

## Volcanic rilles, streamlined islands, and the origin of outflow channels on Mars

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[1] The widely accepted view that catastrophic flow of liquid water was the dominant process involved in formation of outflow channels on Mars has as part of its foundation the assumption that the flow of lava could not have formed Martian features such as streamlined islands and anastomosing channels. However, lunar and Venusian channels, believed to have formed through volcanic processes in the absence of water, are indeed associated with such features. Additionally, many lunar and Venusian rilles head at topographic depressions, a common characteristic of Martian outflow channels. Lunar rilles typically lack positive relief accumulations of volcanic deposits at their mouths, suggesting that contrary to previous assertions, absence of such accumulations at the mouths of Martian outflow channels is not incompatible with a common mode of formation. Consistent with an igneous origin for outflow channels and certain valley systems on Mars, volcanic processes can produce a wide range of landforms that are similar to those normally associated with the flow of water, including channel terraces and complex channel networks. The simplest interpretation of Martian channels that extend from volcanic source regions onto volcanic plains is as conduits formed by the flow of lava. Channel formation hypotheses requiring major changes in Martian atmospheric properties or repeated catastrophic flow of water from volcanic features appear needlessly exotic alongside the igneous hypothesis for channel formation. In light of these points, future investigations of Martian outflow channels should more actively consider volcanic processes as candidate mechanisms for channel formation. *INDEX TERMS*: 5415 Planetology: Solid Surface Planets: Erosion and weathering; 5480 Planetology: Solid Surface Planets: Volcanism (8450); 5470 Planetology: Solid Surface Planets: Surface materials and properties; *KEYWORDS*: channel, Mars, volcanism

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### 1. Introduction

[2] Martian outflow channels, first clearly recognized in images generated by the Mariner 9 mission, are widely interpreted as having necessarily formed in association with water [e.g., McCauley *et al.*, 1972; Masursky, 1973; Milton, 1973; Sagan *et al.*, 1973; Mars Channel Working Group, 1983; Baker *et al.*, 1992a; Carr, 1996; Coleman, 2003]. The most favored process of channel formation is catastrophic aqueous flooding [e.g., Masursky, 1973; Baker and Milton, 1974; McCauley, 1978; Baker, 1979; Mars Channel Working Group, 1983; Baker *et al.*, 1992a; Carr, 1996], although other aqueous and nonaqueous processes have been proposed such as glacial flow [Lucchitta and Anderson, 1980; Lucchitta, 1982], mass flow [Nummedal, 1978; Nummedal and Prior, 1981], lava flow [Carr, 1974; Schonfeld, 1977; Cutts *et al.*, 1978], eolian processes [Cutts and Blasius, 1981], and the flow of carbon dioxide [Hoffman, 2000; Tanaka *et al.*, 2002]. A limited role for

igneous processes in the initiation of formation of many channels has been recognized, as in the melting of large volumes of near-surface water during dike emplacement [e.g., Masursky *et al.*, 1977; Tanaka and Chapman, 1990; Baker *et al.*, 1992a; Wilson and Head, 2002; Wilson and Mouginis-Mark, 2003; Head *et al.*, 2003; Manga, 2004], but the flow of lava has been rejected as a viable or likely process in the formation of Martian outflow channels [e.g., Mars Channel Working Group, 1983; Baker *et al.*, 1992a].

[3] Cited problems with the volcanic hypothesis for outflow channel formation include the apparent absence of large accumulations of volcanic materials at the mouths of Martian channels, a belief that the flow of lava cannot form anastomosing channels, and a perceived lack of volcanic sources at the heads of channels [Carr, 1974, 1996; Baker *et al.*, 1992a]. Rejection of a channel-forming role for lava flows has rested most heavily on the assumption that the dominance of accretionary and constructive processes in the flow of lava excludes the possible action of erosive processes necessary for formation of channel features such as streamlined islands [e.g., Baker, 1978a; Baker and Kochel, 1978, 1979; Mars Channel Working Group, 1983].

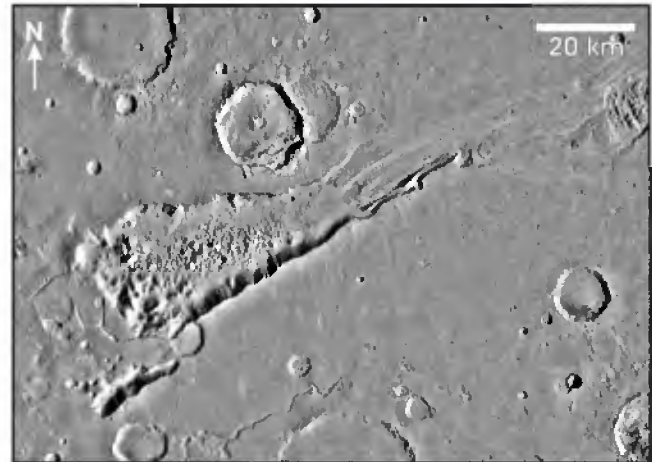
[4] On the Moon, large volumes of basalt are known to have been emplaced by low-viscosity lava flows [e.g., *Head, 1976*], and although many lunar flow units lack obvious channels and source regions [e.g., *Whitford-Stark, 1982; Wilhelms, 1987*], others are associated with clear sources and associated distributary channels [e.g., *Greeley, 1971a; Zisk et al., 1977; Strain and El-Baz, 1977*]. Some of these lunar channels have been used in the past in the assessment of possible roles for flowing lava in formation of Martian channels [*Masursky, 1973; Carr, 1974*], resulting in determinations that at least some Martian channels of relatively simple morphology were likely formed through volcanic processes. Recent studies have suggested that some channels associated with sites of purported ancient Martian lakes show morphological and contextual affinities not with terrestrial fluvial landforms but with lunar volcanic rilles [*Leverington and Maxwell, 2004; Leverington, 2004*].

[5] Venus is characterized by a wide variety of volcanic features, extensive volcanic plains, and several classes of channels [e.g., *Head et al., 1992; Guest et al., 1992; Baker et al., 1992b*]. The flow of low-viscosity lava on Venus is believed to have produced both simple sinuous rilles and complex channel networks, including a prominent outflow channel associated with large streamlined islands [e.g., *Baker et al., 1992b; Head et al., 1992; Baker et al., 1997*]. Venusian lava channels share many attributes with Martian outflow channels [*Baker et al., 1992b, 1997*], and although it has been speculated that these channels may owe their existence to a combination of surface conditions and materials that is unique to Venus [e.g., *Baker et al., 1992b; Kargel et al., 1994*], their value as possible analogs for Martian channels remains clear. In this paper, lunar and Venusian landforms are used to suggest that limitations previously placed on the competence of lava flows to form Martian outflow channels may not be valid and that future studies of Martian outflow channels should more actively consider the flow of lava as a candidate mechanism for channel formation.

## 2. Outflow Channels on Mars

[6] Martian outflow channels may be broadly defined as relatively large channels that head in regions of chaotic or otherwise disturbed terrain, merge downstream with plains units, and have characteristics suggestive of fluid erosion [*Mars Channel Working Group, 1983*], although some features commonly designated as outflow channels lack one or more of these characteristics. For the purposes of this paper this definition will be taken to include channels such as Mangala Valles, Ma'adim Vallis, and the large channels of Elysium and eastern Hellas [e.g., see *Carr, 1995*] in addition to major outflow channels such as Ares Vallis. The outflow channels of Mars are generally located equatorward of  $\pm 30^\circ$  latitude [*Mars Channel Working Group, 1983*] and are characterized by a variety of sizes, morphologies, ages, and relationships with surrounding terrain features [e.g., *Masursky et al., 1977*]. The largest outflow channel system, Kasei Valles, has a length of  $\sim 3000$  km and maximum width of  $\sim 230$  km.

[7] The attributes of individual outflow channels are variable: Some channels have features such as large tributaries or streamlined bed forms, whereas others do not; some



**Figure 1.** Aromatum Chaos and Ravi Vallis, Mars ( $\sim 43^\circ 8'W$ ,  $1^\circ 7'S$ ; Viking Mars Digital Image Model mosaic). The outflow channel feeds into Hydraotes Chaos, ultimately extending onto the plains of Chryse Planitia through Simud Vallis and Tiu Vallis. Illumination is from the right.

channels originate from very broad regions, whereas others originate more locally [e.g., *Milton, 1973; Sharp and Malin, 1975; Masursky et al., 1977; Carr, 1981; Mars Channel Working Group, 1983; Tanaka and Chapman, 1990; Zimbelman et al., 1992; Baker et al., 1992a; Komatsu and Baker, 1997; Nelson and Greeley, 1999; Burr et al., 2002*]. The largest outflow channels typically commence abruptly and at full width in regions of chaotic terrain (Figures 1 and 2) and are associated with features such as streamlined islands [e.g., *Baker, 1978a; Baker and Kochel, 1978, 1979*] (Figure 3) and longitudinal grooves [e.g., *Baker and Milton, 1974; Baker, 1978a; Carr, 1979; Baker and Kochel, 1979*] (Figure 2). Most of the largest outflow channels head in regions adjacent to Chryse Planitia [e.g., *Carr et al., 1973; Mars Channel Working Group, 1983; Baker et al., 1992a*]. Smaller channels located elsewhere on Mars, such as Dao Vallis and Harmakhis Vallis in eastern Hellas [e.g., *Crown and Greeley, 1993*] (Figure 4) and the channels of Elysium [e.g., *Wilson and Mouginiis-Mark, 2003*] (Figure 5), share many of the characteristics of the largest outflow channels, including abrupt commencement at topographic depressions and association with features such as streamlined islands.

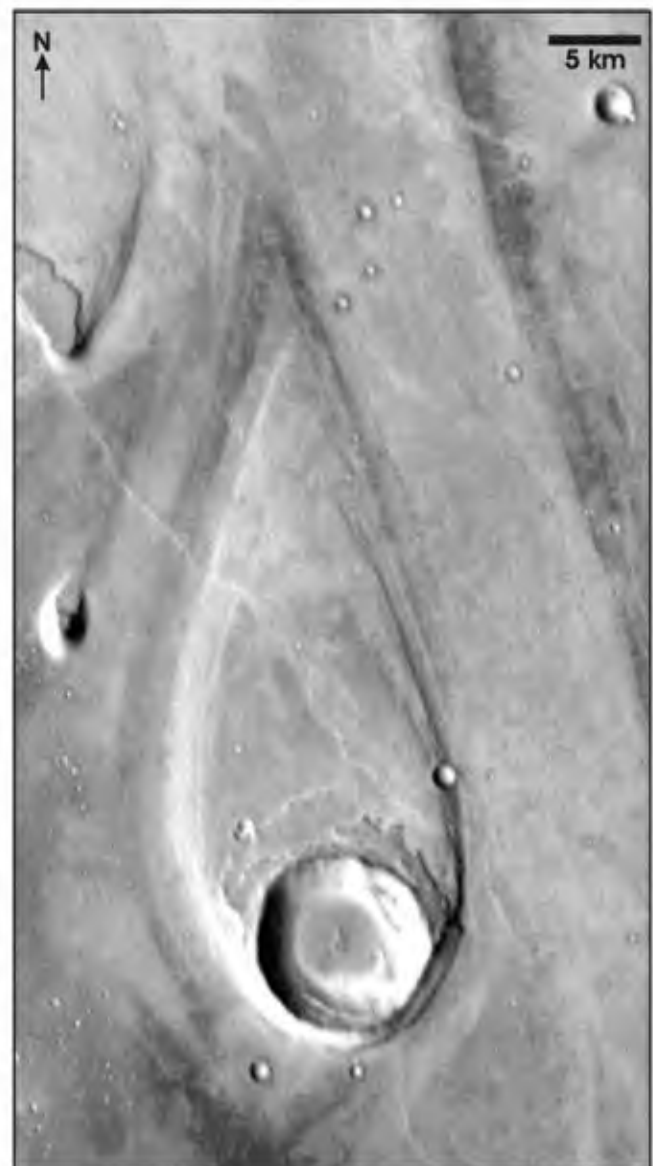
[8] The anastomosing reaches of some Martian outflow channels have been interpreted as strong evidence in support of aqueous origins [e.g., *McCauley et al., 1972; Masursky, 1973; Milton, 1973*]. On the basis of their strong morphological similarity to terrestrial features known to have been produced by catastrophic floods [see, e.g., *McCauley et al., 1972; Milton, 1973; Baker and Milton, 1974; Baker, 1978b*], streamlined features of Martian outflow channels are believed to have formed by relatively rapid releases of large volumes of groundwater [e.g., *Masursky, 1973; Milton, 1973; Baker and Milton, 1974; Masursky et al., 1977; Baker, 1978a, 1979; Mars Channel Working Group, 1983; Baker et al., 1992a; Baker, 2001; Coleman, 2003; Manga, 2004*]. Determination of realistic mechanisms by which these floods might have occurred has been problematic, however. It has been recognized, for example, that the volumes of water that



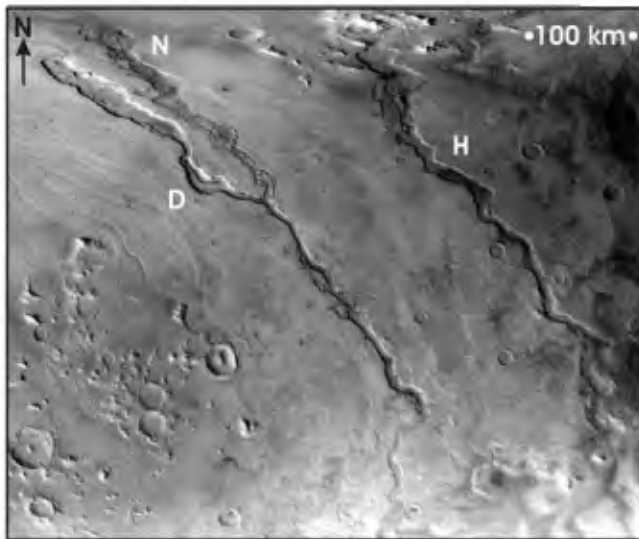
**Figure 2.** An outflow channel that emerges from chaotic terrain associated with Shalbatana Vallis (middle of image at  $12^{\circ}31'N$ ,  $42^{\circ}16'W$ ; Thermal Emission Imaging System (THEMIS) daytime thermal frame I05082023). This channel ultimately extends onto the plains of Chryse Planitia. Illumination is from the left.

could have been produced solely from regions of chaos at the heads of many Martian channels would likely have been insufficient to form the outflow channels, necessitating multiple releases of large volumes of water [e.g., Baker, 1982; Baker *et al.*, 1992a; Manga, 2004]. It seems that in order to have taken place these releases would have required the existence of unusual conditions at and near the Martian surface, such as (1) a global cryosphere that could be locally and repeatedly breached and confined regional aquifers that could supply and convey large amounts of water under high artesian pressures to breached areas [e.g., Carr, 1979; Clifford, 1993; Clifford and Parker, 2001] or (2) large surface lakes from which water could be repeatedly released catastrophically [e.g., McCauley, 1978; Robinson and Tanaka, 1990; Scott *et al.*, 1992].

[9] The view that the flow of lava could not have formed the features of outflow channels of Mars has ultimately been



**Figure 3.** Streamlined island located at the mouth of Ares Vallis at  $\sim 20^{\circ}12'N$ ,  $31^{\circ}15'W$  (THEMIS daytime thermal frame I02560002). Illumination is from the left.



**Figure 4.** Oblique view of Martian outflow channels Dao Vallis (D) and Harmakhis Vallis (H), located in eastern Hellas on the flanks of Hadriaca Patera and Tyrrhena Patera (Mars Orbiter Camera wide-angle frame M1900826) [e.g., *Crown and Greeley, 1993*]. Niger Vallis (N) joins Dao Vallis near the middle of the image (middle of image is at  $\sim 271^{\circ}18'W$ ,  $38^{\circ}S$ ). Scale is valid only in the top right corner of the image. Illumination is from the left.

founded upon the assumption that the nature of these features is indicative of [*Milton, 1973, p. 4040*] “active erosion of material, which would not be accomplished by lava” [see also *Mars Channel Working Group, 1983; Baker et al., 1992a*]. Additional assumptions said to invalidate the volcanic hypothesis for formation of outflow channels include the following: (1) Lava channels should have obvious depositional features at their mouths, (2) lava channels are unlikely to form as parts of complex flow networks, and (3) Martian outflow channels head in regions that lack obvious volcanic sources [e.g., *Mars Channel Working Group, 1983; Gulick and Baker, 1990; Baker et al., 1992a; Carr, 1996*]. In sections 3 and 4, examples of lunar and Venusian features formed by the flow of lava are used to suggest that the above assumptions may not be valid.

### 3. Lunar Analogs for Martian Channels

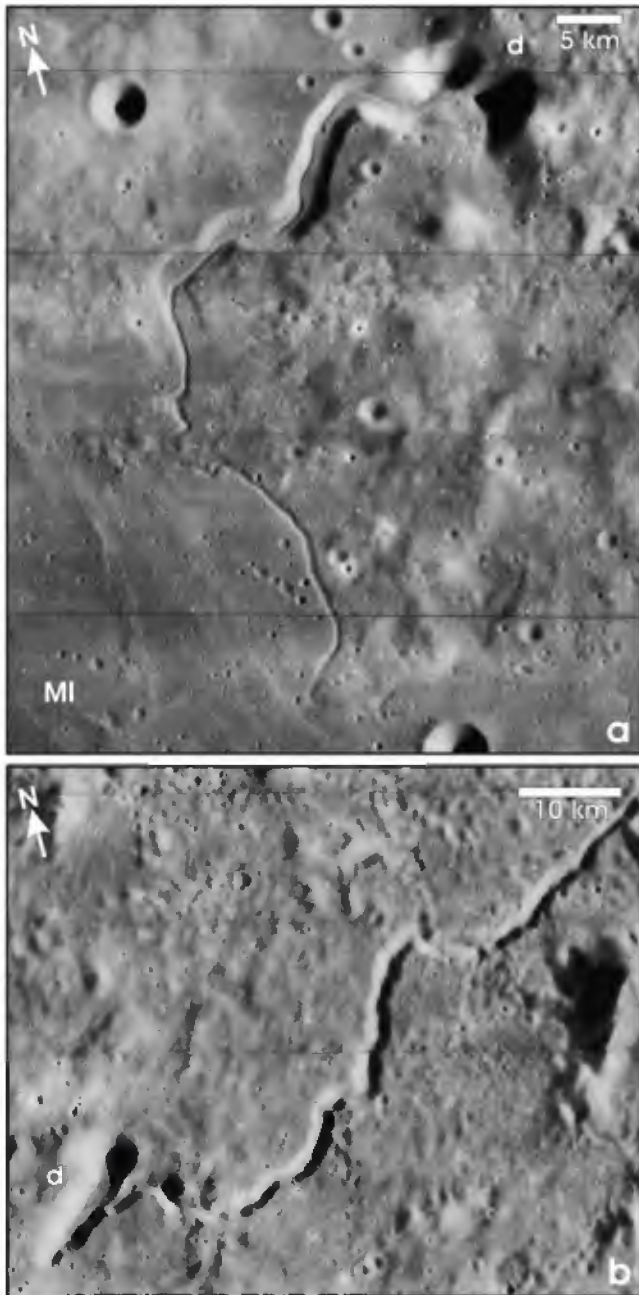
[10] Images generated by the Lunar Orbiter and Apollo missions have been used to identify a large number of lunar lava channels located in both mare and highland regions [e.g., *Greeley, 1971a, 1976; Young et al., 1973; Zisk et al., 1977; Strain and El-Baz, 1977; Wilhelms, 1987*]. The Apollo 15 mission involved direct investigation of one of these channels, Hadley Rille (Rima Hadley), as well as the surrounding basaltic mare units of Palus Putredinis [*Swann et al., 1972; Howard et al., 1972; Spudis and Pieters, 1991*]. Although sinuous lunar rilles were once believed to be ancient river channels and valleys [e.g., *Urey, 1967; Peale et al., 1968; Lingenfelter et al., 1968*; see also *Zimbelman, 2001*], the complete absence of hydrous minerals in sampled lunar materials [e.g., *Schmitt et al., 1970; Papike et al.,*

*1991*] demonstrates that sinuous lunar rilles did not form in the presence of water. Sinuous lunar rilles share numerous characteristics with terrestrial lava tubes and channels and are interpreted to have also formed by the flow of lava [e.g., *Hackman, 1966; McCauley, 1967; Oberbeck et al., 1969; Greeley, 1971b; Cruikshank and Wood, 1972; El-Baz and Roosa, 1972; Young et al., 1973; Schaber, 1973; Carr, 1974*].

[11] Many workers have concluded that the flow of lava can only act to construct landforms and not to incise or otherwise erode them, and this view has been an important factor in the elimination of lava flow as a candidate mechanism by which Martian outflow channels might have formed. However, incision and erosion by the flow of lava are suggested by valleys such as those in the region of lunar crater Plato, where lava once flowed from local sources across highlands onto the surrounding basalt plains of Mare Imbrium and Mare Frigoris [e.g., *M’Gonigle and Schleicher, 1972*]. This flow resulted in formation of valleys up to  $\sim 3$  km across and formation of nested channels in valley fill deposits (Figure 6). It is apparent that the valleys formed as sinuous lava channels after formation of surrounding uplands, and although a constructive origin for parts of these channels is conceivable (e.g., where lava has flooded relatively broad topographic lows), the action of



**Figure 5.** Part of Hrad Vallis, a Martian outflow channel located on the distal flanks of Elysium Mons at  $\sim 34^{\circ}N$ ,  $218^{\circ}15'W$  (Viking Orbiter frame 541A10) [*Wilson and Mouginitis-Mark, 2003*]. The channel commences abruptly at a complex topographic depression (d). Illumination is from the right.



**Figure 6.** Valleys and channels at lunar crater Plato ( $\sim 52^{\circ}\text{N}$ ,  $9^{\circ}\text{W}$ ). (a) Valley and nested channel features that head at a volcanic source marked by a topographic depression (d) and extend southward across local highlands onto adjacent Mare Imbrium (MI) (Lunar Orbiter frame IV-134-H3). (b) Channel and depression (d) with properties similar to those in Figure 6a (Lunar Orbiter frame IV-127-H3). The channel extends northeastward across local highlands toward Mare Frigoris. Illumination is from the right.

erosive processes is also suggested. Channels nested within the larger valleys may have formed by incision, although a dominantly constructive origin related to emplacement of volcanic valley deposits is possible. Numerous similar examples of channels incised across lunar uplands are located in, e.g., the Aristarchus Plateau, Prinz crater, and

Mare Orientale regions [e.g., *Hulme, 1973; Greeley, 1976; Zisk et al., 1977; Strain and El-Baz, 1977*].

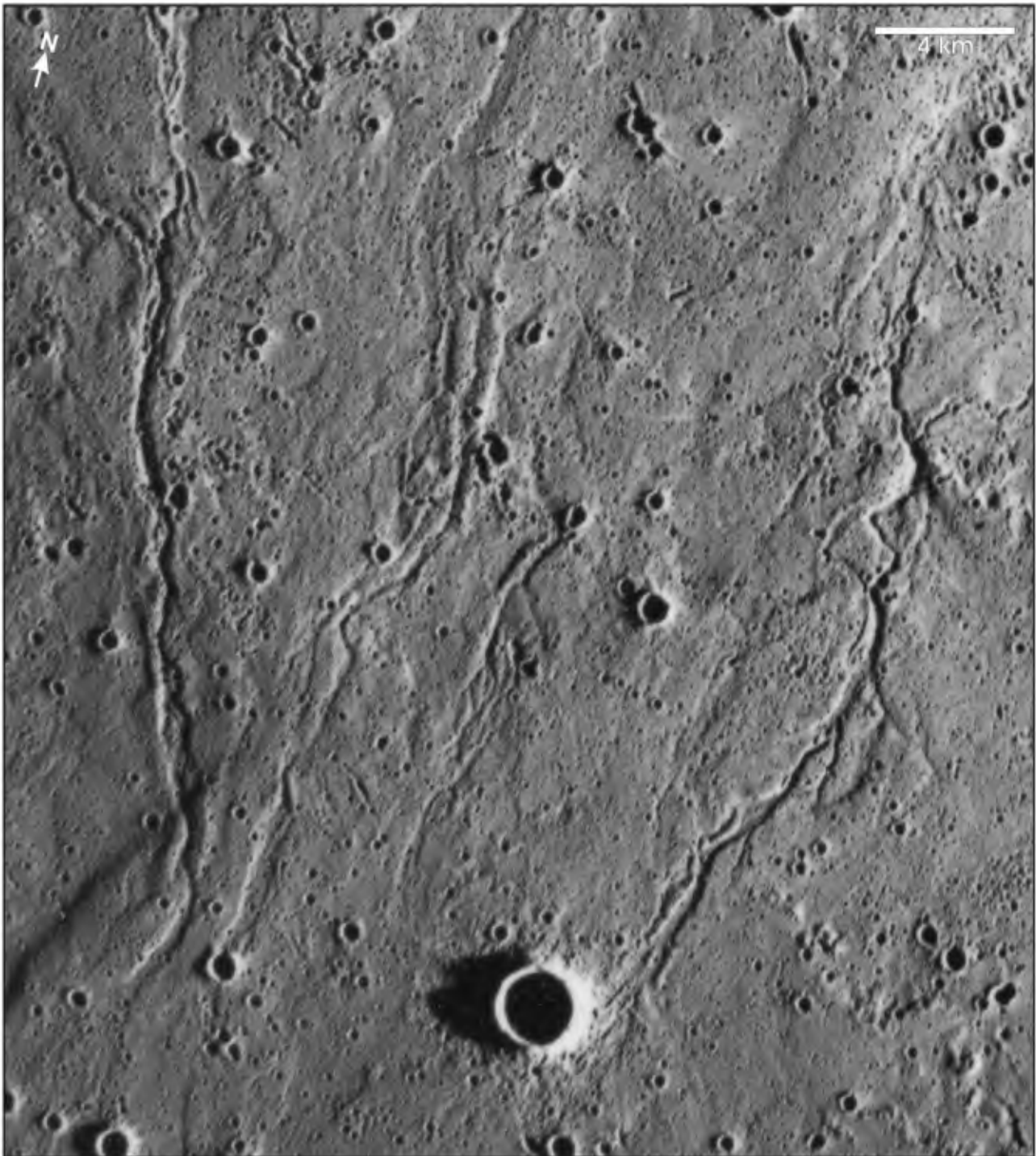
[12] Most workers have concluded that the flow of lava is incapable of forming Martian features such as streamlined islands and anastomosing channels [e.g., *Mars Channel Working Group, 1983; Baker et al., 1992a*]. Yet immediately north of the lunar Aristarchus Plateau, there are examples of streamlined islands that formed by lava flow (Figure 7). Importantly, it is uncertain if these features formed during the same event in which surrounding basalt units were emplaced or if erosion of preexisting terrain took place by confined flow; nevertheless, the final products are streamlined islands that developed by lava flow in the complete absence of water. Streamlined islands and anastomosing rilles exist as part of a large network of lava channels (possibly formed through dominantly constructive processes related to emplacement of broad lava flows) in Mare Imbrium (Figure 8), demonstrating that lava conduits need not be restricted to simple sinuous channels that lack tributaries and that do not branch and recombine in a complex manner.

[13] Erosion by lava is apparently not restricted to the simple vertical incision implied at some lunar sites: Lateral erosion by the sinuous flow of lava is suggested at Hadley Rille, where some meanders appear to cut into adjacent highland massifs [*Howard et al., 1972*]. High sinuosity is a characteristic of numerous lunar rilles [e.g., *Young et al., 1973; Wilhelms, 1987*], and although many such rilles may have formed at least partly through constructional processes, they may also have evolved over time through lateral erosion during eruptive events [e.g., *Hulme, 1973*]. Examples exist of lunar channels with terraces that may have been modified by later lava flows (Figure 9), suggesting that volcanic processes can both form and modify such features.

[14] Absence of large positive relief lava deposits at the mouths of Martian channels has been cited as key evidence against formation of these channels by the flow of lava



**Figure 7.** Streamlined islands (arrows) inside a lunar rille located north of Aristarchus Plateau, Oceanus Procellarum (at  $\sim 29^{\circ}30'\text{N}$ ,  $46^{\circ}30'\text{W}$ ; Apollo 15 panoramic frame 324). This channel extends westward from a breach in the wall of crater Krieger [e.g., *Carr, 1974; Leverington and Maxwell, 2004*]. Illumination is from the right.



**Figure 8.** Anastomosing volcanic channels located in Mare Imbrium ( $\sim 24^{\circ}\text{N}$ ,  $31^{\circ}\text{W}$ ), northwest of lunar crater Euler (Apollo 15 metric frame AS15-M3-1701) [see also *Schaber*, 1973]. Illumination is from the right.

[*Baker et al.*, 1992a]. Yet it is typical for lunar sinuous rilles to entirely lack such distinct accumulations of lava flows at their terminations [*El-Baz et al.*, 1972], a characteristic that can be attributed to processes such as burial of channel mouths by subsequent lava flows. For example, Vallis Schröteri, which extends from the Aristarchus Plateau onto the basaltic plains of Oceanus Procellarum, lacks association with a clear terminal volcanic deposit (Figure 10). Any

perceived lack of volcanic deposits at the mouth of this or other lunar rilles (e.g., Figure 6a) would be incorrect: Terminal accumulations of materials that once flowed through lunar rilles must, in fact, be present in large volumes and, in combination with flow materials derived from other sources, must collectively comprise the materials of both the distal channels and the volcanic plains onto which they flow. In this case, as with many others on the



**Figure 9.** Terraces in one of the channels of Rimae Prinz ( $\sim 27^\circ\text{N}$ ,  $44^\circ 20'\text{W}$ ), located north of lunar crater Prinz (Apollo 15 panoramic frame 318). Illumination is from the right.

Moon, the large volumes and extremely low viscosity of lunar lava flows [e.g., Head, 1976; Hörz *et al.*, 1991] appear to have inhibited preservation of morphologically distinct local accumulations of terminal deposits, favoring instead very broad volcanic deposits that collectively fill substantial volumes of basins and bury any such accumulations that may have once been exposed at the surface [El-Baz and Worden, 1972]. The supposed absence of deposits at the mouths of many Martian outflow channels may similarly be illusory. Most Martian outflow channels extend onto the extensive volcanic plains of the northern lowlands [e.g., Masursky *et al.*, 1977; Carr, 1995], a relation consistent with volcanic origins for these channels. On the basis of lunar analogs such as Vallis Schröteri the typical transition of Martian outflow channels from sharp channel margins in highland regions to indistinct margins on terminal volcanic plains [Carr, 1995] is also consistent with volcanic origins.

[15] Many Martian outflow channels commence abruptly at topographic depressions such as pits, regions of chaotic terrain, and volcanic fissures. Such regions are often interpreted as areas where volcanic materials and water interacted, in some cases explosively, and from which large volumes of water were released to form associated channels [e.g., Masursky *et al.*, 1977; Baker *et al.*, 1992a; Tanaka and

Chapman, 1990; Burr *et al.*, 2002; Wilson and Head, 2002; Wilson and Mouginis-Mark, 2003; Head *et al.*, 2003; Manga, 2004]. However, many lunar sinuous rilles similarly commence abruptly at large topographic depressions that clearly mark the source areas of volcanic flows that formed the rilles [e.g., Greeley, 1971a; Zisk *et al.*, 1977; Strain and El-Baz, 1977] (Figures 6 and 11). If, in the absence of water, volcanism on the Moon can form lava channels that head at large topographic depressions, there is no requirement to invoke the action of water in the formation of either Martian depressions or associated channels. Concentrations of surface and near-surface volatiles are evident on Mars [e.g., Kieffer *et al.*, 1976; Boynton *et al.*, 2002; Feldman *et al.*, 2003], and it follows that significant and sometimes explosive interactions between such volatiles and igneous materials are likely to have taken place during the planet's history. However, on the basis of lunar analogs, large topographic depressions at the heads of channels need not represent the signature of phreatomagmatic eruptions that involved catastrophic releases of large volumes of water from cryosphere-confined aquifers.

#### 4. Venusian Analogs for Martian Channels

[16] The existence and diversity of volcanic channels on Venus were first recognized in images generated by the Magellan mission [Saunders and Pettengill, 1991]. These channels, believed to have formed through a variety of mechanisms involving both constructive and erosive processes, are widely associated with volcanic features such as coronae, shield volcanoes, and rift zones [e.g., Baker *et al.*, 1992b; Komatsu *et al.*, 1992, 1993; Gregg and Greeley, 1993; Komatsu and Baker, 1994]. In addition, Venusian channels are associated with outflows that appear to head at or under the ejecta blankets of many impact craters [e.g., Asimow and Wood, 1992; Chadwick and Schaber, 1993].

[17] Liquid water is unstable on Venus [e.g., Kargel *et al.*, 1993], and although water may have been abundant very early in the planet's history, it is only present today in trace amounts as water vapor [e.g., Donahue and Russell, 1997]. Partly on this basis the channels of Venus are believed to have formed in the essential absence of water [Baker *et al.*, 1992b]. The X-ray fluorescence and gamma ray measurements made by seven Venera and Vega landers are consistent with mafic volcanic compositions such as tholeiitic basalt [e.g., Surkov, 1983; Surkov *et al.*, 1987; Kargel *et al.*, 1993; Fegley *et al.*, 1997]. Venusian channels are hypothesized to have formed by flow of mafic or ultramafic silicate lavas or lavas of exotic compositions such as sulfur or carbonatite [e.g., Baker *et al.*, 1992b; Komatsu *et al.*, 1993; Kargel *et al.*, 1994].

[18] Many Venusian channels are simple in form, being characterized by long channels with few or no tributaries and having general morphologies that are similar to those of simple sinuous lunar rilles [Baker *et al.*, 1992b, 1997; Head *et al.*, 1992; Komatsu and Baker, 1994]. Simple channels on Venus generally head at topographic depressions, have relatively constant widths of  $\sim 1\text{--}2$  km and lengths of tens to hundreds of kilometers, and lack clear associations with lava flow margins [Baker *et al.*, 1992b, 1997; Head *et al.*, 1992]. The longest recognized channel on Venus, located mostly on lava plains located north of Rusalka Planitia, has



**Figure 10.** Oblique view of the distal valley and nested channel of lunar Vallis Schröteri (middle of image at  $\sim 25^{\circ}\text{N}$ ,  $52^{\circ}40'\text{W}$ ), which extend onto Oceanus Procellarum (OP) from a source on the Aristarchus Plateau (Apollo 15 Hasselblad frame AS15-93-12628). Scale is valid only in the top right corner of the image. Illumination is from the left.

a total length of 6800 km [Baker *et al.*, 1992b]. Features associated with simple channels on Venus include meander cutoffs, abandoned channel segments, and levees [Baker *et al.*, 1992b; Head *et al.*, 1992]. The meanders of simple Venusian channels are suggestive of modification of original flow patterns by erosional channel widening during lava flow [Komatsu and Baker, 1994]. As with their lunar counterparts, there are numerous examples of simple Venusian channels that cut across irregular topography, suggesting that formation of these channels involved erosive processes [e.g., Komatsu and Baker, 1994] (Figure 12).

[19] Complex channels, which in numerous cases develop large braided patterns that define streamlined islands (Figure 13), are also found on Venus [Baker *et al.*, 1992b]. Many of these channels head at topographic depressions, and a minority of channels have large delta-like tributary systems at their mouths [Baker *et al.*, 1992b]. A prominent complex Venusian channel, Kallistos Vallis, is located in the northern region of Lada Terra, east of Lavinia Planitia. Kallistos Vallis is over 1200 km long and up to 30 km wide and heads at a collapse feature on the flank of a large volcanic construct [Baker *et al.*, 1992b; Komatsu *et al.*, 1993]. This collapse feature is morphologically similar to regions of chaotic terrain that acted as sources for many outflow channels on Mars [Baker *et al.*, 1992b]. The features of Kallistos Vallis, which include large streamlined islands (Figure 14), are strongly suggestive of formation by

flood waters, although a volcanic origin is widely favored on the basis of the nature of Venusian landforms and environmental conditions [Baker *et al.*, 1992b, 1997].

[20] The existence and properties of complex volcanic channels on Venus are relevant to the search for the origins of outflow channels on Mars. Complex Venusian channels represent evidence that volcanic processes can form chaotic terrain and that the flow of lava from such terrain can form large channels and streamlined landforms; these attributes are consistent with those of smaller but analogous lunar features. Importantly, Venusian channels suggest that the flow of lava can produce landforms that mimic those known to have been formed on Earth by aqueous flood events.

[21] Some workers have hypothesized that formation of complex channels on Venus may have been a consequence of the planet's high surface temperatures and of particular fluid chemistries such as liquid sulfur or ultramafic compositions [e.g., Baker *et al.*, 1992b]. Appeals to special rock chemistries and environmental conditions to justify the existence of Venusian channels may be unnecessary, however. A simpler interpretation of Venusian channels involves a recognition that basaltic lava, erupted in sufficiently large volumes and at sufficiently low viscosities, is capable of formation of large channels through processes that include erosion. This interpretation is consistent with measurements returned by the Venera and Vega landers [e.g., Surkov, 1983; Surkov *et al.*, 1987; Kargel *et al.*, 1993; Fegley *et al.*, 1997],





**Figure 11.** Oblique view of two channels of Rimae Prinz (middle of image at  $\sim 27^\circ\text{N}$ ,  $44^\circ\text{W}$ ), located north of lunar crater Prinz (P) (Apollo 15 Hasselblad frame AS15-93-12608). Like many Martian outflow channels these rilles commence abruptly at topographic depressions (d1 and d2); the rille associated with depression d1 crosses hills at h, suggesting structural control of channel position (see caption for Figure 193 by M. J. Grolier [Masursky *et al.*, 1978]) or incision processes that commenced prior to subsidence of mare materials [e.g., see Greeley and Spudis, 1978]. The head of the rille associated with d1 is not dissimilar in overall appearance from that of the heads of outflow channels such as Aromatum Chaos (Figure 1); both rilles are similar in gross appearance to the outflow channels Dao Vallis and Harmakhis Vallis (Figure 4). Scale is valid only in the top right corner of the image. Illumination is from the left.

the seemingly basaltic nature of volcanic landforms on Venus [Head *et al.*, 1992], and the nature of lunar basaltic landforms such as those described above.

## 5. Discussion

[22] Although the basic processes and materials involved in the formation of Venusian channels remain poorly understood, the channels themselves are nevertheless very likely to have been formed by the flow of low-viscosity lava. Some Venusian channels formed as distributary features of lava flows and do not appear to incise surrounding terrain and, as such, seem to have constructional origins [e.g., Baker *et al.*, 1997]. Other channels lack the characteristics of constructional features (such as association with adjacent flow deposits) and are suggestive of incision [e.g., Komatsu and Baker, 1994; Baker *et al.*, 1997]. Complex

Venusian channels have characteristics and features that are highly suggestive of formation by erosion. The large outflow channel Kallistos Vallis is suggestive of erosion on a massive scale, and the further association of this channel with a source at chaotic terrain is significant to the interpretation of corresponding Martian landforms.

[23] Although the scales of lunar volcanic channels do not approach those of the largest Venusian and Martian channels, lunar analogs nevertheless provide an important and independent perspective on the capacity of lava to form features such as those of Martian channels. Lunar analogs suggest that (1) basaltic lava flows can form large channels through processes that likely include incision and erosion; (2) basaltic lava flows can form anastomosing drainage systems as well as streamlined islands and channel terraces; (3) volcanic channels need not have obvious positive relief accumulations at their mouths; and (4) the association between volcanic channels and sources at local topographic depressions is common and existence of such channels and depressions need not imply the action of phreatomagmatic processes involving catastrophic releases of large volumes of water. These points are fully consistent with the nature of Venusian volcanic channels and similarly suggest that flow of lava should be



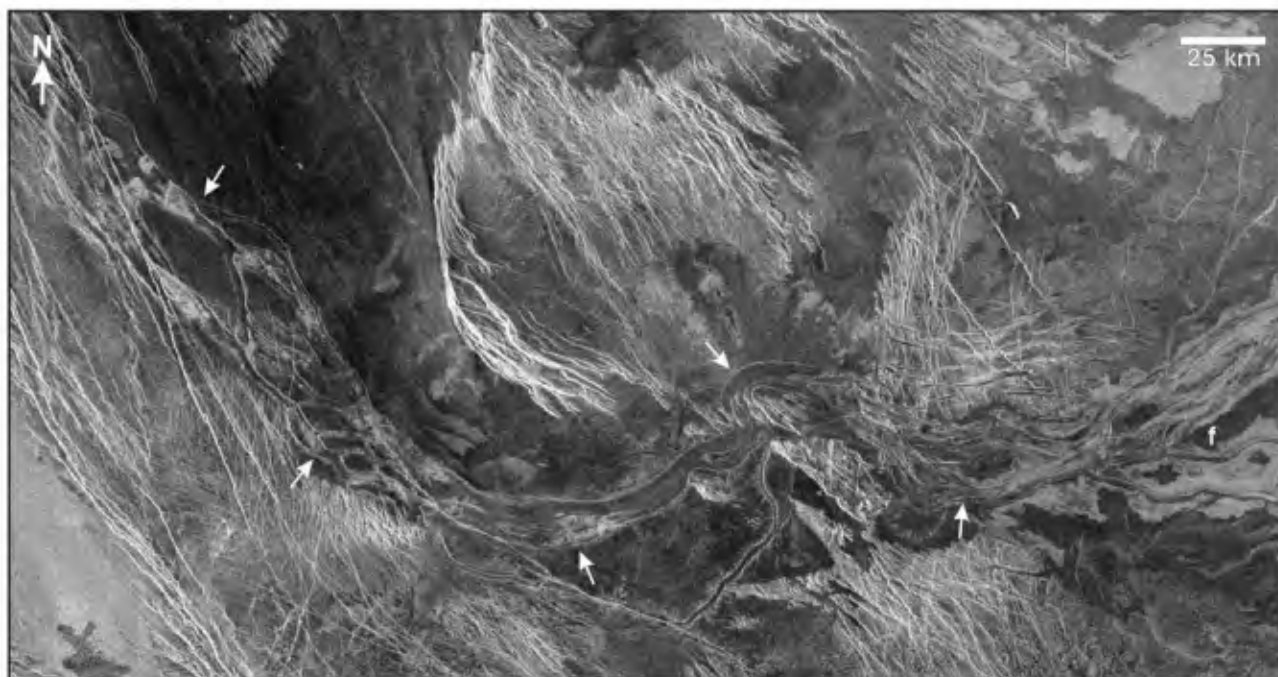
**Figure 12.** Simple Venusian rille located at  $\sim 2^\circ\text{S}$ ,  $273^\circ 18'\text{E}$ , in Phoebe Regio (Magellan Full Resolution synthetic aperture radar (SAR) Map of Venus (FMAP) left-look mosaic). Lava flows that formed this channel emerged from topographic depressions at d, flooding small basins and cutting northwestward across tesserae [Komatsu and Baker, 1994]. Microwave illumination is from the left.



**Figure 13.** Streamlined islands (arrows) associated with a Venusian volcanic channel located at  $\sim 50^{\circ}\text{N}$ ,  $23^{\circ}\text{E}$ , south of Ishtar Terra (Magellan FMAP left-look SAR mosaic) [Baker *et al.*, 1992b]. The channel heads at topographic depressions located northwest of the depicted region. Microwave illumination is from the left.

more actively considered as a viable candidate process for formation of Martian outflow channels.

[24] With typical widths of meters to tens of kilometers, terrestrial lava channels are generally much smaller than their lunar and Venusian counterparts [e.g., Wentworth and Macdonald, 1953; Ollier and Brown, 1965; Carr and Greeley, 1980; Hon *et al.*, 1994]. Terrestrial lava channels nevertheless share a number of characteristics with sinuous lunar and Venusian rilles. For example, terrestrial channels are frequently simple in morphology and often head at volcanic sources that are (or that ultimately develop into) distinct topographic depressions [e.g., Greeley, 1977]. Importantly, terrestrial channels generally form as constructive distributary channels that emplace lava flows [e.g., Hon *et al.*, 1994], and there is a distinct paucity of clear evidence in support of the action of significant erosive processes in modern flows [e.g., Greeley *et al.*, 1998]. No recognized terrestrial lava channels share the erosive characteristics or dimensions of the most intriguing lunar and Venusian channels discussed above. Modern terrestrial eruptive events [e.g., Hon *et al.*, 1994] do not involve the lava volumes believed to have been associated with large lunar and Venusian events [e.g., Head, 1976; Crumpler *et al.*, 1997], and thus the absence today of large erosive terrestrial channels should perhaps not be surprising. While the capacity of ancient terrestrial lava flows to incise channels is poorly understood [e.g., Fagents and Greeley, 2001], the preserved features of some ancient channels are suggestive of a past competence for erosion of bedrock by terrestrial lava flows of various compositions [e.g., Huppert *et al.*,



**Figure 14.** Part of Venusian volcanic outflow channel Kallistos Vallis (at  $\sim 50^{\circ}\text{S}$ ,  $21^{\circ}\text{E}$ ), located in the northern region of Lada Terra, east of Lavinia Planitia (Magellan FMAP left-look SAR mosaic). This portion of the channel has an anastomosing form, and numerous large streamlined islands (arrows) are evident; the channel heads at chaotic terrain located northwest of the depicted region [Baker *et al.*, 1992b, 1997; Komatsu *et al.*, 1993]. Broad volcanic flows (f) are located in the eastern part of the image, downslope from the large channel islands. Microwave illumination is from the left.

1984; Huppert and Sparks, 1985; Barnes and Barnes, 1990; see also Kerr, 2001]. Even modern basaltic lava flows hint at capacities for formation of anastomosing systems and incision of channels. For example, some terrestrial lava channels, such as tubes at Mount Etna [Calvari and Pinkerton, 1998] and lava streams in Hawaii [Carr and Greeley, 1980], can form distinctly complex networks with anastomosing and braided reaches. Some recent and modern terrestrial channels are believed to have formed at least in part through thermal or mechanical erosion by lava flow [e.g., Peterson and Swanson, 1974; Greeley et al., 1998; Kauahikaua et al., 1998, 2002, 2003; Williams et al., 2004]. Most notably, a small Hawaiian lava stream, with a width of only 4 m, is documented to have incised 6 m into bedrock over a period of 60 days [Kauahikaua et al., 1998]. In light of terrestrial measurements such as these a capacity for substantial vertical incision may not be unrealistic for hypothetical Martian high-volume and low-viscosity lava flows with channelized widths of kilometers to tens of kilometers.

[25] Formation of large outflow channels on Mars by flowing lava is consistent not only with the gross morphologies of Martian landforms but also with general global geographic relations on that planet between channels, source regions, and basins of accumulation. Many outflow channels on Mars are within or proximal to Tharsis and Elysium [Mars Channel Working Group, 1983; Baker et al., 1992a; Carr, 1995], volcanic provinces that contain the largest volcanic rises in the solar system [Carr, 1973] and within which channels of likely volcanic origin are known to exist [e.g., Wilson and Mouginis-Mark, 2001]. The largest outflow channels head in the vicinity of Valles Marineris, an immense rift in volcanic units of the Tharsis bulge [e.g., Scott and Tanaka, 1986; McEwen et al., 1999]. The topographic depressions from which Martian outflow channels emerge are located in regions of recognized volcanic activity; indeed, most competing hypotheses of channel formation that involve catastrophic releases of water from confined aquifers rely entirely upon a contemporaneous association between local igneous activity and channel formation processes [e.g., Masursky et al., 1977; Baker et al., 1991, 1992a; Tanaka and Chapman, 1990; Wilson and Head, 2002; Burr et al., 2002; Wilson and Mouginis-Mark, 2003; Russell and Head, 2003; Head et al., 2003; Rodriguez et al., 2003; Manga, 2004]. As with lunar and Venusian volcanic channels the volcanic plains onto which Martian outflow channels extend are among the largest known [see, e.g., Head et al., 2002].

[26] The landing sites of the Viking 1 [e.g., Binder et al., 1977; Greeley et al., 1977], Pathfinder [e.g., McSween et al., 1999; Chapman and Kargel, 1999], and Spirit [e.g., McSween et al., 2004] spacecraft, all of which are located near the mouths of prominent Martian outflow channels, are plains with properties that are entirely consistent with volcanic origins. In a manner similar to that of lunar volcanic plains visited by the Luna, Surveyor, and Apollo landers [e.g., Shoemaker et al., 1966, 1969, 1970; Schmitt and Cernan, 1973; Vaniman et al., 1991; Hörz et al., 1991], surface materials at the three Martian landing sites appear to consist primarily of the remnants of volcanic units that have been subjected to extensive reworking by impacts. As on the Moon, formation of a surface regolith layer at these sites

has apparently reduced original volcanic units to deposits of rock fragments and fines and eliminated the outcrop-scale volcanic textures and structures that were likely once expressed at the surface.

[27] Consistent with a volcanic origin for the largest outflow channels, smaller outflow channels that head in highland regions outside of Tharsis and Elysium (e.g., those in Memnonia, Aeolis, and Hellas) are typically associated with major rift zones (e.g., Memnonia Fossae [Tanaka and Chapman, 1990; Zimbelman et al., 1992]), volcanic rises (e.g., Tyrrhena Patera [Greeley and Crown, 1990]), and large volcanically emplaced plains units [e.g., see Scott and Tanaka, 1986; Greeley and Guest, 1987; Smith et al., 2003]. As with larger outflow features, channels in these regions ultimately flow onto extensive volcanic plains. Even relatively small sinuous valleys and valley networks located in the Martian highlands [e.g., Goldspiel et al., 1993; Carr, 1995; Carr and Malin, 2000] appear in some cases to have characteristics that are more consistent with volcanic than fluvial or sapping origins [e.g., Leverington and Maxwell, 2004; Leverington, 2004], suggesting a possible consistency in the origins of certain Martian channels across a wide range of scales. A minority of outflow channels on Mars (e.g., Ma'adim Vallis) may not have originally formed through incision by the flow of lava, instead forming through other processes and later acting as conduits for large highland lava flows; such a sequence of events would be similar to that hypothesized by Leverington and Maxwell [2004] for a smaller north sloping valley in western Memnonia.

[28] The simplest interpretation of Martian channels that extend from volcanic source regions onto volcanic plains is as conduits formed by volcanic flows. Volcanic processes operate under an extremely wide range of environmental conditions and thus can account for channel formation without appeals to more complex scenarios involving substantial past changes in Martian climate or concepts such as hemispheric aquifers confined under a global cryosphere. Channel formation hypotheses requiring major changes in the properties of the Martian atmosphere or involving repeated catastrophic flow of water from features such as volcanic rifts appear needlessly exotic alongside the igneous hypothesis for channel formation. This hypothesis requires only that large flows of lava have a capacity for erosion and for formation of streamlined landforms and anastomosing channels, a capacity that is implied by the nature of lunar and Venusian volcanic landforms.

## 6. Conclusions

[29] Processes related to the flow of lava have been previously rejected as possible mechanisms by which Martian outflow channels might have formed. This rejection has mainly been based on assumptions that lava flows could not have eroded channels and formed Martian features such as streamlined islands and anastomosing reaches, that formation by lava flows should have resulted in accumulation of large positive relief deposits at the mouths of Martian channels, and that volcanic sources are absent at the heads of Martian channels. However, there are examples on Venus and the Moon in which the flow of lava appears to have resulted in formation of anastomosing channels and streamlined islands. As with many Martian channels it is typical for lunar rilles to

appear to lack large accumulations of volcanic materials at their mouths, though in reality such deposits must certainly be present among the voluminous volcanic plains present at the termini of these channels. Many lunar and Venusian volcanic channels commence abruptly at large topographic depressions, a characteristic shared with most Martian outflow channels. Large lava plains are widespread in both the highlands and lowlands of Mars, representing evidence that massive effusive volcanic events have taken place on that planet. Volcanic processes operate under an extremely wide range of environmental conditions and thus can account for channel formation on Mars without appeals to complex scenarios involving dramatic changes in atmospheric properties or concepts such as hemispheric aquifers confined by a global cryosphere. Formation of outflow channels by aqueous floods remains an important hypothesis for which there is at least partial support from terrestrial analogs. However, on the basis of lunar and Venusian analogs the flow of lava should also be treated in future research as a viable and realistic mechanism by which Martian outflow channels might have formed.

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