Recent aqueous floods from the Cerberus Fossae, Mars

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[1] Streamlined forms and longitudinal grooving seen in Mars Orbital Camera (MOC) images indicate recent aqueous flooding occurred downslope (south) of the southern-most Cerberus Fossae fissure. Topography from the Mars Orbital Laser Altimeter (MOLA), in conjunction with the absence of fluvial features in MOC images immediately to the north of the Fossa, substantiate the idea that floods emanated from this fissure. The floodwater flowed southward onto the western Cerberus Plains, where it probably percolated into existing lava flows. Thus, shallow ice may still be extant beneath young lava flows in this equatorial region. *INDEX TERMS:* 6225 Planetology: Solar System Objects: Mars, 5415 Planetology: Solid Surface Planets: Erosion and weathering, 5480 Planetology: Solid Surface Planets: Volcanism (8450), 5499 Planetology: lid Surface Planets: General or miscellaneous

1. Introduction

[2] The guiding principle in NASA's Mars exploration program, both to understand the planet's geology and to search for past and present life and life environments, is to "follow the water" in all of its phases. Viking imagery showed huge channels having emptied into Chryse Planitia that are generally believed to have been formed by running water [*Baker*, 1982]. These circum-Chryse channels, while extremely impressive, are also quite old (>2 Ga) [*Baker*, 1982, p.38], and in high resolution imagery from the Mars Global Surveyor (MGS), appear heavily modified.

[3] However, Viking imagery also suggested much younger fluvial activity in the western Cerberus Plains [*Tanaka et al.*, 1992; *Edgett and Rice*, 1995]. And images taken by MGS' Mars Orbital Camera (MOC) south of the Cerberus Fossae show well-preserved fluvial geomorphic features and very few craters, indicative of much more recent aqueous flooding (Figures 1A, B, and E).

[4] The Cerberus Plains, located between 0° and 20° N, 150° and 185° E, are a low area just north of the Martian global dichotomy boundary and southeast of Elysium Mons. They are covered by Upper Amazonian lava [*Plescia*, 1990], with some model crater ages as young as a few Ma [*Hartmann and Berman*, 2000]. Stretching from the plains' northwestern edge towards its center are the Cerberus Fossae, a >1000 km long series of subparallel fissures whose morphology suggests formation by volcanic dikes [*Mége and Masson*, 1996]. The Fossae have been inferred to be the main source for the lavas [*Plescia*, 1990; *Keszthelyi et al.*, 2000], and MOC images show them to be the source for at least small recent lava flows (Figure 1C). A channel, previously named Athabasca Vallis, stretches southwestward from the western Cerberus Fossae (Figure 2). Smaller channels branch southward from it, and we will herein refer to the entire channel system as Athabasca Valles. Striking morphologies that strengthen the case for aqueous floods on Mars in the recent geologic past are found throughout Athabasca Valles.

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2. Geomorphic Evidence for Aqueous Flooding South of the Cerberus Fossae

[5] The most distinctive evidence for aqueous flooding is the presence in the channels of streamlined mesas, i.e. flat-topped, topographically higher landforms that have a "tear-drop" shape in planview in which their rounded ends point up slope and their pointed ends down slope (Figures 1A, B). This shape, like the cross-section of an airfoil, minimizes drag in fluid flow and is similar to the shape of streamlined features in the Channeled Scabland in the northwestern United States, formed by catastrophic outflow of glacial meltwater [see *Baker*, 1982, Chapters 7 and 8 for a summary.] These features rise approximately 100 meters above the surrounding channel floors at their upslope ends. The flat upper surfaces support an aqueous origin rather than a glacial one; drumlins or ice rises, although streamlined by ice flow in planview, display an arcuate upper surface highest towards the middle. These Athabasca Valles streamlined mesas are a few hundred to a few thousand meters long. Most are truncated by the edge of 3-km wide MOC frames, but some are discernable in Viking imagery. In width, the mesas range from a few hundred up to a thousand meters.

[6] Most of these streamlined mesas show fine, horizontal layering (Figures 1A, B and D), similar to that described by *Malin and Edgett* [2000]. The layers are clearly visible around the mesas' edges and on their upper surface, by means of which the surface steps gently downward to the rear (Figures 1A, B). Each mesa has a dozen or more layers, each layer standing about 10 meters high, However, the accuracy of this measurement is limited by MOC image resolution (typically 3–6 meters/pixel); there may be many thinner layers and benches. In some instances, large craters are still extant on the upslope sides and would have provided structural obstacles in a fluid flow (e.g., Figure 1B). In other instances, obstacles are less determinate, such as the ridge at the upslope end of the form in Figure 1A, perhaps a remnant rim from an eroded crater. The layering that composes the mesas, in conjunction with the obstacles at their upslope end, suggests mesa formation either by erosion during flow over pre-existing layered terrain, or by episodic deposition during flow in the lee of an obstacle. The mesas' flat upper surfaces in contrast with rougher terrain surrounding the channels support the latter mechanism more strongly. Some mesas show smaller protrusions on top, possibly boulders left by winnowing during wanning stage flow.

[7] More irregular streamlined features are also apparent in a smaller channel that branches southward (Figure 1E). These features also have higher, more rounded ends oriented up the slope and lower, more pointed tails oriented down the slope, but there are differences between these forms and the streamlined mesas. These forms do not have flat upper surfaces, and the upper surfaces do not slope monotonically in the downstream direction. The plan-

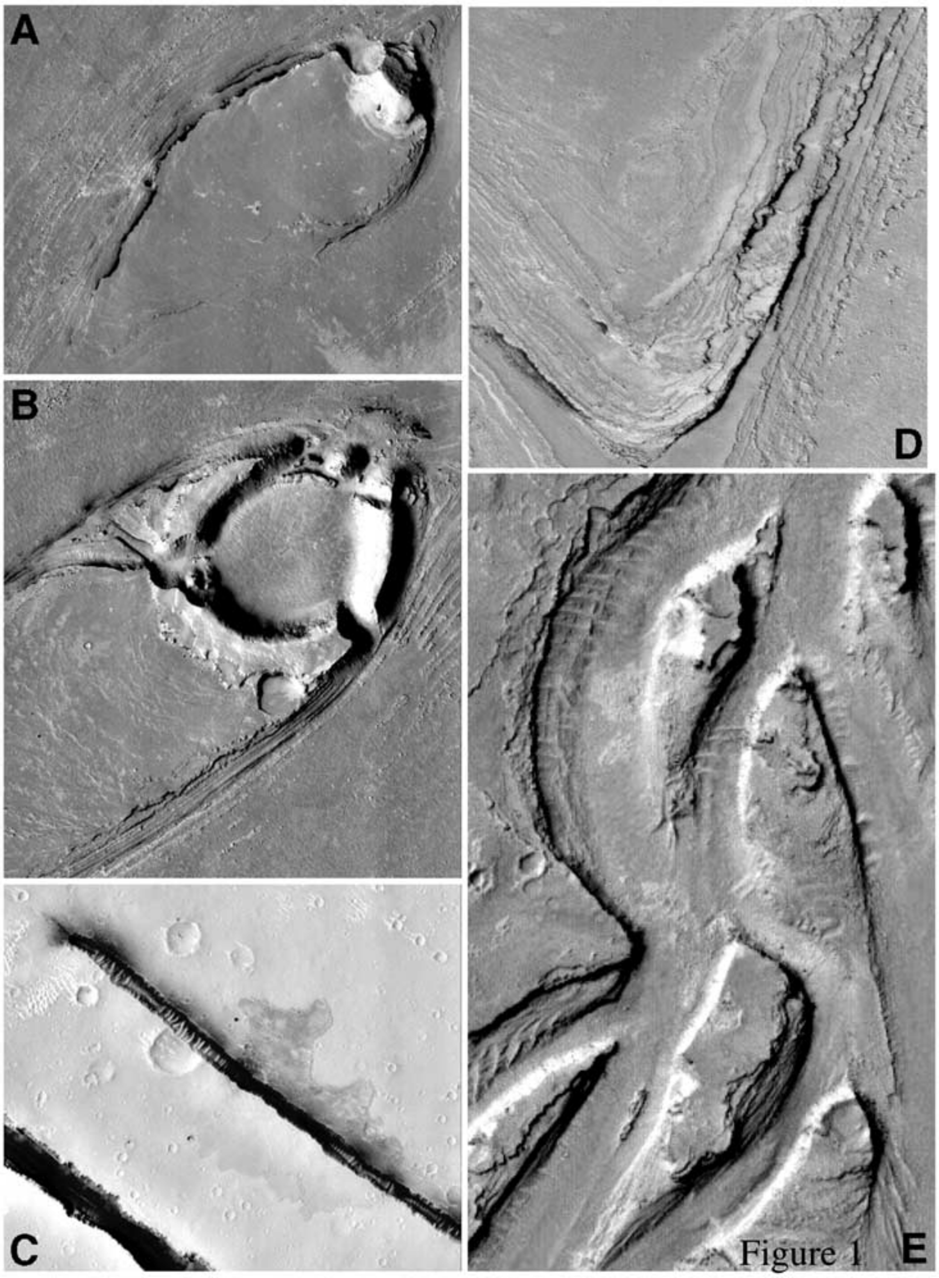

Figure 1. MOC images of Cerberus Fossae and associated channels. A–C are 3 km across, D is 1.5 km across, E is 1.25 km across. North is about 10 degrees right of up; illumination is from the left. A) Portion of M07-00614, (9.66° N, 155.81° E). Streamlined mesa with rounded, topographically higher end pointing upslope (to the right) and pointed, lower end down slope. The mesa slopes gradually downward via thin terracing. Longitudinal grooving is apparent to the north. Inferred flow towards the southwest. B) Portion of M07-00614. Streamlined mesa with similar orientation and terracing. Crater sits at upslope end; mesa formation is hypothesized to be by deposition in its lee during flood flow. C) Portion of M02-01973, (10.35° N, 156.20° E), showing extrusion of lava from Cerberus Fossae as indicated by arrows. D) Portion of M11-00331, (8.98° N, 155.61° E). Down slope end of streamlined mesa showing multiple fine layers. E) Portion of M21-01914, (7.89° N, 153.95° E). Multiple features in a channel southwest of Cerberus Fossae that show streamlining, terracing and rearward-facing slopes, but of a more irregular nature than in sub-Figures A and B. Formation is hypothesized to be by erosion of layered terrain.

view outline of these features is rougher and less axially symmetric than that of the streamlined mesas. These features do show layering, but it does not appear as uniform as the layers in the more symmetric, regular streamlined mesas. These differences suggest formation by a different mechanism, perhaps by fluvial erosion of pre-existing layered terrain.

[8] The channel floor surrounding the streamlined mesas is often lined with grooves interspersed with ridges (Figures 1A, B) which run parallel to the edges of the streamlined mesas or to the channels walls. These grooves are about 100 meters wide and 10 meters deep. As these features have sometimes been embayed with thin, dark lava, this depth is a minimum for that at the time of formation. This width:depth ratio of approximately 10:1 is similar to that of the longitudinal grooving in the Channeled Scabland, which is formed by longitudinal vortices [*Baker*, 1982]. Collectively, the grooving near the Cerberus Fossae can be quite

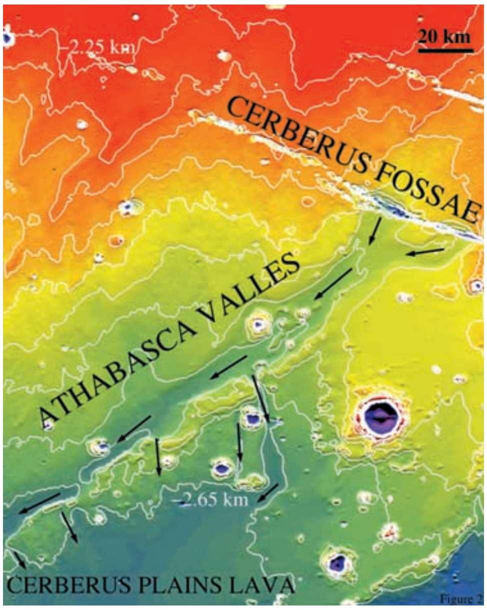

Figure 2. MOLA topography between 7° and 12° N, 153.5° and 157.5° E (202.5° and 206.5° W). Main channel slopes from Cerberus Fossae to the southwest; smaller channels drop southward. Arrows show location of channels and inferred flow directions. Contour interval is 50 meters. Interpolated scale is 256 pixels/°.

extensive, covering over 100 km^2 in a single image (e.g., M02-00581), although individual ridges generally fade out within a few hundred meters. The grooving is parallel to the channel gradient as indicated by MOLA topography, and was formed by a process sensitive to the surface, as indicated by its flow around impact craters.

[9] We outlined above reasons to suppose that the streamlined mesas are depositional behind structural flow obstacles. An alternative hypothesis for at least some of these features is suggested by the northern streamlined mesa in MOC image M11-00331. This form does not have an upstream obstacle and likewise lacks longitudinal grooving in the surrounding channel floor, but otherwise resembles the streamlined mesas in Figures 1A and B. Indeed, the floor shows lava fill with plates separated by 10-meter scale ridges extending underneath the mesa. Thus, the lava must have pre-existed the streamlining. The pre-flood existance of the ridged lava, and its largely unmodified existance afterward, suggest the following scenario: deposition of lava; deposition of layered, possibly weaker material; flooding, which eroded some of this layered, possibly weaker material into a streamlined form; cessation of the flooding before erosion modified the more endurate lava ridges.

3. Discharge Estimate

[10] Assuming a fluvial origin, we can estimate the peak discharge of Athabasca Vallis (Figure 2) with Manning's equation modified by Carr for Martian gravity [see *Baker*, 1982, p. 161.] The slope, channel width and channel depth are derived from the MOLA topography [Figure 2; *Neumann et al.*, 2001]. With a Manning's n value of 0.04, consistent with modeling both the Channeled Scabland and the Snake River floods over lavas [*Baker*, 1982, p. 145–146], the estimated peak discharge, assuming bankfull flow, was 1–2 million cubic meters per second (m^3/s). The cumulative quantity of water released is difficult to estimate; large glacial terrestrial floods help in understanding flood geomorphology, but data on peak discharge, duration and hydrograph shape of floods from volcanically active fissures is unknown to us. Because of this lack of terrestrial data, our calculcations on this issue are somewhat arbitary. However, if we assume a triangular hydrograph with a peak discharge of 2 million m^3/s and a duration of 1 week, then a cumulative quantity of about 600 km^3 of water was released.

4. Source of the Flood Water

[11] The presence or absence of fluvial geomorphic features in MOC images and the major channel seen in MOLA gridded topography together indicate the source of the water to have been the Cerberus Fossae. The fluvial features discussed above were all seen in images taken southward, or down slope, of the Cerberus Fossae. Conversely, no fluvial features are apparent in the images available to date immediately northward of the fractures. The MOLA topography shows Athabasca Vallis originating at the Cerberus Fossae and continuing down slope to the southwest, an orientation apparently controlled by Elysium Mons wrinkle ridges (Figure 2; see also Viking frame 385S42 and several MOC images). Other examples of fluvial channels emanating from structural features have been described at Mangala Vallis [*Tanaka and Chapman*, 1990] and for young channels in northwest Tharsis [*Mouginis-Mark*, 1990].

[12] The Cerberus Fossae fissures (Figure 1C) have very sharp edges and steep slopes (>80° indicated by shadows and viewing geometry in M04-03770) and cut sparsely-cratered plains (e.g., M07-03839). Thus, although their structural trend is also observed in remnant ancient highland terrain [*Tanaka et al.*, 1992], we deduce the fissures to have been recently reactivated. That they appear to have been the source, not only of recent lava flows, but also of recent voluminous aqueous flooding, supports a causative relationship between the two types of flows, such as a scenario in which rising dikes melt ground ice [e.g., *McKenzie and Nimmo*, 1999] and open pathways to the surface. By analogy, the easternmost Cerberus Fossae could have been the main source for the larger aqueous floods down Marte Vallis [*Tanaka et al.*, 1992], although geomorphic and topographic evidence may now be largely buried beneath Cerberus Plains lavas.

5. The Fate of the Flood Water

[13] Down slope the channels disappear under younger Cerberus Plains lavas a few tens of meters thick. But, as the total thickness of Cerberus Plains lava is a few hundred meters [*Plescia*, 1990], the floodwater must have debouched onto lava. The channels may be only slightly older than the younger lavas embaying their distal ends, lavas with model crater ages as young as 10 Ma [*Hartmann and Berman*, 2000]. 600 km^3 of water is less than a few percent of the volume of the Cerberus Plains lava. Much or all of the discharge from these channels could be stored in the lavas if the interconnected porosity (from fractures, lava tubes, etc.) were just a few percent and the infiltration rate along the channels sufficiently high. Fresh lava flows provide the most permeable natural terrains on Earth, and processes that reduce the permeability over time (e.g., weathering to clays, carbonate cementation) may operate very slowly on Mars. Thus, it is plausible that much or all of the water infiltrated into the Cerberus Plains, where some of it may still reside.

[14] Geomorphic evidence for the infiltration of the flood water into the Cerberus Plains exists in the form of rootless cones just southward of where the channels disappear beneath the lava. *Lanagan et al.* [2001] document the regional distribution of the cones and discuss the necessity for their formation of groundwater or ground ice within about 5 meters of the surface when the lavas were emplaced. If the lavas are as young as the model crater ages of *Hartmann and Berman* [2000], then the ground ice is probably

still present at shallow depths beneath the more recent lava, or perhaps closer to the surface near the preserved channels.

6. Conclusion

[15] The western Cerberus Plains are an attractive site for future landed exploration of Mars. MGS observations show geomorphology and topography substantiating the idea that large quantities of water flowed across the plains during the very recent geologic past. The water appears to have originated from the Cerberus Fossae and debouched onto the permeable lavas where it may persist as shallow ground ice. Previous workers concluded that near-surface ice is probably only present at high latitudes [*Squyres et al.*, 1992] but equatorial regions are more amenable to future landed exploration. Furthermore, the streamlined mesas may be comprised of sediments from inside the Cerberus Fossae, and could preserve information on recent geothermal activity. Both shallow ground ice and geothermal deposits are important targets in the search for a record of Martian life [*Farmer and Des Marais*, 1999].

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References

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

Edgett, K. S., and J. R. Rice Jr., Very young volcanic, lacustrine and fluvial features of the Cerberus and Elysium Basin region, Mars: Where to send the 1999 Mars Surveyor Lander (abstract), *Lunar Planet. Sci. Conf., 26th*, 357–358, 1995.

Farmer, J. D., and D. J. Des Marais, Exploring for a record of ancient Martian life, *J. Geophys. Res.*, *104*(E11), 26,977–26,995, 1999.

Hartmann, W. K., and D. C. Berman, Elysium Planitia lava flows: crater count chronology and geological implications, *J. Geophys. Res.*, *105* (E6), 15,011–15,025, 2000.

Keszthelyi, L. P., A. S. McEwen, and Th. Thordarson, Terrestrial analogs and thermal models for Martian flood lavas, *J. Geophys. Res.*, *105*(E6), 15,027–15,049, 2000.

Lanagan, P. D., A. S. McEwen, L. P. Keszthelyi, and Th. Thordarson, Rootless cones on Mars indicating the presense ofshallow equatorial ground ice in recent times, *Geophys. Res. Lett.*, *28*(12), 2365–2367, 2001.

Lucchitta, B. K., Antarctic ice streams and outflow channelson Mars, *Geophys. Res. Lett.*, *28*(3), 403–406, 2001.

Malin, M. C., and K. S. Edgett, Sedimentary rocks of early Mars, *Science*, *290*, 1927–1937, 2000.

McKenzie, D., and F. Nimmo, The generation of martian floods by the melting of ground ice above dykes, *Nature*, *397*, 231–233, 1999.

Mége, D., and P. Masson, A plume tectonics model for the Tharsis province, Mars, *Planet. Space Sci.*, *44*, 1499–1546, 1996.

Mouginis-Mark, P. J., Recent water release in the Tharsis region of Mars, *Icarus*, *84*, 362–372, 1990.

Neumann, G. A., D. D. Rowlands, F. G. Lemoine, D. E. Smithand, and M. T. Zuber, The crossover analysis of Mars orbital LaserAltimeter data, *J. Geophys. Res.*, in press, 2001.

Plescia, J. B., Recent flood lavas in the Elysium region of Mars, *Icarus*, *88*, 465–490, 1990.

Squyres, S. W., S. M. Clifford, R. O. Kuzmin, and F. M. Costard, Ice in the Martian regolith, in *Mars*, (H. H. Kieffer et al., Eds.), pp. 523–556, University of Arizona Press, Tucson, Arizona, 1992.

Tanaka, K. L., and M. G. Chapman, The relation of catastrophic flooding of Mangala Valles, Mars, to faulting of Memnonia Fossae and Tharsis volcanism, *J. Geophys. Res.*, *95*, 14,315–14,323, 1990.

Tanaka, K. L., M. G. Chapman, and D. H. Scott, Geologic map of the Elysium region of Mars, *U.S. Geol. Surv. Map I-2147*, 1992.

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