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Reconciling channel formation processes with the nature of elevated outflow systems at Ophir and Aurorae Plana, Mars

David W. Leverington[1]

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[1] Many Hesperian outflow channels head at elevations compatible with aquifer recharge beneath the Martian south polar cap, and such channels are widely interpreted as the products of this recharge. Some outflow channels head at greater elevations that are inconsistent with southern recharge, including three systems located in Aurorae Planum and eastern Ophir Planum. These three systems have previously been interpreted as having formed through aqueous outbursts from local aquifers recharged by the meltwaters of ancient upland glaciers to the west. However, the viability of this interpretation is weakened by the lack of a geomorphic record supportive of past meltwater flow from western uplands, inconsistencies between hypothesized processes and the nature of regional topography and mineralogy, and the absence of satisfactory analog processes for catastrophic aqueous flow from the subsurface. In contrast, a volcanic origin for the Ophir and Aurorae systems appears to be in accord with the basic characteristics of constituent channels and associated landforms, the volcanotectonic nature of the Valles Marineris system and adjacent upland plains, and the nature of available analog landforms and processes. Though numerous uncertainties remain, a volcanic interpretation of these outflow systems can more simply account for the existence of component channels. The attributes of other elevated outflow systems on Mars similarly appear to be most consistent with volcanic origins. If the Ophir and Aurorae systems formed volcanically, thermal considerations imply minimum erupted lava volumes of 6.4×10^3 km^3 for Allegheny Vallis and 6.2×10^4 km^3 for Elaver Vallis.

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1. Introduction

[2] The Hesperian outflow channels of Mars are widely believed to have been formed by aqueous surface flows sourced primarily from aquifers recharged in the south polar region and maintained under pressure by a cryospheric seal in the upper crust [*Carr*, 1979; *Clifford and Parker*, 2001]. Outburst events are hypothesized to have been triggered by cryospheric breaches resulting from igneous intrusions [e.g., *Masursky et al.*, 1977; *McKenzie and Nimmo*, 1999; *Ogawa et al.*, 2003; *Leask et al.*, 2007] or from the progressive development of especially high pore water pressures within aquifers [e.g., *Gulick et al.*, 1997; *Baker*, 2001]. Surface flow is believed to have been maintained during outflow events by the hydraulic head associated with groundwater perched above the elevations of cryosphere breaches [*Carr*, 1979], possibly supplemented by additional pressure developed during the thickening of the cryosphere into the subsurface [*Carr*, 1996; *Wang et al.*, 2006].

[3] Outflow systems of a wide range of sizes exist on Mars, with constituent channels typically extending hundreds or thousands of kilometers downslope from sites of past surface disturbance and voluminous fluid effusion. Most Hesperian outflow systems head at elevations below the 1500 m level considered to be the uppermost level compatible with aquifer recharge beneath the south polar cap, and these lower systems have been generally interpreted as the products of such recharge [*Carr*, 2002]. However, some Hesperian outflow systems head at greater elevations, and have been alternatively interpreted as the products of the melting of glacial or ground ice at relatively high elevations [e.g., *Carr*, 2002; *Harrison and Grimm*, 2004; *Russell and Head*, 2007]. Many elevated outflow channels are located on the flanks of large volcanic shields [*Carr*, 2002], but other notable examples include three systems located in Aurorae Planum and in the eastern part of Ophir Planum, an upland region located southwest of Ganges Chasma and northeast of Coprates Chasma (Figures 1 and 2) [*Oguchi et al.*, 1998; *Carr*, 2002; *Dinwiddie et al.*, 2004; *Coleman*, 2006; *Coleman et al.*, 2007; *Komatsu et al.*, 2009]. The existence of these three outflow systems (Allegheny Vallis, Walla Walla Vallis, and Elaver Vallis) has been attributed by *Coleman et al.* [2007] to the past catastrophic melt of Tharsis glaciers, subsequent flooding of deep troughs of Valles Marineris, recharge of adjacent aquifers, and outflow of groundwater to the surface at Ophir and Aurorae Plana. *Komatsu et al.* [2009] concur that development of

[1]Department of Geosciences, Texas Tech University, Lubbock, Texas, USA.

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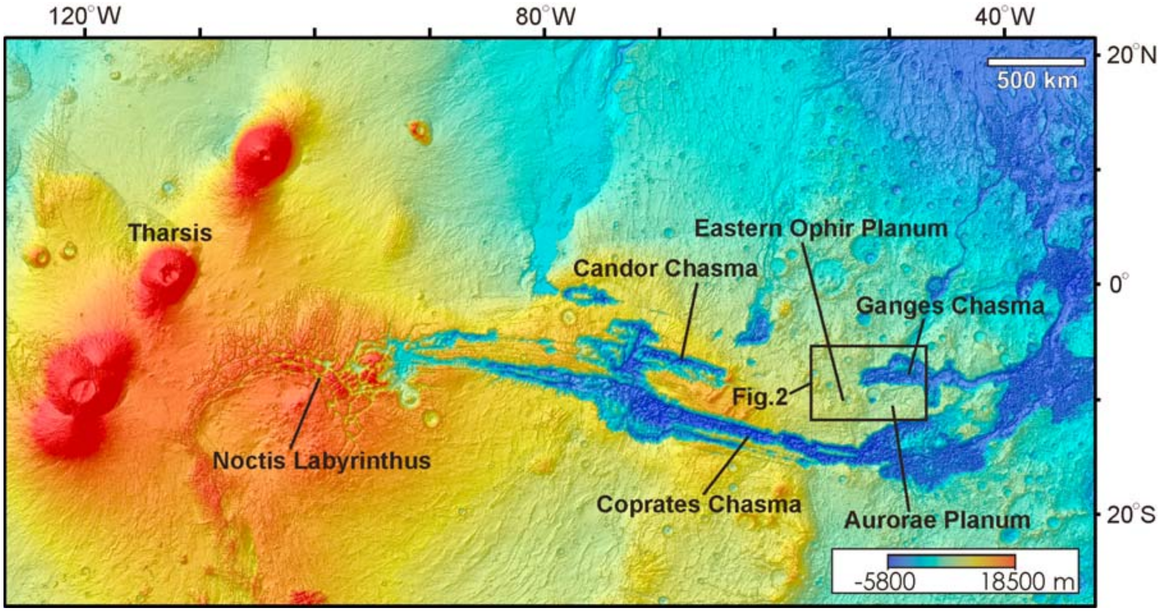

Figure 1. Mars Orbiter Laser Altimeter (MOLA) elevation data superimposed on shaded relief for the Tharsis and Valles Marineris regions (topography after *Smith et al.* [2003]).

the systems might have involved catastrophic release of groundwater originally derived from uplands to the west, but suggest that final mobilization of floodwaters could instead have involved a wide range of possible outburst mechanisms including igneous intrusion [e.g., *McKenzie and Nimmo*, 1999; *Ogawa et al.*, 2003], dehydration of hydrous evaporites [*Montgomery and Gillespie*, 2005], and salt tectonics [*Montgomery et al.*, 2009].

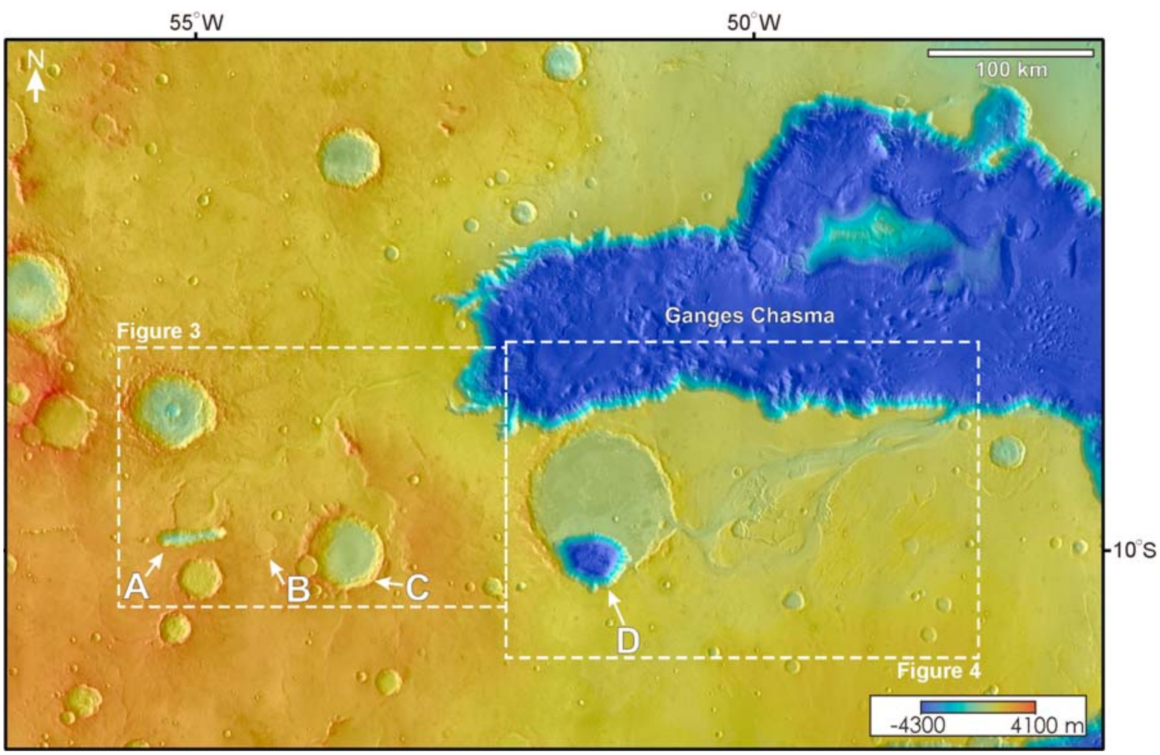

Figure 2. Thermal Emission Imaging System (THEMIS) daytime infrared mosaic of the Ganges Chasma, Aurorae Planum, and eastern Ophir Planum region, superimposed on color-coded MOLA topography. Channel heads are indicated as location A, Ophir Cavus at head of Allegheny Vallis; location B, cavi at head of Walla Walla Vallis; location D, Ganges Cavus at head of Elaver Vallis. An elongated depression located along the southern interior rim of a 40-km-wide impact crater (location C) is also indicated. THEMIS mosaic courtesy of Arizona State University; topography after *Smith et al.* [2003].

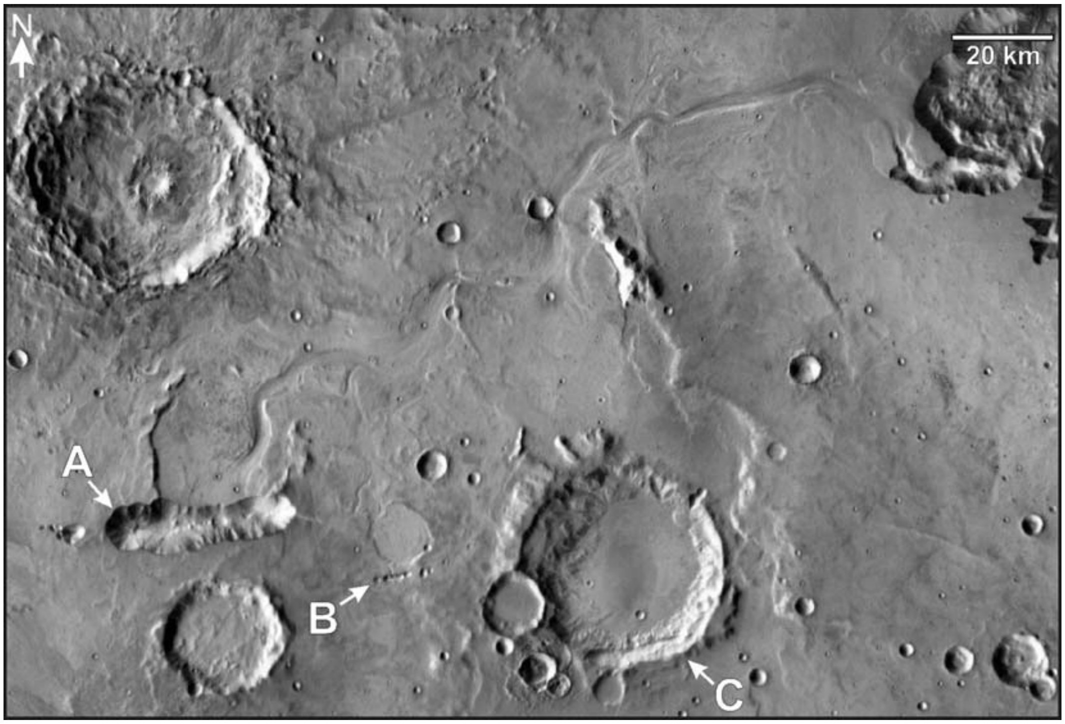

Figure 3. The Allegheny Vallis and Walla Walla Vallis systems head at elongate topographic depressions (locations A and B, respectively), and extend northward and eastward to the western rim of Ganges Chasma (top right). A third elongate depression (location C) is positioned along the southern interior rim of a 40-km-diameter impact crater; effusion of fluids from this depression may have played a role in development of the shallow lowlands that extend northward from the impact crater to Allegheny Vallis. THEMIS daytime infrared mosaic courtesy of Arizona State University. (Center is 53°55′W, 9°20′S.)

[4] Although a catastrophic aqueous origin for the channels of Ophir and Aurorae Plana would be consistent with past interpretations of other outflow systems on Mars [e.g., *Mars Channel Working Group*, 1983], key aspects of the aqueous model of *Coleman et al.* [2007] do not appear to be consistent with the basic nature of these channels, the adjacent Valles Marineris canyon system, and the uplands that comprise the Tharsis region. In this paper, possible difficulties with aqueous interpretations of the Ophir and Aurorae systems are identified, and the origin of these systems is reconsidered on the basis of the congruence between channel characteristics and those expected of volcanic landforms. The potential of volcanic processes to more generally account for the existence of other elevated Hesperian outflow systems is outlined.

2. Basic Characteristics of the Outflow Channels of Ophir and Aurorae Plana

[5] Allegheny Vallis, Walla Walla Vallis, and Elaver Vallis (Figures 1–4) are Hesperian outflow systems located in Aurorae Planum and in the eastern part of Ophir Planum [*Coleman et al.*, 2007]. The Ophir and Aurorae regions predominantly consist of Hesperian ridged plains that are contiguous with, and generally comparable in nature to, the surface of Lunae Planum to the northwest [e.g., *Scott and Tanaka*, 1986]. The three outflow systems of Ophir and Aurorae Plana head at elevations above the 1500 m threshold considered consistent with south pole recharge [*Carr*, 2002; *Dinwiddie et al.*, 2004; *Coleman et al.*, 2007]. The Allegheny and Walla Walla systems (Figure 3) head at elevations ~1000 m above this threshold [*Coleman et al.*, 2007] and extend across uplands of Noachian to Hesperian age [e.g., *Scott and Tanaka*, 1986; *Witbeck et al.*, 1991; *Komatsu et al.*, 2009]. The main Allegheny Vallis system heads at an elongated depression (Ophir Cavus, 37-km-long, 10-km-wide, with a floor up to ~1700 m below its rim), has typical channel widths of ~3 to 5 km, and runs almost 200 km to the western rim of Ganges Chasma. In addition, small branches of Allegheny Vallis originate from shallow topographic depressions near Ophir Cavus [*Komatsu et al.*, 2009]. The smaller Walla Walla Vallis system has typical channel widths of ~0.8 km and extends ~45 km from its head at a row of rimless pit craters northward across Wallula crater (12 km diameter) to the Allegheny Vallis system, with channels terminating at and appearing to be truncated by the larger Allegheny channels [*Coleman et al.*, 2007; *Komatsu et al.*, 2009]. A 20-km-long depression is located along the southern interior rim of a 40-km-wide impact crater in the region (Figures 2 and 3); this depression may mark the site of past fluid effusions from the subsurface [*Komatsu et al.*, 2009], with northward flow possibly contributing to development of the Ophir and Aurorae drainage system. The Elaver Vallis system (Figure 4) has typical widths of ~4 to 35 km and extends 150 km across Hesperian uplands to Ganges Chasma from its head at a 42 × 33 km depression within Morella crater (Ganges Cavus, the floor of which is up to ~5.2 km below its northern rim) [*Coleman et al.*,

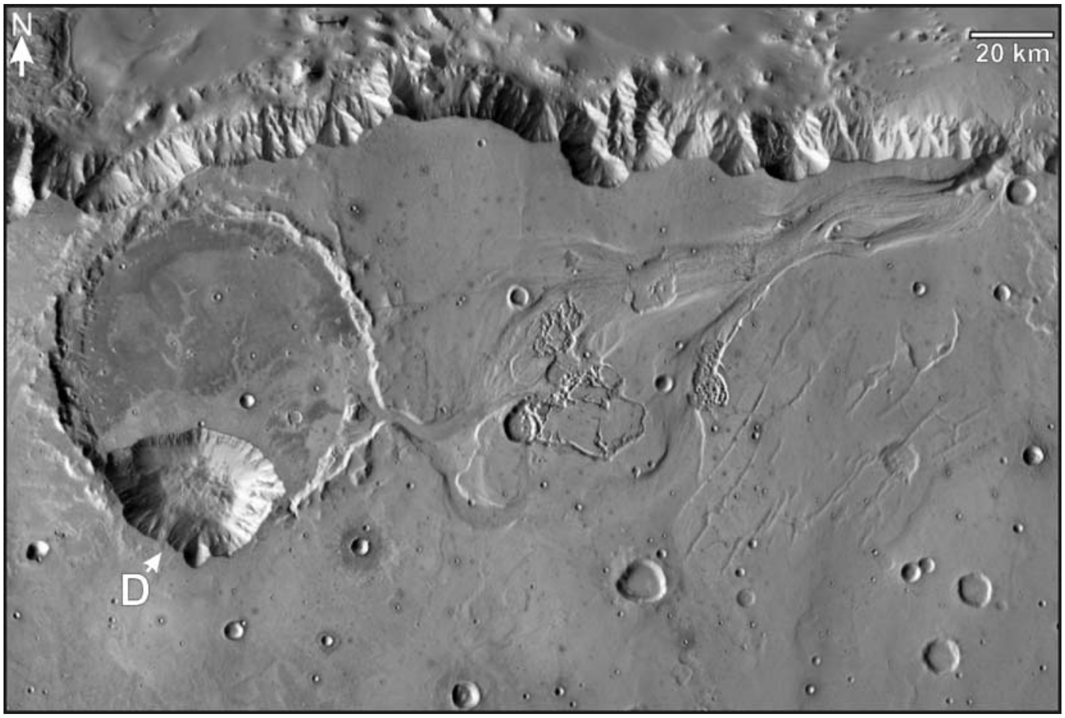

Figure 4. The Elaver Vallis system heads at a distinct topographic depression (D, Ganges Cavus) located along the southern interior rim of impact crater Morella. The channels of this system extend eastward to the southern rim of Ganges Chasma (top right). THEMIS daytime infrared mosaic courtesy of Arizona State University. (Center is 50°0′W, 9°30′S.)

2007; *Komatsu et al.*, 2009]. A high-flow mark of 1780 m is inferred for overflow prior to the breach of the eastern rim of Morella crater [*Coleman et al.*, 2007].

[6] The outflow systems of Ophir and Aurorae Plana are composed of relatively simple channels that, along some reaches, complexly anastamose about apparent erosional residuals. Such reaches are most notable at Elaver Vallis, a system also characterized along parts of its floor by patches of chaotic terrain [*Komatsu et al.*, 2009]. Many reaches of the Ophir and Aurorae channels have floors marked by parallel sets of longitudinal ridges [*Komatsu et al.*, 2009], an attribute typical of outflow systems on Mars [*Mars Channel Working Group*, 1983]. The margins of the troughs of Valles Marineris show evidence for scarp recession [*Lucchitta*, 1979; *Lucchitta et al.*, 1994], and at the Allegheny and Elaver systems the retreat of these margins has undercut distal channel floors by a minimum lateral distance of 10 km. Layered and poorly consolidated deposits that discontinuously mantle the upland plains surrounding Valles Marineris, and that appear to be enriched in hydrated silicates [*Milliken et al.*, 2008], overlie distal parts of the Allegheny Vallis system [*Le Deit et al.*, 2008].

3. Aqueous Mechanisms of Channel Formation

[7] The Ophir and Aurorae systems head at topographic depressions that mark the sites of fluid effusion from the subsurface. As at other Hesperian outflow systems on Mars [e.g., *Mars Channel Working Group*, 1983], the fluid involved in channel formation is interpreted to have likely been water [*Coleman et al.*, 2007; *Komatsu et al.*, 2009]. The Ophir and Aurorae systems head at elevations above the 1500 m limit considered consistent with south pole recharge [*Carr*, 2002; *Dinwiddie et al.*, 2004; *Coleman et al.*, 2007; see also *Carr*, 1979], suggesting that aqueous formation of these channels should not have directly involved flow from the extensive aquifers considered by most workers to have driven formation of lower systems. Instead, the aquifers responsible for development of the Ophir and Aurorae systems are inferred by *Coleman et al.* [2007] to have been recharged from deep lakes that once filled the canyons of Valles Marineris, and these lakes are hypothesized to have formed as a result of the catastrophic melting of Hesperian-aged ice sheets at Tharsis. The Tharsis ice sheets are interpreted to have been larger versions of the glaciers inferred by some workers to have existed at each of the three main Tharsis volcanoes [e.g., *Head and Marchant*, 2003; *Shean et al.*, 2005], and the ice sheets are hypothesized to have been partly melted by subglacial eruption of flood basalts. Glacial meltwaters are hypothesized by *Coleman et al.* [2007] to have catastrophically flowed eastward from central Tharsis to the Noctis Labyrinthus region, or directly to Valles Marineris itself, ultimately recharging regional aquifers at Valles Marineris and hydrostatically forcing aquifer outbursts along preexisting tectonic fractures extending eastward from Candor Chasma.

[8] The sequence of events previously inferred by *Coleman et al.* [2007] to have led to aqueous formation of the outflow systems of Ophir and Aurorae Plana is problematic. Most fundamentally, although there is abundant evidence for the past action of a range of volcanic processes across the Tharsis region [e.g., *Carr*, 1974a; *Solomon and Head*, 1982; *Phillips et al.*, 1990; *Mouginis-Mark*, 2002; *Baloga et al.*, 2003; *Warner and Gregg*, 2003;

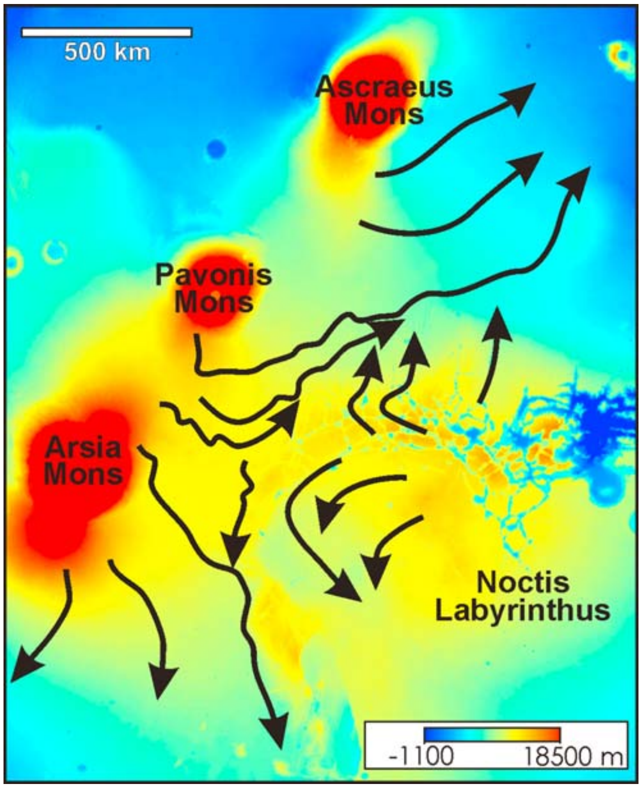

Figure 5. Selected Tharsis drainage paths determined through hydrological analysis of MOLA topography using the Arc Hydro Data Model. Unless modern topographic trends near Noctis Labyrinthus were reversed at the time of channel formation at Ophir and Aurorae Plana, hypothesized Tharsis glacial outbursts would likely have been diverted to the northeast and south, inhibiting the flooding of Valles Marineris to the east. The utilized MOLA Mission Experiment Gridded Data Records (MEGDR) database has a spatial resolution of 128 pixels per degree [after *Smith et al.*, 2003]. The Arc Hydro algorithms are described by *Maidment* [2002].

Mouginis-Mark and Christensen, 2005; *Bleacher et al.*, 2007a; *Hiesinger et al.*, 2007; *Baptista et al.*, 2008; *Mangold et al.*, 2008a; *Plescia and Baloga*, 2008; *Tyson et al.*, 2008], the geomorphic evidence for the past existence of large Tharsis glaciers is equivocal [e.g., *Mouginis-Mark and Rowland*, 2008], and there is no geomorphic record supportive of the hypothesized catastrophic flow of Hesperian meltwaters from Tharsis to Noctis Labyrithus or Valles Marineris. The volume of modern Valles Marineris is $\sim 3.6 \times 10^6$ km^3 [*Lucchitta et al.*, 1994], and the volume of void space available for ancient aquifers at east Tharsis is estimated to have exceeded 1×10^7 km^3 [*Dohm et al.*, 2001]. The water volumes involved in aqueous scenarios may thus be comparable to the 5×10^6 km^3 minimum estimate for total known water volume at high and middle latitudes today [*Christensen*, 2006], and the 3×10^6 km^3 minimum total volume estimated to have been required to form the circum-Chryse outflow systems [*Harrison and Grimm*, 2004]. To be consistent with presumed mechanisms of formation of the outflow channels that head at lower elevations, catastrophic eastward transfer of this volume of water would have necessarily produced a massive geomorphological imprint of diluvial landforms (e.g., large flood channels, associated streamlined erosional residuals, and widespread erosional and depositional bed forms of alluvial character) [e.g., *Baker*, 1978a, 1978b; *Fisher*, 2004] connecting central Tharsis with the Valles Marineris region. The absence of any such drainage imprint here, or in the zones located directly downslope of the eastern flanks of Tharsis Montes, brings into question the past occurrence of hypothesized glacial outbursts. Certainly, restriction of channel formation to the Ophir and Aurorae region, located 3000 km to the east of the area of hypothesized outbursts, would not be expected.

[9] Beyond the absence of geomorphic evidence for massive glacial outbursts from Tharsis, it is not clear that the topography of the Tharsis and Valles Marineris regions is consistent with the hypothesized outburst scenario of *Coleman et al.* [2007]. The peripheries of Noctis Labyrinthus and Valles Marineris are marked by elevated plateaus that, unless absent during Hesperian channel formation at Ophir and Aurorae Plana, should have inhibited the funneling of glacial meltwaters from the Tharsis volcanoes into Valles Marineris, instead diverting meltwaters to the south and northeast (Figure 5). Also of significance are the relatively low elevations of the bounding uplands of eastern Valles Marineris, which are inconsistent with accumulation of high-elevation lakes in the canyons to the west. Specifically, development of the channels at Ophir and Aurorae Plana has been attributed to the presence of an elevated (>2500 m) ice-covered lake at Candor Chasma [*Coleman et al.*, 2007], perched hundreds of meters above the heads of the three channel systems. However, east of central Coprates Chasma, the rim of the Valles Marineris system is more than 1 km lower than the proposed elevation of the lake at Candor Chasma. Subsidence of parts of the eastern Valles Marineris system during the Hesperian is possible [e.g., *Mège and Masson*, 1996] and could conceivably account for aspects of the topographic variations across the Valles Marineris region, but accumulation of water at Candor Chasma should nevertheless not have been possible at elevations approaching those of the heads of the outflow systems at Ophir Chasma unless barriers to flow extended across Coprates Chasma at the time of hypothesized glacial outbursts.

[10] Potential difficulties with aqueous mechanisms of channel formation at Ophir and Aurorae Plana extend to the mineralogical properties of materials exposed at the channels and along distal canyon reaches. Some landforms and deposits of the Valles Marineris region have been previously interpreted as possible indicators of the long-term presence of water at and near the surface, with light-toned and sulfate-rich deposits at Ganges Chasma tentatively linked to a range of possible aqueous processes [e.g., *Chojnacki and Hynek*, 2008; *Rossi et al.*, 2008; *Fueten et al.*, 2008; *Mangold et al.*, 2008b], deposits along trough margins interpreted as possible subaqueous fans [*Dromart et al.*, 2007], benches in Valles Marineris interpreted as possible wave cut shorelines associated with large water bodies [*Harrison and Chapman*, 2008], reflectance properties of units along peripheral uplands interpreted as suggestive of aqueous alteration during the late Hesperian [*Milliken et al.*,

2008], and deformation at Tharsis and Valles Marineris interpreted as consistent with the action of tectonic processes related to the presence of underlying salt deposits accumulated in Noachian drainage basins or aquifers [*Montgomery et al.*, 2009]. However, all three Ophir and Aurorae outflow systems terminate at Ganges Chasma, a deep trough of eastern Valles Marineris that, though partly mantled by unconsolidated materials, shows evidence for being floored by flow units of basaltic composition and high thermal inertia [e.g., *Mellon et al.*, 2000; *Christensen et al.*, 2003; *Edwards et al.*, 2008; *Rossi et al.*, 2008]. A particular basalt unit near the floor of Ganges Chasma has been identified as olivine-rich on the basis of Thermal Emission Spectrometer (TES) hyperspectral data and Thermal Emission Imaging System (THEMIS) multispectral data [*Christensen et al.*, 2003; *Edwards et al.*, 2008] and is likely to be readily altered under aqueous conditions [e.g., *Hausrath et al.*, 2008]. This olivine-rich unit forms a thick ($\sim$50 m) layer in the north and south walls of Ganges Chasma, with exposed outcrops appearing to be remnants of a once continuous unit [*Edwards et al.*, 2008], indicating that emplacement of this unit likely substantially predates development of the outflow systems of Ophir and Aurorae Plana. In addition, olivine-rich units have been identified at Morella crater, which forms part of the head region of the Elaver Vallis system, on the basis of analysis of TES data [*Koeppen and Hamilton*, 2008] and Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité (OMEGA) hyperspectral data [*Komatsu et al.*, 2009]. Though uncertainties remain, the apparently pristine nature of the basalt units exposed in the walls of Ganges Chasma is potentially incompatible with significant aqueous weathering [*Christensen et al.*, 2003], and may not be easily reconciled with the past existence here of canyon-filling water bodies, massive groundwater stores, and a water-saturated cryospheric seal. Similarly, if the olivine-rich units near the head of Elaver Vallis do not postdate development of associated channels, their presence may be incompatible with aqueous scenarios of channel growth involving the longer-term presence of water at or near the surface [*Komatsu et al.*, 2009].

[11] The existence of an ice-rich cryospheric seal of hemispheric or global extent is widely considered to have been necessary for pressurization and later discharge of large volumes of southern groundwater, processes presumed to have formed the most prominent Hesperian outflow systems on Mars [e.g., *Carr*, 1979, 2002; *Clifford*, 1993; *Rodriguez et al.*, 2005; *Andrews-Hanna and Phillips*, 2007; *Leask et al.*, 2007; *Harrison and Grimm*, 2008]. Problematically, the deep infiltration of glacial floodwaters at Tharsis and Valles Marineris hypothesized by *Coleman et al.* [2007] is inconsistent with the existence of such a seal. *Coleman et al.* [2007] acknowledge this difficulty, and suggest that the pooling of water at Valles Marineris could have resulted in the thaw of a deep talik beneath canyon floors, permitting local recharge of an underlying or adjacent regional aquifer. However, this scenario remains inconsistent with the absence of large channel systems linking central Tharsis and Valles Marineris, and does not provide a mechanism for corresponding thaw beneath the heads of the Ganges Chasma systems. More fundamentally, it is unclear that floodwaters would have had sufficient thermal energy to flow several thousand kilometers across the Martian surface, to pool at Valles Marineris, to thaw a thick cryospheric seal, and to deeply infiltrate before the waters themselves became frozen (or were vaporized). Regardless of the capacity of water to reach and pool at Valles Marineris, the thaw of a kilometers-thick ice-rich cryosphere at both Valles Marineris and at the sources of the Ophir and Aurorae systems should not have taken place as a catastrophic event, since even magma-driven thawing of an ice-rich Martian cryosphere has been estimated to require up to several million years for completion [e.g., *McKenzie and Nimmo*, 1999; *Ogawa et al.*, 2003], in part because the thaw of any ice-rich body of permafrost is slowed by the absorption of thermal energy related to the latent heat of fusion of water [e.g., *Williams and Smith*, 1989].

[12] Aqueous interpretations of the outflow systems of Ophir and Aurorae Plana are based on the premise that catastrophic release of water from regional or hemispheric aquifers is a viable process that is likely to have operated in this region and at the heads of numerous other outflow systems on Mars. However, it is not clear that confidence in this premise is warranted. Continued investigation into proposed aqueous mechanisms of outflow channel formation on Mars has served to highlight their many associated limitations. Perhaps most critically, the volumes and peak discharge rates of hypothesized Martian floods remain unreconciled with the expected regional-scale permeabilities of even highly porous materials [e.g., *Harrison and Grimm*, 2008]. Outburst models have been modified to reduce the impact of these permeability issues through the proposition of widespread physical disruption of host aquifer materials [e.g., *Carr*, 1996], but these modified models nevertheless appear to be inconsistent with the sediment-water ratios required for flow of disrupted materials to occur, and cannot account for the constraints on outflow rates imposed by the diffusion limits of intact aquifers surrounding disrupted zones [*Andrews-Hanna and Phillips*, 2007]. The hypothesized scenario of *Coleman et al.* [2007] for outflow channel formation at Ophir and Aurorae Plana is further complicated by reliance upon the catastrophic nature of hypothesized events, with sudden outbursts from aquifers presumably preceded by some form of catastrophic infiltration from deep Valles Marineris lakes to these aquifers.

[13] Hypotheses for the existence of large cryosphere-confined aquifers on ancient Mars were originally formulated as a means to account for the basic nature of outflow systems on that planet [*Carr*, 1979], but, although efforts to identify possible evidence for the past existence of large Martian aquifers continue [e.g., *Treiman*, 2008; *Mangold et al.*, 2008b], the past existence of such aquifers remains uncertain [e.g., *Russell and Head*, 2002; *Fassett and Head*, 2008]. Related hypotheses for the catastrophic aqueous development of Martian outflow systems continue to be weakened by the absence of satisfactory analog processes for the sudden release of large volumes of water from the subsurface. Although terrestrial landscapes such as the Channeled Scabland of Washington and the flood systems of the Mongolian plateau have been cited as possible analogs to the terrain that characterizes outflow systems on Mars [e.g., *Baker and Milton*, 1974; *Sharp and Malin*, 1975; *Komatsu et al.*, 2004; *Andrews-Hanna and Phillips*, 2007], including the channels of Ophir and Aurorae Plana

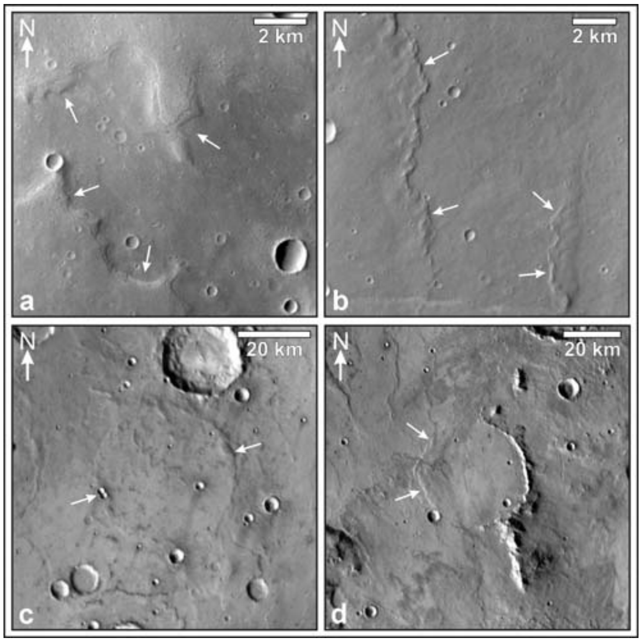

Figure 6. Landforms common at Ophir and Aurorae Plana include (a) lobate- and cuspate-margined units, (b) wrinkle ridges, and (c and d) ridges associated with the mantled rims of impact craters. On the Moon, such features are characteristic of mare-style lava inundation and subsidence (Figure 7). THEMIS image V26986004, center 54°14′30″W, 12°26′S (Figure 6a); THEMIS image V27635002, center 57°21′W, 10°11′S (Figure 6b); THEMIS daytime infrared mosaic courtesy of Arizona State University, centers 51°52′W, 6°10′S and 56°50′W, 6°14′S (Figures 6c and 6d).

[*Coleman et al.*, 2007], the mechanisms of formation of terrestrial systems may offer little in the way of insight into the root causes of outflow channel formation on Mars [*Leverington*, 2007]. Whereas outflow systems such as those of Ophir and Aurorae Plana developed as a result of voluminous flow from the subsurface, the widely cited landforms of the Channeled Scabland formed in response to entirely different processes related to the release of floodwaters from an ice-dammed lake [e.g., *Bretz et al.*, 1956; *Baker*, 1978a; *Smith*, 1993]. In the near term, substantial progress in our understanding of Martian outflow systems such as those of Ophir and Aurorae Plana may depend upon identification of genuine analog processes to those that initiated development of these systems.

4. A Volcanic Alternative to Aqueous Development of the Outflow Channels of Ophir and Aurorae Plana

[14] The difficulties associated with hypothesized aqueous mechanisms of channel development at Ophir and Aurorae Plana suggest that promising alternative processes should be investigated. Although aeolian, glacial, and CO_2-based processes of channel formation have been previously rejected for the Ophir and Aurorae systems [*Coleman et al.*, 2007], volcanism [*Cutts et al.*, 1978; *Schonfeld*, 1979; *Leverington*, 2004a, 2007] has not yet been closely examined as a possible mechanism for initiation and development of these systems. Significantly, a volcanic origin for these systems appears to be in accord with numerous basic considerations, including the volcanotectonic nature of the Valles Marineris region, the likely development of much of the Ophir and Aurorae Plana region itself through extrusive igneous processes, the consistency between properties of local channel deposits and those expected of volcanic materials, the correspondence between channel characteristics and those of volcanic analogs of the inner solar system, and the consistency between defining features of the Ophir and Aurorae Plana systems and recognized volcanic processes involving voluminous flow from the subsurface.

4.1. Consistency of Channel Properties With Volcanic Origins

[15] A volcanic origin for the outflow channels of Ophir and Aurorae Plana is consistent with the volcanotectonic nature of the Valles Marineris system. This system consists of deep (~5 to 10 km) Hesperian-aged troughs that have attributes congruous with formation by rift-like processes involving extension, normal faulting, and subsidence [e.g., *Plescia and Saunders*, 1982; *Lucchitta et al.*, 1992; *Schultz*, 1995; *Mège and Masson*, 1996; *Wilkins and Schultz*, 2003; *Borraccini et al.*, 2007]. Formation of the Valles Marineris system appears to have been at least partly related to development of structural features oriented radially to Tharsis [*Carr*, 1974a], a large volcanic province characterized by an extended history (Noachian to Amazonian) of igneous processes involving substantial crustal construction and uplift [e.g., *Carr*, 1974a; *Phillips et al.*, 1990; *Okubo and Schultz*, 2003; *Williams et al.*, 2008; *Jellinek et al.*, 2008]. Although mantling deposits of the interior of Valles Marineris consist in part of layered and partly eroded Hesperian units of apparent sedimentary origin [e.g., *Komatsu et al.*, 1993a; *Quantin et al.*, 2005; *Fueten et al.*, 2008], as well as mass wasting deposits that have accumulated along trough flanks [e.g., *McEwen*, 1989; *Lucchitta et al.*, 1994; *Peulvast et al.*, 2001; *Komatsu et al.*, 2009], exposed floor units consist at least partly of volcanic flows [e.g., *Christensen et al.*, 2003] and the layered units of canyon walls have properties consistent with formation through extrusive and intrusive igneous processes [e.g., *Geissler et al.*, 1990; *McEwen et al.*, 1999; *Williams et al.*, 2003; *Edwards et al.*, 2008].

[16] Aurorae Planum and eastern Ophir Planum together comprise an upland that is substantially composed of Hesperian-aged ridged plains that are contiguous with and comparable in nature to the plains of Lunae Planum to the northwest [e.g., *Scott and Tanaka*, 1986]. These plains consist in part of surface units that have lobate and cuspate margins, that are associated with ring-like ridges and zones of deformation, and that are structurally overprinted by wrinkle ridges (i.e., broad low-relief arches with narrow superimposed ridges) [e.g., *Watters*, 2004] (Figure 6). On other bodies of the solar system, this combination of characteristics is typical of volcanic plains, with lobate or cuspate margins corresponding to the flow fronts of volcanic units [e.g., *El-Baz*, 1972; *El-Baz and Roosa*, 1972; *Schultz*, 1976; *Wilhelms*, 1987; *Hörz et al.*, 1991; *Zimbelman*, 1998; *Keszthelyi et al.*, 2004], ring-like ridges and zones of

Figure 7. The Herigonius region of the Moon is mantled by mare-style lava flows [*Marshall*, 1963; *Greeley and Spudis*, 1978]. Landforms of this region include wrinkle ridges (w), ridges associated with lava-mantled crater rims (arrows), and sinuous volcanic channels (R). Crater Herigonius (H) is located at image bottom, and the gamma ray spectrometer boom of the Apollo 16 Command Module is visible at right. Apollo 16 Metric Photo 2836. (Center is 34°30′W, 10°30′S.)

deformation corresponding to areas of subsidence of volcanic units onto the thinly mantled rims of flooded impact craters [e.g., *Schultz*, 1976; *Greeley and Spudis*, 1978; *Wilhelms*, 1987], and wrinkle ridges corresponding to structural features formed through subsidence and contraction of layered volcanic units [e.g., *Bryan*, 1973; *Schultz*, 1976; *Maxwell*, 1978; *Whitford-Stark and Head*, 1980; *Wilhelms*, 1987; *Watters*, 1988, 2004] (Figure 7). Although alternative aqueous interpretations have been forwarded [e.g., *Battistini*, 1984], the existence of these features at Ophir and Aurorae Plana is consistent with development of surface units through effusion of low-viscosity lavas [e.g., *Scott and Tanaka*, 1986], with the scarcity of well-exposed volcanic vents consistent with the nature of flood lavas on bodies such as the Earth, Moon, and Venus [e.g., *Young et al.*, 1973; *Greeley and Spudis*, 1978]. As with numerous other Martian regions mantled by volcanic flows, Imaging Spectrometer for Mars (ISM) data indicate that the materials of Ophir and Aurorae Plana have visible and infrared reflectance properties that are in accord with those expected of two pyroxene shergottite basalts [*Mustard et al.*, 1997].

[17] The varying competence of layers exposed at eastern Coprates Chasma suggests that deposition of the units that comprise the stack underlying Ophir and Aurorae Plana could have involved changes in volcanic sources or in environmental conditions over time [*Beyer and McEwen*, 2005]. The weathering characteristics of the most resistant units visible at high resolution in chasma walls are consistent with those expected of volcanic flows, whereas the characteristics of lighter toned and less resistant layers are suggestive of materials of pyroclastic or sedimentary origins [*Malin et al.*, 1998; *McEwen et al.*, 1999; *Watters*, 2004; *Beyer et al.*, 2007]. Along the Ophir and Aurorae channels, the presence of angular blocky ejecta is typical of fresh impact craters formed in well-exposed flat-lying units near channel heads (e.g., the infill materials of Morella crater) and along the floors of many channel reaches (e.g., Figure 8a), suggesting a relatively high level of consolidation in such areas. Reaches along which small craters generally lack this

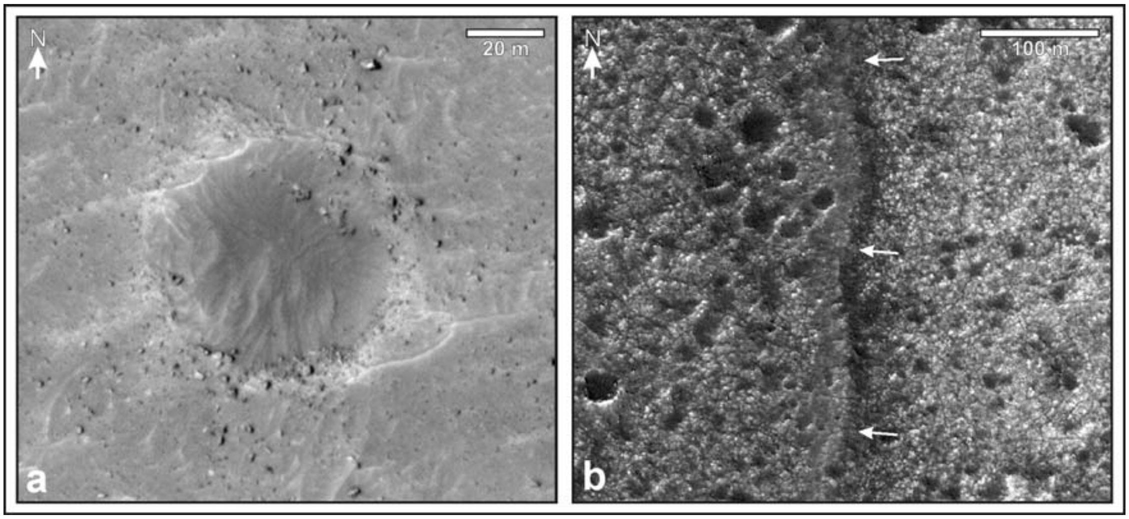

Figure 8. (a) Blocky impact ejecta associated with a small (~70-m-diameter) impact crater in floor materials of Elaver Vallis, and (b) the lobate periphery of a dark-toned unit that forms part of the infill of Morella crater [*Komatsu et al.*, 2009]. HiRISE images PSP_006229_1700 (Figure 8a) and PSP_005728_1705 (Figure 8b).

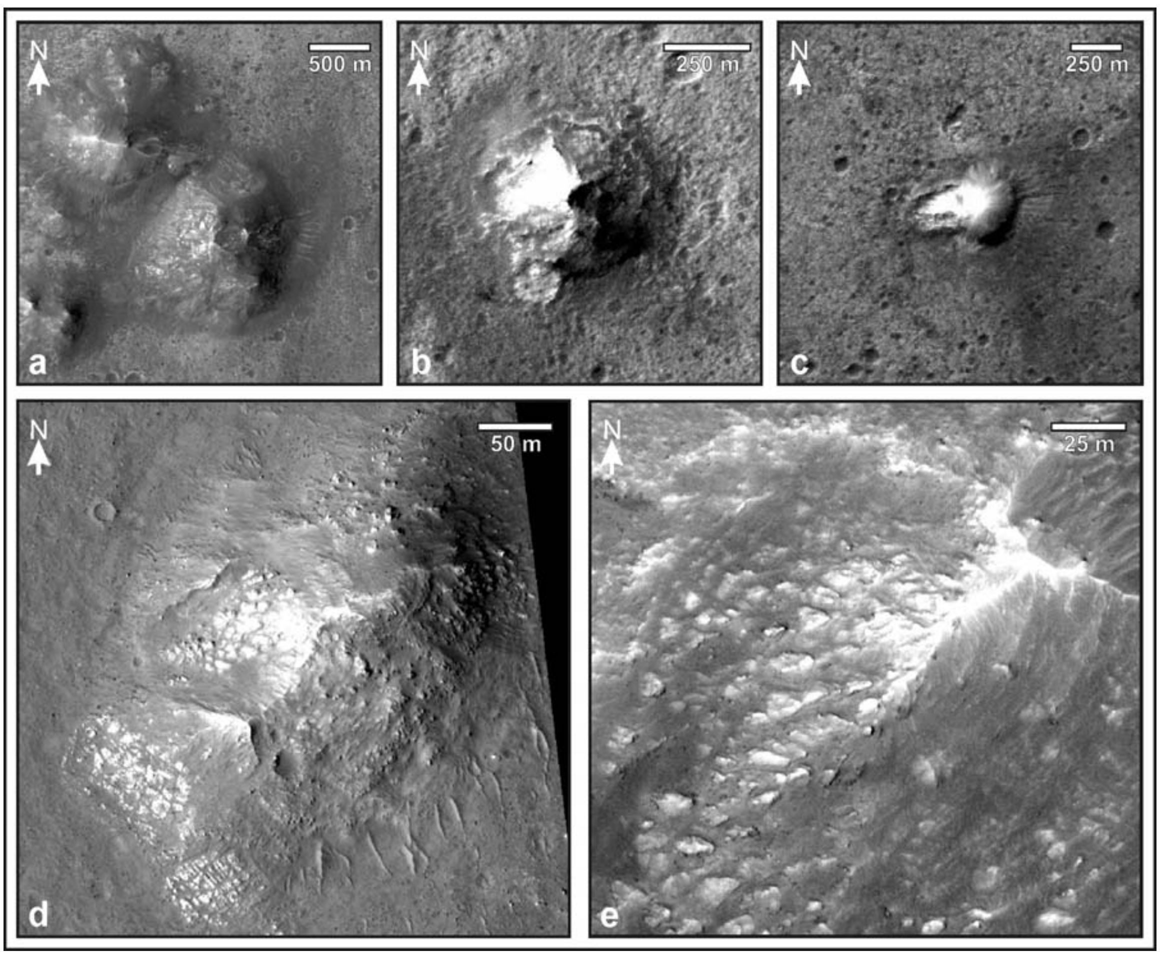

Figure 9. Mound and cone landforms of the interior of Morella crater, a component of the head region of Elaver Vallis. The flanks of some landforms are partly composed of materials with a platy or slabby nature (e.g., Figures 9a, 9d, and 9e), and some cones have summit pits (e.g., Figures 9a and 9b). Mars Orbiter Camera (MOC) images (a) R0600262, (b) E0302359, and (c) E2001359, and HiRISE images (d) PSP_003183_1705 and (e) PSP_005728_1705.

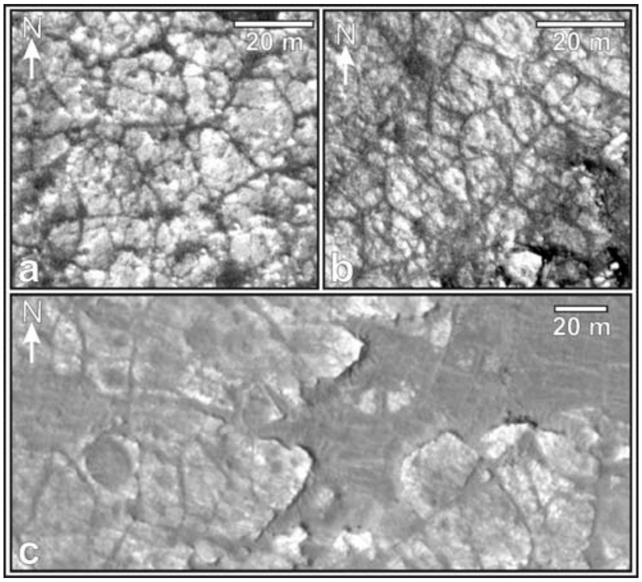

Figure 10. The fractured, slabby, and blocky character of the infill materials of (a) Morella crater is similar to that of volcanic flows that extend across the caldera of (b) Nili Patera. Patches of materials sharing this character are also present along peripheral uplands to the heads and main channels of the Ophir and Aurorae systems, including uplands located north of (c) Ophir Cavus. Nighttime thermal data suggest a relatively high level of consolidation for these materials (e.g., see THEMIS images of Morella crater, Nili Patera, and Allegheny Vallis uplands: I18306006, I08293012, and I16846011, respectively). The relatively dark line segments that define polygons are likely to be composed mainly of loose sediments. HiRISE images PSP_005728_1705 (Figure 10a), PSP_005684_1890 (Figure 10b), and ESP_011991_1700 (Figure 10c).

blocky character include the head area of Allegheny Vallis, where THEMIS nighttime thermal imagery and cross-sectional exposures at Ophir Cavus suggest the presence of a surface veneer of poorly consolidated materials.

[18] Although not uniquely indicative of volcanic origins, the properties of exposed channel materials at Ophir and Aurorae Plana are compatible with those expected of volcanic materials and landforms. Surface layers present at all three channel heads, and along some channel reaches, have raised and lobate margins (e.g., Figure 8b) that are broadly consistent with the properties expected of flows of a range of possible types, including both mudflows and volcanic flows [e.g., *Mouginis-Mark*, 1985; *Squyres et al.*, 1987; *Christiansen*, 1989; *De Hon*, 1992; *Burr et al.*, 2002; *Wilson and Mouginis-Mark*, 2003; *Leverington and Maxwell*, 2004; *Williams and Malin*, 2004]. Though other possibilities cannot be ruled out, the lobate margins, dark tones, and apparent subsurface sources of deposits located at the heads of the Walla Walla and Elaver systems are consistent with volcanic origins [*Komatsu et al.*, 2009]. A volcanic origin for these and related deposits would be congruous with volcanic interpretations of mound and cone landforms associated with the infill deposits of Morella crater. The diameters of these landforms (∼200 to 1200 m) exceed those of common terrestrial tumuli by more than an order of magnitude [e.g., *Walker*, 1991; *Duncan et al.*, 2004], but are, along with the summit pits that characterize some cones (Figure 9), consistent with the properties of candidate volcanic cones located in other regions of Mars [e.g., *Meresse et al.*, 2008]. The flanks of some mounds and cones at Morella crater have a distinctly platy or slabby nature that is consistent with volcanic origins involving disruption and heaving of chilled lava crusts by processes involving the dynamics of underlying magma bodies, though a range of other possible formation mechanisms is possible, including subsidence of volcanic crusts upon the surfaces of volcanically submerged landforms. Some mound and cone landforms associated with other Martian outflow systems have previously been interpreted as possible ice cored hills [e.g., *Burr et al.*, 2005, 2009; *Page and Murray*, 2006] on the basis of morphological similarities to terrestrial pingos [e.g., *Mackay*, 1990]. Although at least some of the mounds of Morella crater possess the outward-dipping flanks that are commonly associated with pingos (e.g., Figure 9d), this characteristic is not unique to ice cored hills, and the long-term temperature and pressure conditions expected of low Martian latitudes [e.g., *Farmer and Doms*, 1979] are not favorable here for development and preservation of ice cored landforms. Development of the Morella features through spring-related processes or mud volcanism [e.g., *Bourke et al.*, 2007; *Skinner and Mazzini*, 2009] cannot be ruled out, but the presence of unaltered olivine-rich units here and at Ganges Chasma [*Edwards et al.*, 2008; *Koeppen and Hamilton*, 2008; *Komatsu et al.*, 2009] may be incompatible with these mechanisms.

[19] The fractured and disrupted characteristics of the flanks of landforms at Morella crater are also typical of associated flat-lying and polygonally jointed infill units (Figure 10a), with the platy or slabby nature of Morella surface units suggested by the tilting or lateral offset of a minority of polygonal facets in a manner suggestive of rigid cohesion. Materials sharing these properties are also found in upland locations adjacent to the Ophir and Aurorae channels (Figure 10c), and across parts of the infill deposits of the 40-km-wide crater located southeast of the head of Walla Walla Vallis (e.g., High Resolution Imaging Science Experiment (HiRISE) image PSP_010435_1700). The slabby nature of the Ophir and Aurorae Plana materials implies that the polygonal texture here is unlikely to be the product of ice wedge development or freeze-thaw convection in loose sediments. Polygonal fracture systems commonly develop in the upper crusts of lava flows and lava lakes as a response to tensile stresses related to thermal contraction, shear stresses related to lava flow and convection, and crustal deformation related to processes including flow inflation and subsidence [e.g., *Peck and Minakami*, 1968; *Hon et al.*, 1994; *Dance et al.*, 2001]. Importantly, the polygonal fractures and slabby nature of the Ophir and Aurorae materials also characterize some Martian lava units, including those that extend across the Nili Patera caldera in Syrtis Major (Figure 10b). Also, cross-sectional exposures of Ophir and Aurorae units characterized by the polygonal fractures (Figure 11) have a blocky character that suggests consolidation, and that is shared with lava flows located in other regions of Mars [e.g., *Mouginis-Mark and Rowland*, 2008]. The fractured and blocky nature of the Ophir and

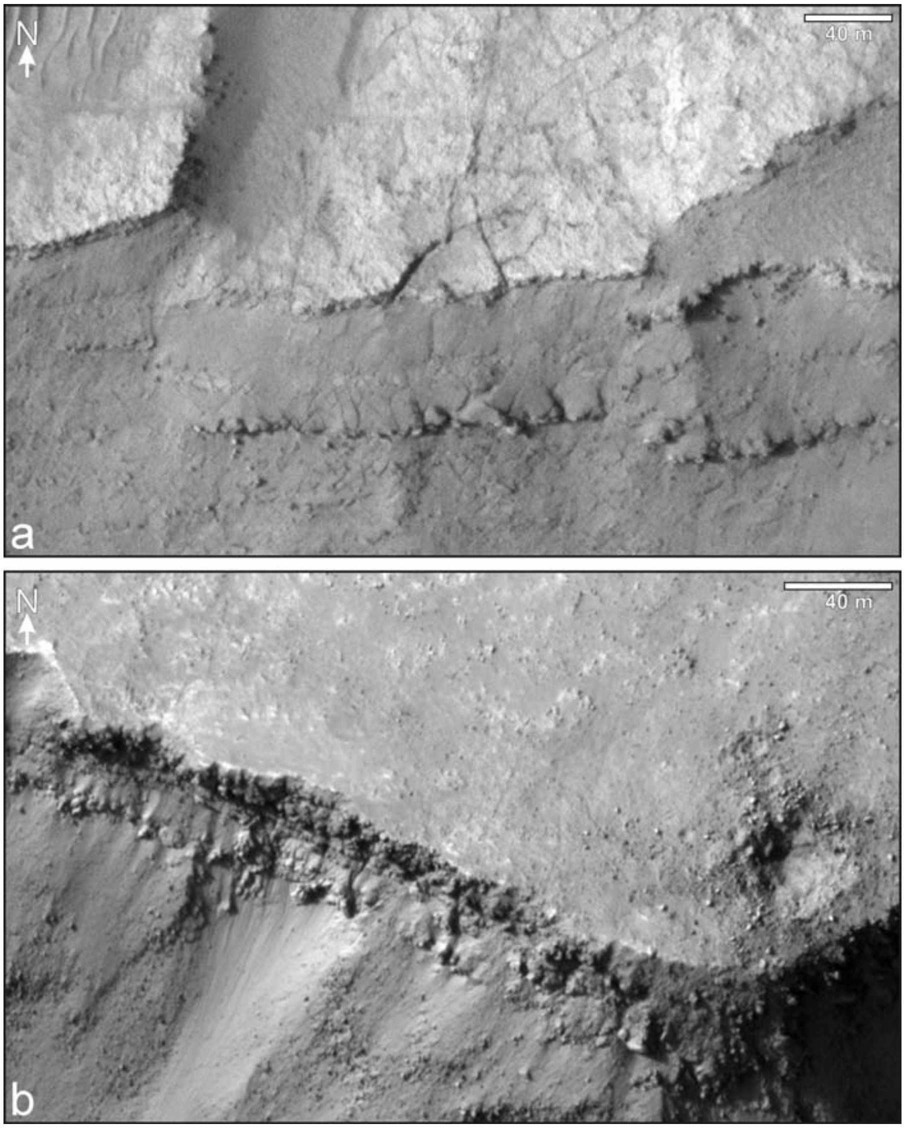

Figure 11. (a) Resistant units that form the upper layers of Ophir Planum near the easternmost reaches of the Allegheny Vallis system are exposed along the walls of western Ganges Chasma; bedrock layers are offset along two high-angle faults in the depicted exposure. (b) Units that form part of the upper infill deposits of Morella crater are exposed along the northern rim of Ganges Cavus. A relatively high level of consolidation is implied in Figures 11a and 11b by the blocky or platy nature of materials and by the relatively high nighttime thermal temperatures of well-exposed outcrops (e.g., THEMIS images I05888006 and I06612006, respectively). HiRISE images ESP_011292_1720 (Figure 11a) and PSP_009802_1700 (Figure 11b).

Aurorae units, and the relatively consolidated nature of associated materials as inferred from nighttime THEMIS images, distinguishes them from the poorly consolidated and polygonally subdivided deposits that discontinuously mantle upland plains in the Valles Marineris region and that are believed to be enriched in hydrated silicates [*Le Deit*, 2008; *Milliken et al.*, 2008].

[20] Units subdivided by fine polygonal surface patterns are exposed along at least one reach of Allegheny Vallis, though the slabby property noted above is not evident here (Figure 12). The ~3–5 m diameters of individual polygons fall within the size ranges of fractures that commonly develop in lava flows and lava lakes [e.g., *Peck and Minakami*, 1968] but, as at Morella crater, there is no clear evidence here for the subtle upbowing of polygon centers that is sometimes associated with fractured volcanic units. Although the smallest terrestrial ice wedge polygons fall within the 1–5 m size range [e.g., *Mollard and Janes*, 1984], and excellent examples of patterned ground of likely periglacial origin have been recognized on Mars at higher latitudes [e.g., *Seibert and Kargel*, 2001; *Kargel*, 2004; *Mangold*, 2005; *Mellon et al.*, 2008], development of ice wedge polygons is generally not expected at the low latitudes of Ophir and Aurorae Plana. Desiccation and a wide range of weathering processes can also result in development of patterned ground with polygon sizes that fall within this size range [e.g., *Huddart and Bennett*, 2000;

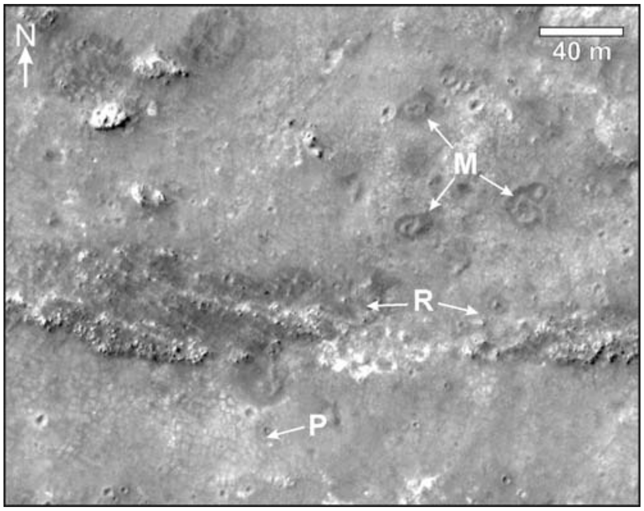

Figure 12. Fine polygonal networks (P), block-rich longitudinal ridges (R), and small ring-like mounds (M) exposed along the floor of Allegheny Vallis. Individual polygons are ~3–5 m across, and the dark lines that define polygons are likely composed of loose sediments. HiRISE image PSP_009868_1715.

Chan et al., 2008], and represent candidate mechanisms for formation of this surface texture.

[21] Boulder-rich residual mantles are locally found along some reaches of Allegheny Vallis, and small ring-like mounds are found along at least one reach of this system (Figure 12). The ring-like mounds typically have small diameters (<20 m) and relatively large central pits. The significance of these mounds is unclear, as is the relation (if any) between the mounds and underlying channel materials. Interestingly, the volcanic flows of Athabasca Valles (one of several prominent outflow systems of the Cerberus plains region) are associated with igneous "ring-mound landforms" (RML's), features that commonly have a ring-like form and distinctly platy or upturned flanks [e.g., *Jaeger et al.*, 2007]. There is no obvious relation between the small ring mounds of Allegheny Vallis and the generally larger (typically ~20–120 m diameter) and platy Cerberus RML's, but the Cerberus mounds suggest that ring-like igneous landforms should not be unexpected along well preserved reaches of Martian outflow systems.

[22] The systems of longitudinal ridges and gullies that characterize some reaches of the Ophir and Aurorae channels (Figure 13) [see also *Komatsu et al.*, 2009] are similar in nature to those found along many other outflow systems on Mars [e.g., *Baker*, 1982; *Mars Channel Working Group*, 1983]. On the basis of preserved diluvial landforms of the Earth, including the longitudinal ridges of the Channeled Scabland of Washington [*Baker*, 1978b], the ridge systems of Martian outflow channels are widely interpreted as bed forms produced by deep scour related to vortices in aqueous floods [e.g., *Baker and Milton*, 1974; *Baker*, 1982; *Carr*, 1996; *Burr*, 2003]. An aqueous origin for the longitudinal ridges and gullies of the channels at Ophir and Aurorae Plana would be consistent with such interpretations. However, the possibility of volcanic origins for these features should not be dismissed. As at other Martian outflow systems, the longitudinal features of Ophir and Aurorae Plana are in some cases characterized by morphological irregularities unexpected of landforms developed through aqueous scour of flat-lying basalt units (e.g., the tilted units depicted in Figures 13c and 13d). The combined capacity of volcanic flows both for erosion [e.g., *Hulme and Fielder*, 1977; *Hulme*, 1982] and construction of bedrock landforms [e.g., *Greeley*, 1973; *Wanless*, 1973; *Carr et al.*, 1977; *Bleacher et al.*, 2007b; *Pain et al.*, 2007] may in the future help to account for the existence of such irregular features along channel floors.

[23] Significantly, the nearly pristine lava flows of young outflow systems in the Cerberus plains region of Mars are characterized along some reaches by parallel sets of longitudinal features previously interpreted as the products of aqueous scour [e.g., *Berman and Hartmann*, 2002; *Burr et al.*, 2002; *Rice et al.*, 2002] (Figure 14a). These features exist as a morphological continuum that extends from sharp longitudinal ridges to blocky ridges to ridges composed partly of upturned layers or ridge-forming arrangements of RML's (Figure 14b), landforms now recognized as primary volcanic features that developed during emplacement of related lava flows [*Jaeger et al.*, 2007]. The existence of this continuum suggests that the large sets of longitudinal features of young outflow systems such as Athabasca Valles are themselves primary volcanic features and not the products of aqueous scour. Interestingly, the Ophir and Aurorae landforms depicted in Figures 13c and 13d have forms that are similar to the tilted or upturned layers of channelized lava flows of the Cerberus plains region (Figures 14c and 14d), though any shared morphological qualities may be merely superficial and unrelated to common mechanisms of formation. There is no clear link between the well-preserved longitudinal features of the Cerberus plains region and the weathered and more widely spaced ridges of the channels of Ophir and Aurorae Plana, but the Cerberus landforms nevertheless indicate that the dynamics involved in emplacement of large channelized lava flows on Mars can result in development of large systems of parallel longitudinal channel features.

[24] The pristine channelized flows of the Cerberus plains region also show clear evidence for having periodically overflowed channel margins, resulting in the partial mantling of adjacent uplands by lobate-margined volcanic deposits [e.g., *Jaeger et al.*, 2007]. Lobate-margined flow units similarly mantle uplands adjacent to some reaches of the Ophir and Aurorae channels (Figure 15), and, as in the Cerberus plains region, these units appear to have been emplaced as overflow deposits during periods of high discharge.

4.2. Proposed Solar System Analogs to the Outflow Channels of Ophir and Aurorae Plana

[25] The basic attributes of the Ophir and Aurorae channels are potentially consistent with volcanic origins involving processes of effusion, construction, erosion, and subsidence. The capacity of volcanic processes for generation of outflow systems has previously been recognized, and numerous channel systems of the inner solar system are

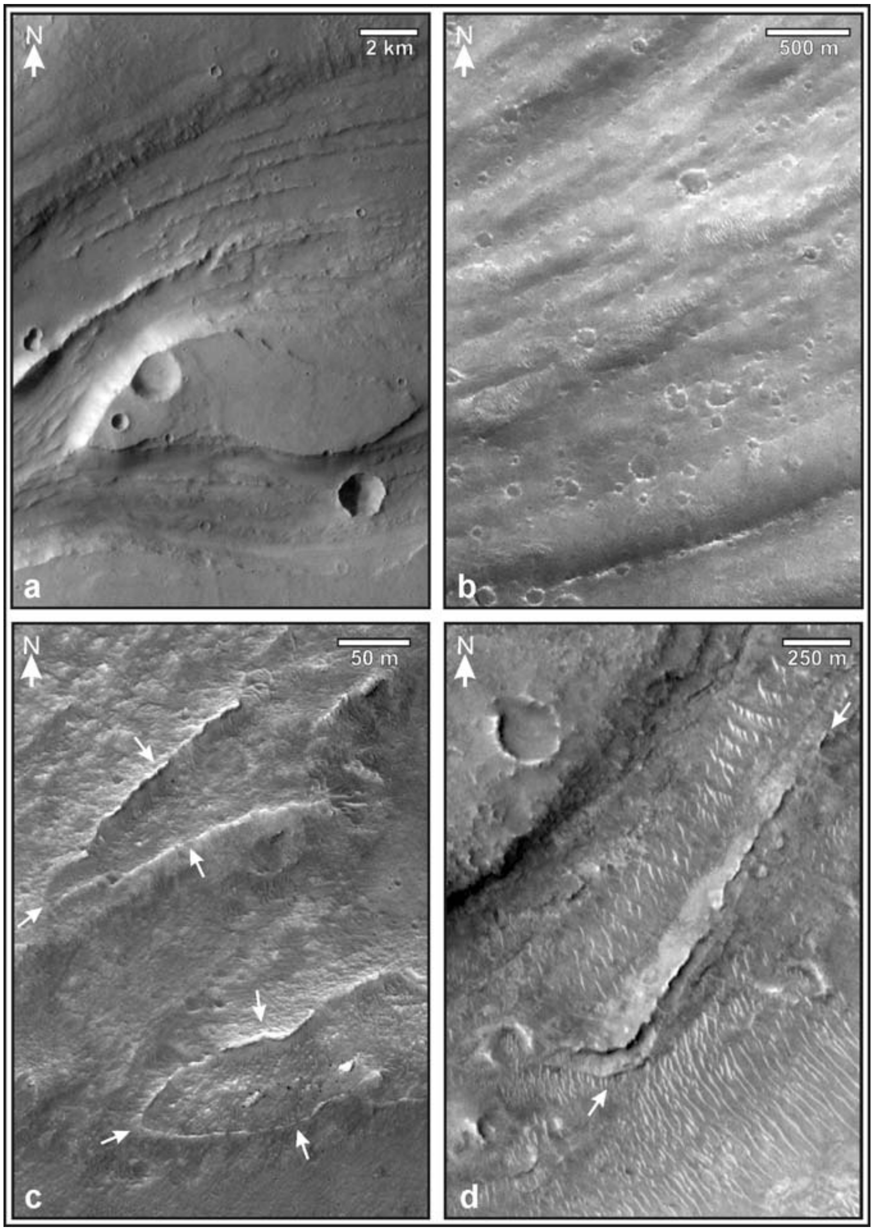

Figure 13. Longitudinal ridges exposed along channel reaches of (a–c) Elaver Vallis and (d) Allegheny Vallis. The landforms in Figures 13c and 13d have axes oriented parallel to the direction of paleoflow and appear to be partly composed of tilted or upturned layers; such landforms are unlikely to be the products of aqueous scour of flat-lying units. THEMIS image V26886003, center 48°47′W, 8°57′S (Figure 13a), MOC image E0902605, center 48°19′W, 8°55′S (Figure 13b), HiRISE image PSP_005662_1700, center 50°07′W, 9°38′ S (Figure 13c), and MOC image M0302478, center 53°38′W, 8°36′S (Figure 13d).

interpreted as volcanic [e.g., *Greeley*, 1971, 1977; *Greeley and Spudis*, 1978; *Schultz*, 1976; *Wilhelms*, 1987; *Baker et al.*, 1992, 1997; *Komatsu and Baker*, 1994; *Oshigami et al.*, 2009]. For the purposes of the present paper, channels are categorized as "outflow systems" on the basis of their development through voluminous fluid effusion from the subsurface. Although alternative aqueous interpretations have been proposed [e.g., *Jones and Pickering*, 2003; *Waltham et al.*, 2008], the outflow systems of Venus and the Moon are generally believed to have formed through extrusive igneous processes in the absence of water [e.g., *Greeley*, 1971; *Wilhelms*, 1987; *Baker et al.*, 1992, 1997]. Igneous interpretations of these systems are based in part upon the widespread association of channel systems with volcanic landscapes and flows, the apparently depleted nature of Venus and the Moon with regard to bulk volatile contents [e.g., *Papike et al.*, 1991; *Donahue and Russell*, 1997; *Nimmo and McKenzie*, 1998; *Taylor*, 2005], the likely long-term instability of water at the surfaces of Venus and the Moon [e.g., *Wilhelms*, 1987; *Kargel et al.*, 1993; *Taylor*, 2005], and the absence of associated landforms suggestive of past wet conditions. Samples collected at lunar Rima Hadley are predominantly of basaltic composition and lack aqueous alteration [e.g., *Swann et al.*, 1972], and the

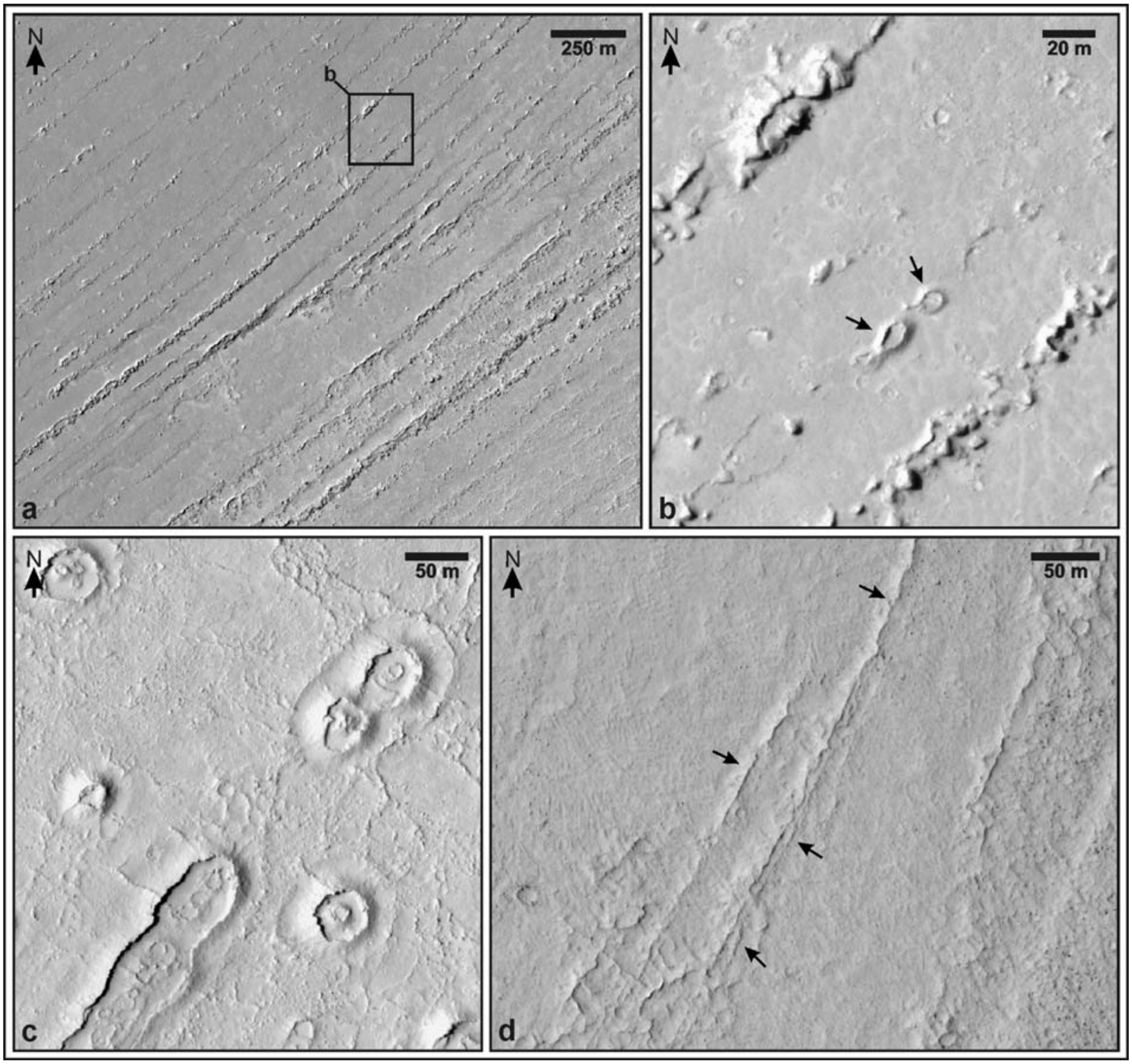

Figure 14. Large systems of (a) longitudinal features developed in lava flows at Athabasca Valles are partly composed of both (b and c) equant and elongate classes of RML features, each mound partly defined by upturned layers. Longitudinal ridge systems of the Cerberus plains are also partly formed by lineate exposures of upturned layer edges, as at (d) Lethe Vallis. All of these landforms appear to be primary volcanic features developed during emplacement of associated flows [*Jaeger et al.*, 2007, 2008], suggesting a capacity for development of longitudinally oriented features by large channelized lava flows. HiRISE image PSP_008344_1895, centers 156°07′E, 9°30′N and 156°09′E, 9°36′N (Figures 14a and 14b), HiRISE image PSP_002226_1900, center 156°26′30″E, 9°39′N (Figure 14c), and HiRISE image PSP_006762_1840, center 155°26′30″E, 3°43′N (Figure 14d).

reflectance characteristics of units exposed at other large lunar channels do not suggest major compositional deviations from nearby mafic units. Although exotic magma compositions have been cited as necessary for Venusian outflow channels and canali to have developed as volcanic systems [e.g., *Kargel et al.*, 1994; *Bray et al.*, 2007; *Treiman*, 2009], the lunar record strongly suggests that lavas of mafic composition can indeed have the capacity for low-viscosity flow [e.g., *Murase and McBirney*, 1970; *Weill et al.*, 1971; *Head*, 1976; *Hulme*, 1982], substantive vertical and lateral erosion [e.g., *Howard et al.*, 1972; *Carr*, 1974b; *Schultz*, 1976; *Strain and El-Baz*, 1977; *Hulme and Fielder*, 1977; *Greeley and Spudis*, 1978; *Leverington*, 2004a, 2006], and extreme lengths for both open flows [e.g., *Schaber*, 1973; *Schaber et al.*, 1976] and flows conveyed by sinuous channels (e.g., Rima Brayley) [*Young et al.*, 1973]. Geochemical data collected at the Venera and Vega landing sites are consistent with mafic igneous compositions [*Surkov*, 1983; *Surkov et al.*, 1987; *Kargel et al.*, 1993], though data are not presently available for units exposed at Venusian channels.

[26] Many Venusian and lunar channel systems head at sites of fluid effusion marked by distinct topographic depressions that are similar in nature to those located at

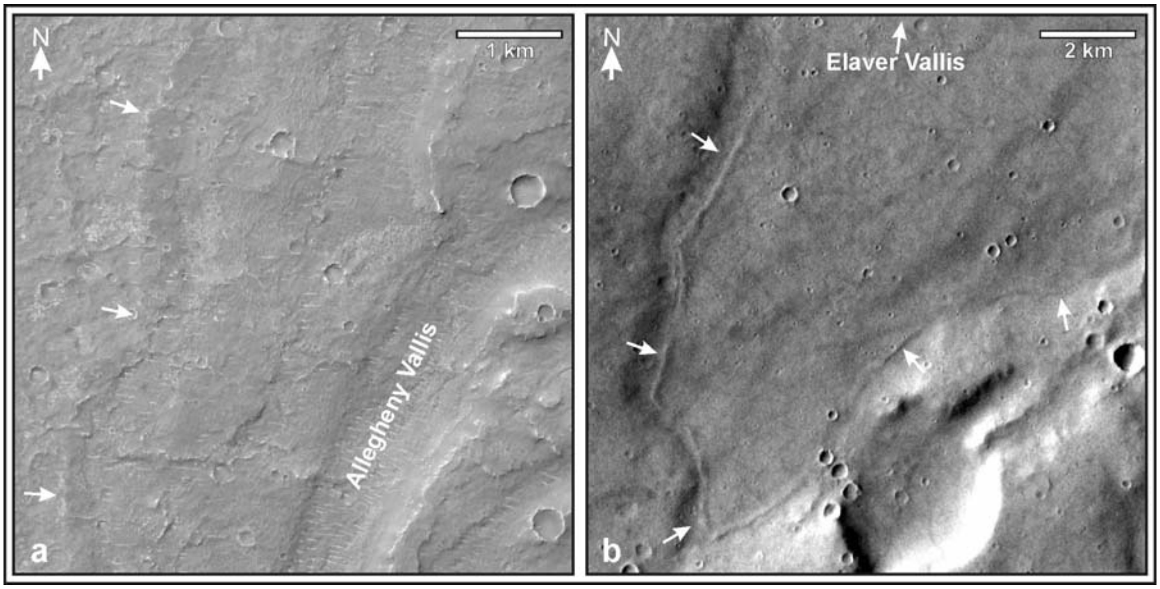

Figure 15. Uplands that are peripheral to the outflow channels of Ophir and Aurorae Plana are mantled along some reaches by lobate-margined flow units that appear to be overflow deposits or, alternatively, flows emplaced prior to main channel development. The above images show flow materials emplaced along the distal reaches of (a) Allegheny Vallis and (b) Elaver Vallis. The positions of distinct flow fronts are marked by arrows. HiRISE image PSP_009578_1715, center 53°34′W, 8°19′S (Figure 15a) and THEMIS image V27173003, center 48°44′W, 9°34′S (Figure 15b).

the heads of the Ophir and Aurorae systems. The heads of some lunar and Venusian systems have elongate geometries suggestive of structural control, and thus are potential analogs to the heads of Allegheny Vallis and Walla Walla Vallis. Other lunar and Venusian systems head at depressions that share the relatively symmetrical geometry of the head of Elaver Vallis. Of fundamental importance in the consideration of lunar and Venusian outflow systems as possible analogs to the Ophir and Aurorae channels is the presumed common mechanism of channel initiation and development: voluminous effusion of fluid from the subsurface.

[27] A partly roofed volcanic channel located northeast of lunar crater Plato heads at a 15-km-long depression (Figure 16) and sinuously extends across Imbrian-aged uplands toward Mare Frigoris [*M'Gonigle and Schleicher*, 1972; *Leverington*, 2004a]. Other lunar channel systems that head at elongate depressions include those of the Rimae Herigonius system [*Greeley and Spudis*, 1978], Rima Hadley [*Greeley*, 1971; *Howard et al.*, 1972], and the four large channels of Rimae Prinz [*Schultz*, 1976; *Strain and El-Baz*, 1977]. Examples of lunar channels that head at relatively symmetric topographic depressions include the largest of the sinuous lunar rilles, Vallis Schröteri [*El-Baz and Worden*, 1972; *Schultz*, 1976]. All three of the elevated Martian outflow systems of Ophir and Aurorae Plana extend across topographic barriers in a manner consistent with incision by surface flows, a characteristic shared with numerous lunar channels including Rima Beethoven [e.g., *Strain and El-Baz*, 1977; *Wilhelms*, 1987; *Leverington*, 2004a] and the upland-crossing channels of Rimae Herigonius and Rimae Maupertuis [e.g., *Young et al.*, 1973; *Greeley and Spudis*, 1978; *Leverington*, 2006]. Streamlined landforms are associated with a minority of lunar channels, including a rille at crater Krieger that contains a 2-km-long "teardrop island" [*Leverington*, 2004a]. Subsidence below the rims of flooded basins, likely resulting from processes including phase change, devolatization, and magma drainback, is typical of volcanic infill of lunar topographic depressions [e.g., *Schultz*, 1976; *Greeley and Spudis*, 1978].

[28] There are numerous examples of Venusian channels that share key characteristics with the outflow systems at Ganges Chasma. For example, Belisama Vallis, a system located immediately south of the Sigrun Fossae deformation

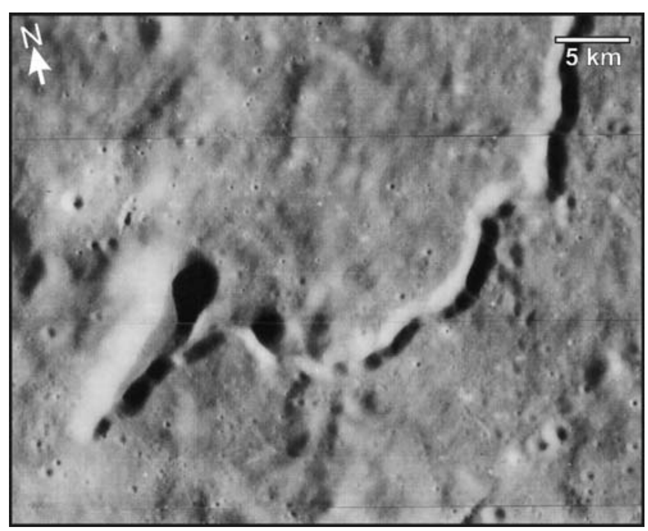

Figure 16. A 160-km-long lunar channel that heads at a 15-km-long topographic depression in highlands near crater Plato. Lunar Orbiter image IV-127-H3, center 4°0′W, 52°40′N.

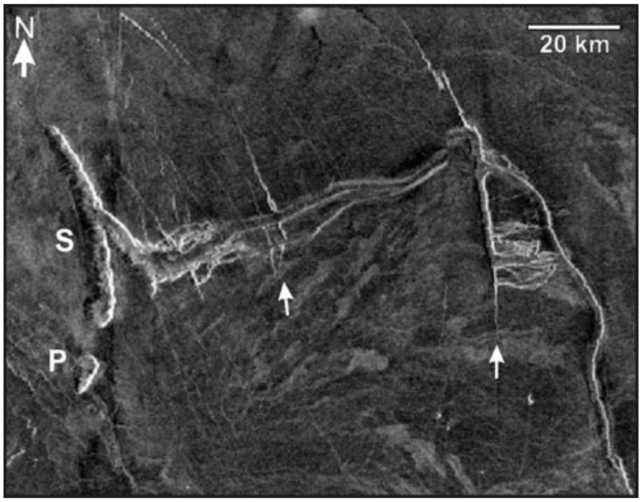

Figure 17. Belisama Vallis, a 350-km-long Venusian channel system located in Ishtar Terra, heads at a 42-km-long topographic depression (S). An associated pit (P) is located south of the main depression, and the orientation of both depressions is approximately concentric with prominent structural features in the region (arrows). Further downslope, southeast of the depicted region, this system broadens to a width of ~10 km and anastamoses complexly about streamlined landforms with long axes of up to ~10 km [*Baker et al.*, 1992]. Magellan full-resolution radar map (FMAP) left-look Synthetic Aperture Radar (SAR) mosaic; the slight vertical offset of the rightmost quarter is a mosaic artifact. SAR illumination is from the left. Center is 22°08′E, 50°30′N.

belt in southern Ishtar Terra, heads at a 42-km-long topographic depression that is concentric with structures formed in response to regional crustal extension [e.g., *Baker et al.*, 1992; *McGill*, 2004] (Figure 17). The Belisama Vallis system has channel widths as great as ~10 km, and along some reaches complexly anastamoses about streamlined landforms that appear to be erosional residuals [*Baker et al.*, 1992]. Other Venusian channels interpreted as volcanic systems head at outflow sources marked by relatively symmetric topographic depressions, including examples at and near Aphrodite Terra [*Baker et al.*, 1992; *Komatsu et al.*, 1993b; *Komatsu and Baker*, 1994]. Although future access to high-resolution topographic data will be necessary for confident conclusions to be drawn, numerous examples of Venusian channel systems have characteristics consistent with incision across topographic barriers, including systems at Aphrodite Terra and Phoebe Regio [e.g., *Komatsu et al.*, 1993b; *Komatsu and Baker*, 1994], and the 1200-km-long Kallistos Vallis outflow system [e.g., *Baker et al.*, 1997; *Leverington*, 2004a] (Figure 18). The floors of some Venusian systems are characterized by lineaments oriented parallel to the longitudinal axes of channels, although the nature of these lineaments remains uncertain due to the resolution limitations of available radar and topographic data [*Leverington*, 2007].

[29] A volcanic origin for the outflow systems of Ophir and Aurorae Plana would be consistent with the recognized capacity of Martian volcanic processes for the past development of channel systems, anastamosing reaches, and streamlined landforms. For example, the existence of complex segments of a 690-km-long channel that fed emplacement of flows at Martian shield Ascraeus Mons has been attributed to the combined action of thermal and mechanical erosion by the flow of lava [*Garry et al.*, 2007]. Volcanic channels that fed emplacement of prominent lobate-margined volcanic flows at Daedalia Planum are also in some cases characterized by anastamosing subchannels separated by streamlined islands [*Keszthelyi et al.*, 2008] (Figure 19a). Incision by low-viscosity lava has been cited as a key process involved in development of Arnus Vallis, a

Figure 18. Examples of streamlined landforms of the largest Venusian outflow system, Kallistos Vallis. Located north of Lada Terra and southeast of Alpha Regio, this system is part of the Ammavaru volcanic complex and is over 1000 km long [*Baker et al.*, 1992, 1997; *Komatsu et al.*, 1993a]. The system heads in a region of chaotic terrain located northwest of the depicted area. The channel extends downslope from bottom left to middle right. Magellan FMAP left-look SAR mosaic. SAR illumination is from the left. Center is 22°55′E, 51°00′S.

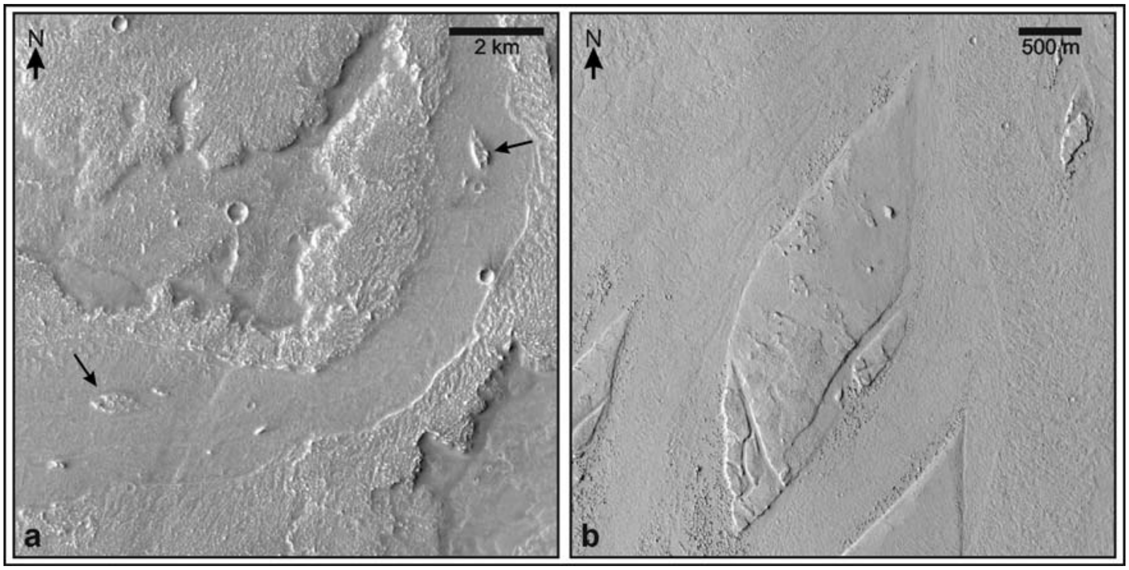

Figure 19. (a) Relatively small streamlined landforms are associated with a Martian flow-feeding volcanic channel at Daedalia Planum (see arrows) [*Keszthelyi et al.*, 2008]. (b) Larger streamlined features are commonly associated with Martian outflow systems, including the Marte Vallis outflow system of the Cerberus plains region. Images are CTX P04_002711_1560, center 122°50′W, 23°27′S (Figure 19a) and HiRISE PSP_007130_2020, center 175°07′W, 22°05′N (Figure 19b).

>300-km-long sinuous channel on the northeastern flank of Syrtis Major [*Rampey and Harvey*, 2008]. Igneous interpretations of the sinuous and partly roofed Tinto Vallis channel system [*Leverington*, 2006] are supported by widespread regional evidence for multiple episodes of crustal extension and associated flood volcanism across much of northern Tyrrhena Terra [*Caprarelli et al.*, 2007]. The young outflow channels of the Cerberus plains (e.g., Figure 19b) are entirely mantled by volcanic flows [e.g., *Jaeger et al.*, 2007], and it is not yet clear that there is any necessary role for water to have played in channel development. Considerations such as these suggest that the presence of sinuous channels, anastamosing reaches, and streamlined landforms at Martian outflow systems is not a sufficient basis for confident determinations of aqueous origins.

5. Discussion

[30] The *Coleman et al.* [2007] hypothesis for aqueous development of the Ophir and Aurorae outflow channels does not appear to be consistent with the geomorphological characteristics of the Tharsis and Valles Marineris regions. More generally, aqueous mechanisms for channel development at Ophir and Aurorae Plana are potentially undermined by mineralogical considerations, inconsistencies between hypothesized processes and anticipated physical properties of the Martian crust, and the absence of satisfactory analog processes.

[31] The volumes of the outflow systems of Mars are too great for component channels to have been incised by floodwaters derived solely from the missing material at channel heads or from immediately underlying aquifers [e.g., *Carr*, 1996; *Andrews-Hanna and Phillips*, 2007]. The hypothesis for aqueous development of Martian outflow channels by floods sourced from cryospherically sealed aquifers is attractive because it offers a mechanism for repeated flooding involving regional stores of groundwater. However, recent work suggests that even extraordinary regional-scale aquifer permeabilities of $\sim 10^{-9}$ m^2 might allow mature channel development only through the action of dozens to thousands of individual flood events, each event necessarily preceded by gradual replenishment from surrounding aquifers and reestablishment of an impermeable crysopheric cap [e.g., *Manga*, 2004; *Andrews-Hanna and Phillips*, 2007]. Complicating these issues further are the elevated outflow systems of Mars, including the Ophir and Aurorae systems, the existence of which cannot be accounted for on the basis of the hydrological processes inferred to have driven formation of lower channels. In some regards, hypothesized aqueous mechanisms for formation of the Ophir and Aurorae systems contradict the presumed need for cryospherically capped aquifers on Mars, through the implication that Martian outflow systems can readily form from surface water sources after all.

[32] The broader aqueous hypothesis for development of the outflow channels of Mars suffers from additional weaknesses, including an inability to account for the relatively high elevations of the heads of the largest outflow systems of Mars. Given the widespread capacity for volcanism to have breached hypothesized cryospheric caps across all Martian elevations during the Hesperian, a cryospherically confined aquifer system with dynamics driven partly or entirely by hydrostatic pressures should have favored outbursts at relatively low elevations rather than at elevated terrain located deep within the southern highlands [*Carr*, 2002]. From a mineralogical perspective, it is not clear that the existence of pristine olivine-rich units along Martian outflow channels [*Koeppen and Hamilton*, 2008] is consistent with aqueous models of channel development involving the long-term presence of massive groundwater stores and water-saturated cryospheric seals, and recurring releases of large volumes of water to the surface. Issues such as these

do not preclude the possibility that the Martian systems were indeed formed by expulsion of voluminous floodwaters to the surface, just as uncertainties associated with early aqueous interpretations of the Channeled Scabland of Washington had no effect upon the ultimate veracity of the shaping of that landscape by large deglacial floods. However, these issues strongly suggest the need for continued refinement of aqueous hypotheses, and for consideration of promising nonaqueous mechanisms of outflow channel development.

[33] Though many uncertainties remain, the characteristics of the Ophir and Aurorae outflow systems appear broadly consistent with those expected of volcanic landforms. If the channels of Ophir and Aurorae Plana were indeed formed through nonaqueous volcanic processes, crude estimates of the minimum lava volumes involved in channel development can be made on the basis of channel volumes and basic thermal considerations [*Leverington*, 2007]. The Allegheny and Elaver outflow systems are of sufficient size to be well represented in available MOLA Mission Experiment Gridded Data Records (MEGDR) topographic data with a spatial resolution of 128 pixels per degree [*Smith et al.*, 2003]. On the basis of these data sets, the volumes of the head depressions at the Allegheny and Elaver systems are calculated to be 140 and 1740 km^3, respectively. The respective surface areas of the Allegheny and Elaver systems are $\sim$1140 and 3620 km^2, and assuming average depths below channel rims of $\sim$125 and 250 m, the respective volumes of these channel systems are estimated as $\sim$140 and 900 km^3. Greatly simplified thermal considerations that neglect the possible action of mechanical processes related to the flow of lava [*Leverington*, 2007] imply erupted lava volumes of at least 6.4×10^3 km^3 for Allegheny Vallis and 6.2×10^4 km^3 for Elaver Vallis. The lesser of these lava volumes is of the same order of magnitude as that estimated for a relatively small lunar channel at Marius Hills [*Hulme*, 1973], and both estimates span the range believed to be typical of Martian flood lavas [*Keszthelyi et al.*, 2000].

[34] Other examples of elevated Hesperian outflow systems on Mars are, as with those of Ophir and Aurorae Plana, associated with regions possessing distinct volcanotectonic characteristics [*Carr*, 2002]. The most prominent of these regions include the shields of Alba Patera, Ceraunius Tholus, Ascraeus Mons, and Elysium Mons [*Gulick and Baker*, 1990; *Carr*, 2002]. As at Ophir and Aurorae Plana, some of these elevated Martian systems have anastamosing reaches that define streamlined landforms, features that have previously been considered diagnostic of past surface flow of water [e.g., *Mouginis-Mark and Christensen*, 2005; *Mangold et al.*, 2008c]. On the basis of the findings of the present study and other recent work [e.g., *Leverington and Maxwell*, 2004; *Leverington*, 2004a, 2004b, 2006, 2007; *Garry et al.*, 2007; *Jaeger et al.*, 2007; *Keszthelyi et al.*, 2008; *Rampey and Harvey*, 2008; *Hauber et al.*, 2009], future investigations of elevated outflow systems on Mars should involve consideration of volcanic mechanisms of channel development. Elevated outflow systems collectively have the potential to be more simply understood as the products of volcanic processes, and this perspective is consistent with recent volcanic interpretations of large flow-feeding channels at Ascraeus Mons and Syrtis Major [*Garry et al.*, 2007; *Rampey and Harvey*, 2008]. A volcanic origin for the elevated outflow systems of Mars would be consistent with a broader igneous hypothesis previously developed for all outflow channels [*Leverington*, 2004a, 2007, 2009].

[35] The origin of the Martian outflow channels is of central importance to our understanding of the geology and climate history of Mars. Aqueous interpretations of outflow systems have motivated hypotheses for the past existence of oceans and large lakes on Mars, as well as for the past occurrence of major changes or oscillations in global climate [e.g., *Baker et al.*, 1991]. Aqueous interpretations have also served as a basis for inferences of Martian volatile abundances [e.g., *Carr*, 1996]. A nonaqueous volcanic origin for the outflow systems of Mars would undermine conclusions drawn from aqueous models, and would instead be consistent with the maintenance of predominantly dry Martian conditions throughout the Hesperian and Amazonian epochs. A volcanic origin would also be congruous with interpretations of Hesperian "crater lake" landforms as the products of regional volcanic resurfacing [*Leverington and Maxwell*, 2004; *Leverington*, 2004b, 2006], and would be consistent with possible mineralogical constraints imposed upon the nature of past aqueous processes [e.g., *Goetz et al.*, 2005; *Bibring et al.*, 2006; *Chevrier and Mathé*, 2007; *Koeppen and Hamilton*, 2008].

6. Conclusions

[36] Most outflow systems in the southern highlands of Mars head at elevations below the 1500 m level considered to be the uppermost level compatible with aquifer recharge beneath the south polar cap, and these lower systems are widely interpreted as the products of such recharge. However, some outflow systems head at greater elevations, and have been alternatively interpreted as the products of the melting of glacial or ground ice at high elevations. The existence of the three elevated outflow systems of Ophir and Aurorae Plana (Allegheny Vallis, Walla Walla Vallis, and Elaver Vallis) has been previously attributed to a sequence of events involving rapid melt of Tharsis glaciers, flooding of deep troughs of Valles Marineris, recharge of adjacent aquifers, and sudden outflow of groundwater to the surface. The problematic nature of aspects of these hypothesized events, combined with the consistency between channel properties and those expected of volcanic systems, suggests that volcanic origins should be considered for these systems. A volcanic origin for the outflow systems of Ophir and Aurorae Plana is in accord with the volcanotectonic nature of the Valles Marineris region, the likely development of much of the Ophir and Aurorae Plana region through extrusive igneous processes, and the correspondence between channel properties and those of volcanic systems on the Moon, Venus, and Mars. If the Ophir and Aurorae systems formed volcanically, simplified thermal considerations imply erupted lava volumes of at least 6.4×10^3 km^3 for Allegheny Vallis and 6.2×10^4 km^3 for Elaver Vallis.

[37] Elevated Hesperian outflow systems on Mars are widely associated with regions possessing distinct volcanotectonic affinities. In past studies, these systems have been interpreted as having developed through aqueous mecha-

nisms involving the melting of glacial or ground ice, but, as at Ophir and Aurorae Plana, these systems have the potential to be more simply understood as the products of volcanic processes. A volcanic origin for the elevated outflow systems of Mars would be consistent with a broader igneous hypothesis previously developed for all outflow channels.

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D. W. Leverington, Department of Geosciences, Texas Tech University, Lubbock, TX 79409, USA.