleodischarge values, does pose a reasonable approximation to the largest paleodischarges.

Regardless of the various limitations on the accuracy of the estimate, it is clear that the topography of the narrow reach results in the concentration of extremely high discharges because of a flow constriction. Figure 5 illustrates how this incised, constricted channel, with its locally steep slope, is related to a nearby topographic rise.

Expanding reach. In this reach, the flood levels were estimated to be much lower than those in the constricted section. This is a result of the pronounced expansion of the channel reach. However, the extensive evidence of erosional landforms around the landing site suggests that, even on the outwash fan deposited in this expansion, the peak flood power was still very high. The maximum flow velocity may still have been several tens of meters per second. The total possible maximum discharge rate should have ranged between 10^8 and 10^9 m^3/s, because of flow continuity to the constricted reach. *Craddock and Tanaka* [1995] showed calculations of the flood velocity based on the shear stress inferred from the surface particle size derived from thermal inertia observation made by Viking Infrared Thermal Mapper (IRTM). Their velocity estimate represents the waning state of flooding, since the estimate was made based on the surface particle size. Their estimate also assumed that surface particle size reflects primary flood deposit. The estimated flow velocities are generally less than 1 m/s.

As flow velocity decreases, the sorting of sediments occurs. The sediments transported through constricted reaches will settle on the outwash fan of the expanding reach. Hence, on the outwash fan, it is considered that the largest boulders accumulated near the mouth, and the particle size should have decreased away from the mouth of the channel. As the flood level lowers toward the end of flood event, the sediment transport decreases. This leads to deposition of smaller size particles. As a result, the flood deposit stratigraphy probably displays an upward decrease of particle size. Moreover, the flooding may have occurred in multiple events, which would have caused redistribution of flood deposits.

Sediment Transport

Using criteria proposed by *Bagnold* [1966], *Komar* [1980] estimated the regimes of Martian sediment transport by cataclysmic flood flows. The distinction between suspension and bedload transport was based on Bagnold's comparison of particle settling velocities w_s to vertical velocity components of turbulent eddies. The latter are presumed to correlate to bed shear stress τ,

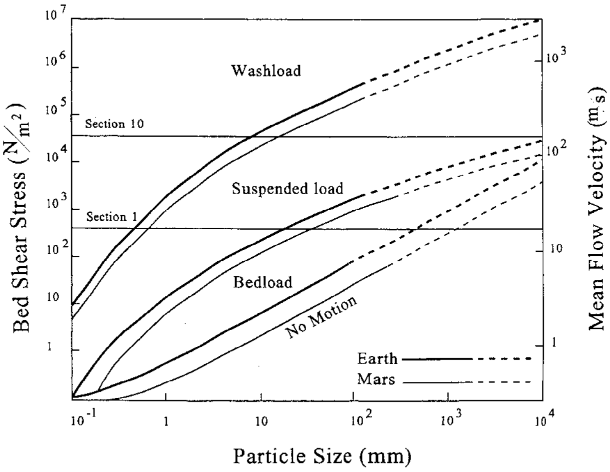

Figure 6. Modes of transport for sedimentary particles in cataclysmic floods. Mars conditions are for silicate particles (quartz, ρ= 2.65 g/cm³), as estimated by *Komar* [1980] from equation (5). Earth conditions are also for silicate particles (quartz, ρ= 2.65 g/cm³), as partially verified for the Bonneville Flood by *O'Connor* [1993]. The extrapolation to sizes larger than 100 mm (dotted lines) is unverified and highly conjectural, as discussed in the text. Flow conditions for the narrow reach of Ares Vallis (Figure 3a) are also indicated.

$$\tau = \rho g R s, \tag{4}$$

where ρ is fluid density, g is gravity, R is hydraulic radius, and s is slope. This is related to settling velocity w_s,

$$\tau = \rho w_s^2 / k^2, \tag{5}$$

where k is a dimensionless parameter, estimated to be 1.25 by *Komar* [1980]. Since w_s is related to particle size, the distinction between suspension and bedload transport can be found for a given particle size or bed shear stress.

Figure 6 gives Komar's results as well as relationships for incipient motion of bed particles (distinguishing bedload from no motion) and autosuspension considerations, used by *Komar* [1980] to distinguish suspended load from washload. The comparable Earth values have been determined and verified by field observations of suspended load transport in the cataclysmic Bonneville flooding [*O'Connor*, 1993]. The results of *Komar* [1980] and *O'Connor* [1993] are extrapolated to particle sizes larger than 100 mm in Figure 6. This extrapolation presumes analogous scaling relationships of the larger particle sizes to flow power as occurring in observed terrestrial examples. There is no way to test this assumption, so the extrapolation must be considered conjectural.

The bed shear stress and associated mean flow velocities of maximum paleoflows in the narrow reach are shown in Figure 6. Note that in the steep section (section 10), particles greater than 10 m in diameter might move in suspension and that even gravel 10 mm in size would be washload. *Komar* [1980] remarked on the latter result as indicative of immense erosional capacity in the Martian outflow channels. In a downstream, gently sloping section (section 1), boulders 1 m in diameter could still be initiated in transport, and cobble/pebble-sized gravel (4-256 mm) could be the suspended load. Large boulders may also have been comminuted because of their fractured zones of weakness and collisions during transport.

Discussion

Flood History

Based on the channel geomorphology and paleohydraulics, it is possible to outline a simplified flood history of the Ares Vallis. From source areas at Iani Chaos (Figure 2a) in the cratered highlands, cataclysmic flood flows ran northwestward (Figures 2b and 2c), following the geopotential gradient. Where the flood water was in more rugged terrains (Figure 5), it was locally confined, and it incised deeply into the heavily cratered upland terrain. When the flow reached the Chryse Planitia, the flood water had to expand, and lost velocity, leading to the deposition of considerable sediment (and presumably of large boulders) at the mouth of the channel. The flood water continued to flow northward, and still was capable of eroding local areas in the vicinity of the Pathfinder landing site, as evidenced by streamlined hills and other erosional features. These hills are about an order of magnitude larger than those in the Channeled Scabland. Finer scale landforms, such as giant current ripples, may have been precluded from forming because of the very high flood power of the immensely scaled Martian floods, even when compared to Earth cataclysmic floods.

As cataclysmic flooding through Ares waned, sediment-carrying capacity would drastically decrease (Figure 6). Large boulders (if available for transport from appropriate outcrops) would be deposited on the floor of the narrow reach described above. Finer particles could readily be conveyed to Chryse Planitia, including the Pathfinder Landing Site. The scale of flooding is consistent with hypothesis of an immense depositional fan at the mouths of the southern Chryse Planitia outflow channels [*Rice and Edgett*, this issue]. The Pathfinder landing site region, which is about 100 km away from the mouth of Ares, must have received considerable sediment deposition, including boulders. Finer-grained sediments, deposited in the waning stages of cataclysmic flooding, would have likely buried this whole sedimentary sequence. Later flooding, emanating from Tiu and Simul Valles to the west, likely modified this original depositional surface. Various postflooding, secondary processes, such as wind erosion and deposition, would have also contributed to channel flood landform development.

The above history is simplified and presented in the context of a single, perhaps prolonged, outflow flooding event. Flooding may well have been repeated, leading to greater complexity in the record.

Implications for Pathfinder Mission

The prime landing site for Mars Pathfinder is in the expanding reach of Ares Vallis [*Golombek et al.*, this issue]. Geological aspects of this area [*Komatsu et al.*, 1995; *Ori et al.*, 1995] will be closely related to paleodischarge characteristics of upstream channel sources. It is likely from the Viking imagery of the landing site area (Figure 2d) that the lander camera will image flood landforms such as streamlined islands, grooves, and scabland. Certainly, these landforms are large enough to be imaged by the camera, if the lander arrives in their proximity, although identifying these landforms correctly can be challenging owing to the relatively small 3-km local horizon [*Smith*, 1994]. The analysis of Viking orbiter IRTM data in the Pathfinder landing ellipse indicates high rock abundance and variable finer particles, such as sand and dust [*Edgett and Christensen*, this issue]. The hydraulics and sediment transport relationships upstream of the landing site suggest that coarse gravel and boulders may well be present, and the finer sediments could have deposited in the waning stage floods. These flood sediments may explain some of the IRTM data [*Rice and Edgett*, this issue]. However, post-flood periglacial activity, impact cratering, and eolian processes may also have fragmented and redistributed these sediments. These processes may well have modified the small-scale landscape (meters to kilometers) that will be imaged by the lander camera.

Conclusions

Ares Vallis is one of the largest and best defined outflow channels on Mars. Based on the available topographic data of the region, including the channel, we estimated the possible maximum peak paleodischarge rates. The range of possible maximum discharge is 10^8-10^9 m^3/s in the narrow, deep constricted reach. This range is at least an order of magnitude greater than the Pleistocene Lake Missoula flood, one of the largest known prehistoric floods on Earth. This range is also comparable to the estimated discharge rates of the Kasei Valles floods. The maximum range of the flood velocity could have exceeded 100 m/s at the deep reach of the channel. This reach was formed by the blocking of the flood flow by a topographic barrier, thereby resulting in deep incision in front of the barrier. Boulders larger than 10 m in diameter could have been transported through the narrow reach and deposited in downstream expansions, perhaps extending as far as the expanding reach where the Mars Pathfinder is proposed to land. Landforms in that expanding reach indicate that flood power was very high. A complex stratigraphic sequence of sediments can be expected because of the flood hydraulics, varying sediment transport characteristics, and likely secondary modification of the primary erosional and depositional flood landforms.

Acknowledgments. This research was funded by the National Aeronautics and Space Administration through the Planetary Geology and Geophysics Program, grant NAGW-285. We thank Gian Ori and Kyle House for aid in the analysis and for constructive discussion. The manuscript was improved through reviews by R. DeHon and K. Tanaka.

References

Bagnold, R.A., An approach to the sediment transport problem from general physics, *U.S. Geol. Surv. Prof. Pap. 422-I*, 1966.

Baker, V.R., Paleohydrology and sedimentology of Lake Missoula flooding in eastern Washington, *Geol. Soc. Am. Spec. Pap. 144*, 1973.

Baker, V.R., A preliminary assessment of the fluid erosional processes that shaped the Martian outflow channels, *Proc. Lunar Planet Sci. Conf., 9th*, 3205-3223, 1978.

Baker, V.R., *The Channels of Mars*, 198 pp., Univ. of Texas Press, Austin, 1982.

Baker, V.R., and D.J. Milton, Erosion by catastrophic floods on Mars and Earth, *Icarus, 23*, 27-41, 1974.

Baker, V.R., and D. Nummedal, *The Channeled Scabland*, 186 pp., Natl. Aeronaut. and Space Admin., Washington, D.C., 1978.

Baker, V.R., G. Benito, and A.N. Rudoy, Paleohydrology of late Pleistocene superflooding, Altay Mountains, Siberia, *Science, 259*, 348-350, 1993.

Carr, M.H., Formation of Martian flood features by release of water from confined aquifers, *J. Geophys. Res., 84*, 2995-3007, 1979.

Carr, M.H., *Water on Mars*, 256 pp., Oxford Univ. Press, New York, 1996.

Costard, F.M., and J.S. Kargel, Outwash plains and thermokarst on Mars, *Icarus, 114*, 93-112, 1995.
Craddock, R.A., and K.L. Tanaka, Estimates of the maximum and minimum flow velocities of the circum-Chryse outflow channels, *LPI Tech. Rep., 95-01*, Part 1, 9-10, 1995.
De Hon, R.A., and E.A. Pani, Duration and rates of discharge: Maja Valles, Mars, *J. Geophys. Res., 98*, 9129-9138, 1993.
Edgett, K.S., and P.R. Christensen, Rocks and aeolian features in the Mars Pathfinder landing site region: Viking infrared thermal mapper observations, *J. Geophys. Res.*, this issue.
Golombek, M.P., R.A. Cook, H.J. Moore, and T.J. Parker, Selection of the Mars Pathfinder landing site, *J. Geophys. Res.*, this issue.
Komar, P.D., Comparison of the hydraulics of water flows in Martian outflow channels with flows of similar scale on Earth, *Icarus, 37*, 156-181, 1979.
Komar, P.D., Modes of sediment transport in channelized water flows with ramifications to the erosion of Martian outflow channels, *Icarus, 42*, 317-329, 1980.
Komatsu, G., and V.R. Baker, Catastrophic flood spillways: comparison of Mars and Earth examples (abstract), *Lunar Planet. Sci. Conf., 27*, 685-686, 1996.
Komatsu, G., V.R. Baker, and J.R. Johnson, Ares Vallis: Flood geomorphology of Mars Pathfinder landing site (abstract), *Lunar Planet. Sci. Conf., 26*, 779-780, 1995.
Mars Channel Working Group, Channels and valleys on Mars, *Geol. Soc. Am. Bull., 94*, 1035-1054, 1983.
O'Connor, J.E., Hydrology, hydraulics, and sediment transport of Pleistocene Lake Bonneville flooding on the Snake River, Idaho, *Geol. Soc. Am. Spec. Pap., 274*, 1993.
O'Connor, J.E., and V.R. Baker, Magnitudes and implications of peak discharges from glacial Lake Missoula, *Geol. Soc. Am. Bull., 104*, 267-279, 1992.
Ori, G.G., G. Komatsu, and V.R. Baker, Geological history of the area surrounding the mouth of the Ares Vallis (Mars) (abstract, *Lunar Planet. Sci. Conf., 26*, 1085-1086, 1995.
Rice, J.W., Jr., and K.S. Edgett, Catastrophic flood sediments in Chryse Basin, Mars, and Quincy Basin, Washington: Application of sandar facies model, *J. Geophys. Res.*, this issue.
Robinson, M.S., and K.L. Tanaka, Magnitude of a catastrophic flood event at Kasei Valles, Mars, *Geology, 18*, 902-905, 1990.
Smith, P.H., Imager for Mars Pathfinder (IMP), *LPI Tech. Rep., 94-04*, 40-41, 1994.
Tanaka, K.L., Sedimentary history and mass flow structures of Chryse and Acidalia Planitiae, Mars, *J. Geophys. Res.*, this issue.

V. R. Baker and G. Komatsu, Department of Geosciences, University of Arizona, Building 77, Gould-Simpson Building, Tucson, AZ 85721. (e-mail: baker@pirl.lpl.arizona.edu)

(Received March 4, 1996; revised July 23, 1996; accepted August 8, 1996.)