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Valleys on Hecates Tholus, Mars: origin by basal melting of summit snowpack

Caleb I. Fassett*, James W. Head, III

Department of Geological Sciences, Brown University, Providence, RI 02912 USA

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Abstract

Valley networks observed on the martian surface are found mostly on Noachian-aged highlands units, but a few occur on younger volcanic edifices. Enigmatically, they do not occur on all younger volcanoes of similar age or location. Using new data, we reanalyze the radially arrayed valleys on the flanks of Hecates Tholus, a Hesperian-aged shield volcano, and test the hypothesis that these valleys might have formed via basal melting of summit snowpack. We find that magmatic intrusions with reasonable geometries provide sufficient heat flux to cause basal melting of snowpack, with the resulting meltwater interpreted to be responsible for incision of the observed valleys. Valley morphology is similar to valleys observed adjacent to seasonally melting Antarctic Dry Valley glaciers formed on comparable slopes, supporting the hypothesis of a snowmelt origin. These relatively young valley networks are thus plausibly interpreted to form under circumstances in which summit snow accumulation was melted during one or more episodes of high localized heat flux.

Keywords: Mars; Mars surface; Valley networks; Erosion; Heat flow

1. Introduction

Martian valley networks are integrated, branching valley systems that occur in the martian highlands and are interpreted to be largely Noachian in age (e.g., Carr, 1996). The geomorphology of these valleys has often been interpreted to require atmospheric pressures and temperatures conducive to liquid precipitation, thus requiring a climate that was 'warmer and wetter' than that of today (Baker, 2001; Craddock and Howard, 2002), though there is disagreement over whether a substantially different climate is necessary (see, e.g., Brackenridge et al., 1985; Gulick and Baker, 1989, 1990; Gaidos and Marion, 2003). The detailed formation mechanism for valley networks remains an open question despite the vast amount of new information that has been obtained in recent years. Distinguishing between the various models is difficult due to (1) ongoing uncertainty in the morphological differences between valleys on Mars and drainage systems on Earth (e.g. Irwin and Howard, 2002; Stepinski and Coradetti, 2003), (2) remaining questions about the relative importance of groundwater sapping and surface runoff, and (3) difficulty reconciling the observations which suggest minimal near-surface water interaction (Christensen et al., 2001) with the widespread geomorphologic evidence for water erosion (such as the valley networks themselves) (Carr, 1996).

Interestingly, younger valley networks are observed on several volcanoes on the martian surface, including Hecates Tholus and Ceraunius Tholus (Gulick and Baker, 1989, 1990). Both have crater retention ages consistent with a Late Hesperian age (Plescia, 2000, 2001). The valleys on these volcanoes thus appear to have formed well after any early period of postulated warmer climate; other volcanoes of similar age do not appear to have been modified by fluvial erosion. Three possibilities are consistent with the presence of these valley systems: (1) 'warm, wet' conditions may have recurred later in martian history (perhaps in an episodic way (Baker, 2001)), (2) Noachian-aged valley

*Corresponding author. Tel.: +1 401 8633485; fax: +1 401 8633978.
E-mail address: Caleb_Fassett@brown.edu (C.I. Fassett).

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networks may not require a 'warmer, wetter' climate, or, (3) these younger valleys found on volcanoes formed via a different mechanism than older highland valley networks.

Mouginis-Mark et al. (1982) assessed pyroclastic flow, lava thermal erosion, and fluvial origins for the valleys and concluded that the most plausible origin was fluvial activity, citing the branching patterns, the variations in width and depth along valley, craters intersected by valleys without signs of lava fill, and the apparent influence of local and regional topography on valleys (see also Gulick and Baker, 1990). Mouginis-Mark et al. also point out that intervalley regions appear undisturbed, with few tributaries found low on the flanks, making a pluvial origin unlikely. We concur with these observations and further interpret the intervalley areas as lying between meltwater drainages, similar to those seen in the Dry Valleys where pluvial activity is essentially absent (Marchant and Head, 2004).

These young valley networks provide potentially important constraints on the hydrological history of Mars and new developments have improved our understanding of how such younger valley networks could have formed on volcanoes. Numerical modeling has suggested that the present obliquity of Mars is anomalously small, and the planet may have spent much of its history at obliquities $>35^{\circ}$ (Laskar et al., 2004). Sophisticated atmospheric general circulation models predict that at these higher obliquities water is lost from the polar caps and redistributed equatorward (Richardson and Wilson, 2002; Mischna et al., 2003). Geological evidence has been presented for ice ages and snow/ice deposition in the mid-latitudes (Head et al., 2003) and tropical mountain glaciers on volcanic edifices (Head and Marchant, 2003; Shean et al., 2005).

Past workers have suggested the possibility that geothermal melting of snow may be responsible for valley network formation (Gulick et al., 1997; Zent, 1999; Gulick, 2001; Carr and Head, 2003). Although several of these workers briefly discuss the energy requirements to initiate and sustain such a process, many of the specific details remain uncertain. Thus, in this study, we aim to build upon these earlier results to test the plausibility of valley network formation via snowmelt on Hecates Tholus. First, we examine the energy requirements for snowmelt. Then, we re-examine the geomorphology of the valley networks on Hecates Tholus for clues to their origin, compare these valleys to morphological analogs in the Antarctic Dry Valleys, and discuss the potential sources of snow accumulation on these volcanoes. We then discuss how a basal snowmelt mechanism, caused by local enhancement of heat flow, may help explain existence of valley networks on some young volcanic surfaces but not on others.

2. Heat transfer modeling and energy balance calculations

We formulated a transient conductive heat flow model to test the magnitude and pattern of heat flow enhancement that results from cooling of a magmatic intrusion within Hecates Tholus. The model uses a forward-time, centered space finite difference technique to numerically solve the heat flow equation and calculate temperatures in every cell of a MOLA-derived, three-dimensional grid of the volcano (gridded at 1 km horizontal by 0.1 km vertical resolution). The thermophysical parameters of the substrate used (thermal conductivity $k = 2\,\mathrm{W/(m\,K)}$; diffusivity $\kappa = 10^{-6}\,\mathrm{m^2/s}$) are taken from typical measurements of basaltic material on Earth (Robertson and Peck, 1974; Clifford, 1993). The atmosphere-ground boundary (above any snow pack) was held at a constant 210 K, and the model was run both with and without a background geothermal gradient, as discussed in more detail below.

We tested the variable space in an attempt to assess model sensitivities for the least well constrained parameters. The intrusion geometry was tested as an ellipsoid or cylinder, the depth of the center of the emplacement was set between 5 and 10 km, and the initial temperature of the magmatic intrusion was put as 1000–1300 K. The modeled peak heat flow is very sensitive to changes in depth of the intrusion. Reasonable values for Mars can be calculated using neutral buoyancy or gravity scaling to be roughly 7.5–8.5 km (Wilson and Head, 1994). Our nominal model uses a depth of 8 km with an ellipsoidal intruded magma body (equatorial radii $a = b = 12\,\mathrm{km}$, polar radius $c = 1.2\,\mathrm{km}$). In our nominal case, the horizontal scale of this intrusion was chosen to match the approximate scale of the collapsed summit caldera. The intrusion thickness is more uncertain, so an ellipsoid with a large flattening was chosen to give a conservative volume for the modeled intrusion, since larger volumes will add greater energy to the subsurface. All else being equal, this would result in higher-peak heat-flow and lengthened cooling time. The details of the intrusion shape have only second-order effects on the cooling of intrusions of similar volumes at the same depth from the surface; a cylindrical intrusion cools somewhat more quickly than an ellipsoidal intrusion because of the sharp edges on its bounding surfaces.

The distribution of the heat flow anomaly on the surface as it changes during a nominal intrusive phase is shown in Fig. 1. We assume that the location of the magma intrusion is beneath the summit regions and calderas. Given the shallow slopes of these shield volcano flanks (6–9°) most of the conductive heat transport is vertical, and if the modeled intrusion is centered beneath the summit any heat flow anomalies are also concentrated in the summit region. This concentration of heat flow near the summit qualitatively holds for a variety of different intrusion geometries. Any effects of convection will tend to enhance the predominance of vertical heat transport over horizontal heat transport (assuming an isotropic permeability) (Gulick, 1998; Harrison and Grimm, 2002).

In our nominal case, the peak surface heat flow anomaly in the summit region is $\sim 120\,\mathrm{mW/m^2}$. Fig. 2 shows how changing the depth by 0.5 km might increase ($\sim 150\,\mathrm{mW/m^2}$) or decrease ($\sim 100\,\mathrm{mW/m^2}$) the heat flow anomaly from the intrusion. To more fully reflect the

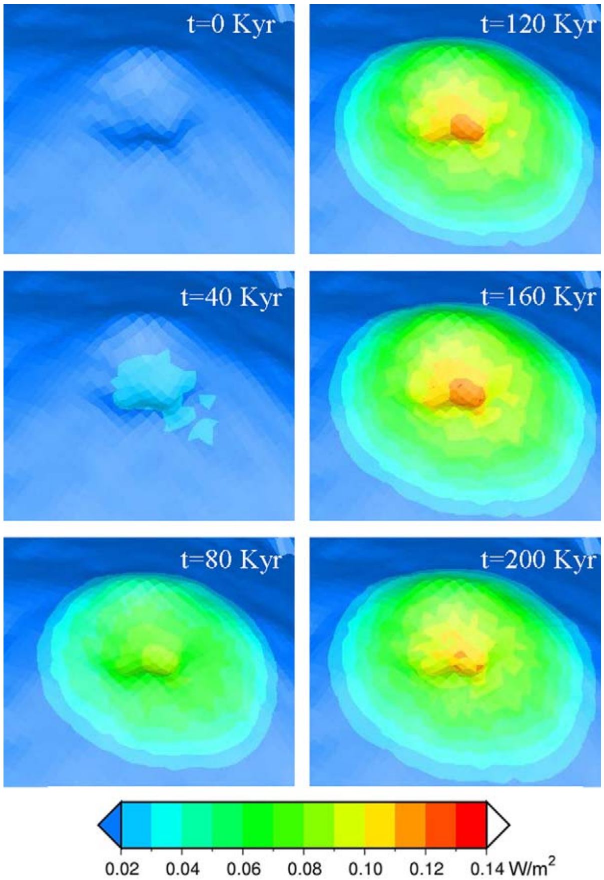

Fig. 1. Oblique perspective view of the summit region of Hecates Tholus showing the distribution of anomalous heat flow over a 200 Kyr model run (using nominal model parameters). The image is ~20 km across at the caldera.

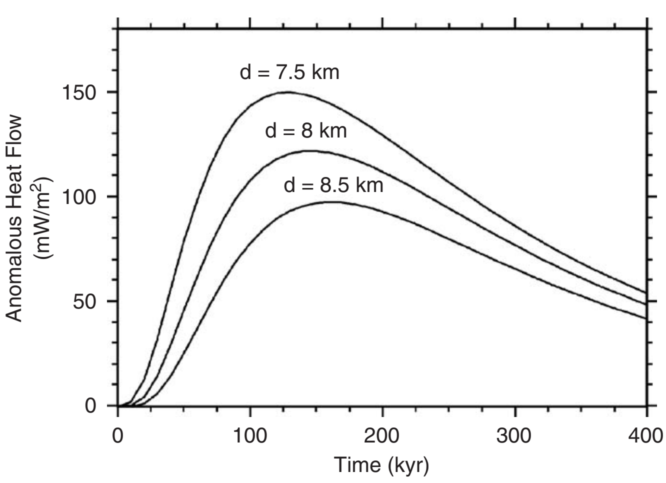

Fig. 2. Peak heat flow evolution over time for three model runs illustrating the sensitivity of results to the average depth (d) of the magma chamber.

relevant thermal boundary conditions, effects of the background geothermal heat flux need to be included to obtain the total surface heat flow. The geothermal heat flux in the Hesperian has been estimated to be ~20–50 mW/m^2 (McGovern et al., 2004). Including a background heat flux of 35 mW/m^2 in our model increases the nominal peak heat flow to ~140 mW/m^2 (with a range of peak heat flow results from 120–200 mW/m^2).

We can use the results of Carr and Head (2003) to assess the snowpack thickness required for basal melting to occur. We find that summit snow thicknesses on the order of 300–700 m would permit basal melting under these conditions. Furthermore, our modeling suggests that sufficient heat flow to melt such thicknesses of snow might persist for ~50 Kyr.

Our model neglects advective contributions for cooling. Gulick's (1998) modeling assumed a completely saturated substrate, which does not seem applicable if climate conditions are similar to those of today, as we assume, because the local groundwater system lacks a clear recharge mechanism. Neglecting advection is conservative, as the process accelerates subsurface heat transport, so if it occurred it would serve to enhance peak heat flow and the intensity of snowpack melting (though it would likely decrease its duration). In summary, the results of our transient conductive heat flow modeling are consistent with the possibility of melting of surface snow on Hecates Tholus.

An independent approach to test whether a magmatic intrusion provides sufficient heat to create meltwater is to examine the time-independent energy balance, following Ghatan et al. (2003). The total heat released by an intruded magma body as it cools is the product of its mass (M_{int}), its heat capacity (C), and the change in temperature (ΔT) it undergoes

$$Q = M_{\text{int}}(C\,\Delta T). \qquad (1)$$

The energy needed to melt a volume of ice is

$$Q = M_{\text{ice}}L \qquad (2)$$

where M_{ice} is the mass of the melted ice and L is its latent heat of fusion. We can make a rough estimate of the amount of water that flowed through the system by measuring the volume of eroded material in the valleys if we assume a sediment to water ratio for the formative flows.

Gulick (2001) suggested that the Hecates erosion removed 10–40 km^3 of material, with the range depending on the internal slopes of valley walls (10–30°). We have used new altimetry and image data to update this analysis. To calculate the volume removed by erosion, we measured the length of the valleys shown in Fig. 3, and made a direct determination of representative cross-sectional areas using MOLA profiles across valleys. Care was taken to correct for the fact that MOLA more effectively resolves wider valleys than smaller ones, the effects of regional slope, and that MOLA tracks were usually not orthogonal to valleys. The removed material at locations measured was then extrapolated to make an estimate over the whole shield. Our results give a range of 30–60 km^3 of eroded material, equivalent to removal of ~2.5–5 m of material over the

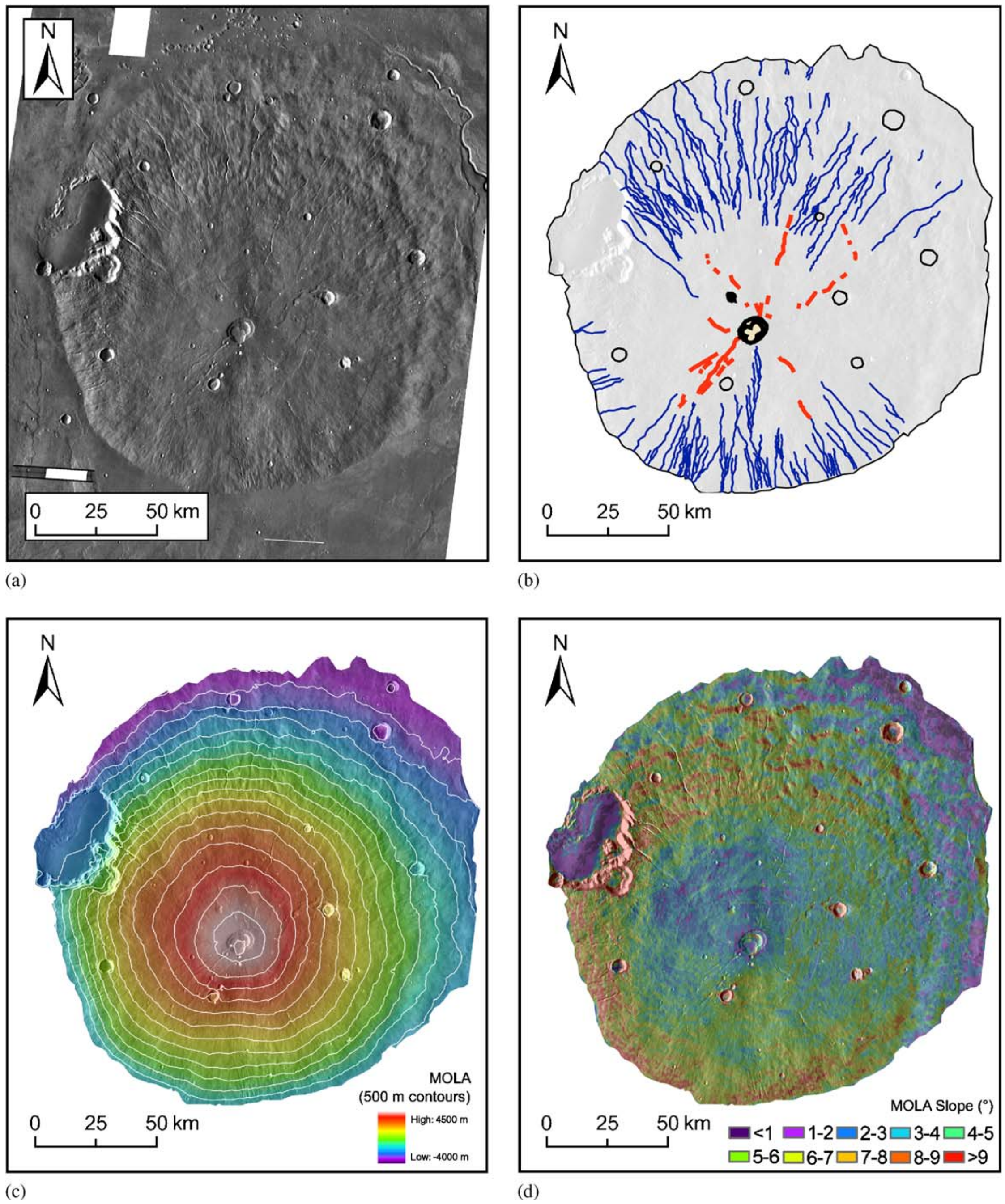

Fig. 3. Hecates Tholus. (a) A daytime THEMIS IR mosaic (IR images: I02017005, I02404005, I02429005, I02716006, I02741004, I03128002, I04289002, I04988015, and I08683018). (b) Sketch map based on the THEMIS basemap. Valleys interpreted as fluvial are shown in blue, continuous lines; chains of collapse pits or probable volcanic rilles are shown in red. The lack of valleys mapped on the eastern flank of the volcano is partially a result of the lighting geometry of the observations. (c) MOLA gridded topography (at resolution 128 pixel per degree) (Smith et al., 2003). At this scale, only the largest valleys are resolved, for example those that enter the large reentrant on the northwest flank of Hecates. (d) Slope map constructed from MOLA data with a baseline of 463 m/pixel. Hecates has an undulating surface (especially on its north flank), with steep slopes alternating with less steep regions. The fluvial valleys found on Hecates have greater surface expression on steeper surfaces, supporting the idea that surface slope substantially controlled valley incision, consistent with a model of runoff and overland flow as the primary mechanism of valley formation rather than sapping.

entire region of the flanks which was modified by fluvial erosion.

To calculate the volume of water that this amount of erosion implies, we need to assume a sediment to water ratio for the erosion that formed the Hecates Tholus valleys. A wide range of sediment to water ratios have been inferred for Mars. Gulick (1998, 2001) has argued that ratios as low as 1:1000 are appropriate, whereas other workers have suggested ratios as low as 1:3 (Goldspiel and Squyres, 1991). Given the steepness of Hecates' slopes, compared to many regions of valley formation in the highlands, we believe a ratio of 1:100 is conservative,

Table 1
Energy balance calculations that give the minimum size of an intrusion needed to produce a given volume of meltwater

Water volume (km^3)	Sed: Water ratio	Water mass (kg)	Energy required for melting (kJ)	Minimum volume of intrusion (km^3) at 100% efficiency	Minimum volume of intrusion (km^3) at 10% efficiency
300	10:1	3.0×10^{14}	1.0×10^{17}	34	340
450	10:1	4.5×10^{14}	1.5×10^{17}	51	510
600	10:1	6.0×10^{14}	2.0×10^{17}	68	680
3000	100:1	3.0×10^{15}	1.0×10^{18}	340	3400
4500	100:1	4.5×10^{15}	1.5×10^{18}	510	5100
6000	100:1	6.0×10^{15}	2.0×10^{18}	680	6800
30000	1000:1	3.0×10^{16}	1.0×10^{19}	3400	34000
45000	1000:1	4.5×10^{16}	1.5×10^{19}	5100	51000
60000	1000:1	6.0×10^{16}	2.0×10^{19}	6800	68000

Our nominal intrusion ($V = 724\,km^3$) would produce more than $6000\,km^3$ of water at 100% efficiency of melting or $600\,km^3$ of water at lower efficiency (10%).

though for the sake of the energy balance calculations, we consider the possibility that this could be an order of magnitude smaller or larger than this 1:100 value.

We can use Eq. (2) to calculate the energy required to produce water by melting of ice for a range of water volumes (see Table 1), using a latent heat of fusion of ice, $L = 335\,kJ/kg$. Likewise, assuming a heat capacity of $C = 1.1\,kJ/kg\,K$ for basaltic rock and applying Eq. (1), we can then calculate the minimum intruded volume of basaltic magma that would have sufficient energy content to melt snowpack to derive a given volume of water (Table 1). The transfer of heat to the ice is inefficient, with only some of the energy from the intrusion going into melting of ice. However, in a variety of circumstances delineated by Table 1, sufficient energy is available to melt the needed water volume. If the formation of the valleys happened in a single intrusive episode, this is most consistent with a scenario where the sediment to water ratio is greater than 1:100 (and the total water volume to erode the Hecates valleys is less than $6000\,km^3$). We favor this as the most likely scenario. Note, however, that this does not entirely rule out the possibility that lower sediment to water ratios may be relevant. Volcanoes on Mars are likely to be episodically active over an extended period of time (e.g. Wilson et al., 2001; Mouginis-Mark et al., 1982), and multiple intrusive episodes may have occured.

If we assume snow or ice accumulation is limited to the ‘‘melting region’’ centered at the summit caldera, with area $\sim 700\,km^2$, we can calculate a minimum thickness of ice which needs to be melted to produce a given estimate for the water volume (Table 2). For the minimum water volumes, the amount of melted ice could be accommodated in a single melting episode with minimal resupply of water to the summit. The larger water volumes would likely require episodic precipitation to resupply water to the summit.

We conclude that both the modeling and calculations presented here support the idea that intrusive magmatic heating of summit snow is a plausible mechanism for the production of surface meltwater that could have carved the Hecates Tholus valleys.

Table 2
Equivalent ice thicknesses calculated for the range of water volume estimates needed to form the Hecates Tholus valleys.

Water volume (km^3)	Equivalent melted ice thickness (m) ($700\,km^2$ melting region)
300	47
450	70
600	94
3000	470
4500	700
6000	940
30000	4700
45000	7000
60000	9400

Water volumes of order 10^4 would likely require significant resupply of water by precipitation or a larger melting region.

3. Morphology of valleys on Hecates Tholus and in the Antarctic Dry Valleys

The small valleys found on Hecates Tholus are typically hundreds of meters wide and tens of meters deep (Figs. 3 and 4). Shield volcanoes like Hecates Tholus are likely to have a range of ‘‘valley’’ landforms with a variety of origins (e.g., sinuous rilles of lava flow origin, ash flow erosion, fluvial valleys, chains of collapse pits, etc.) (Gulick and Baker, 1990). In compiling the map in Fig. 3b we attempted to distinguish between valleys that formed via fluvial erosion and those that are of volcanic origin. Valleys in the immediate summit region appear to be dominated by volcanic processes of collapse and possibly lava erosion (Williams et al., 2005). Lower on the flanks, valley morphology is consistent with a fluvial origin (Mouginis-Mark et al., 1982; Gulick and Baker, 1990), and valleys are distributed in an approximately radially-symmetric

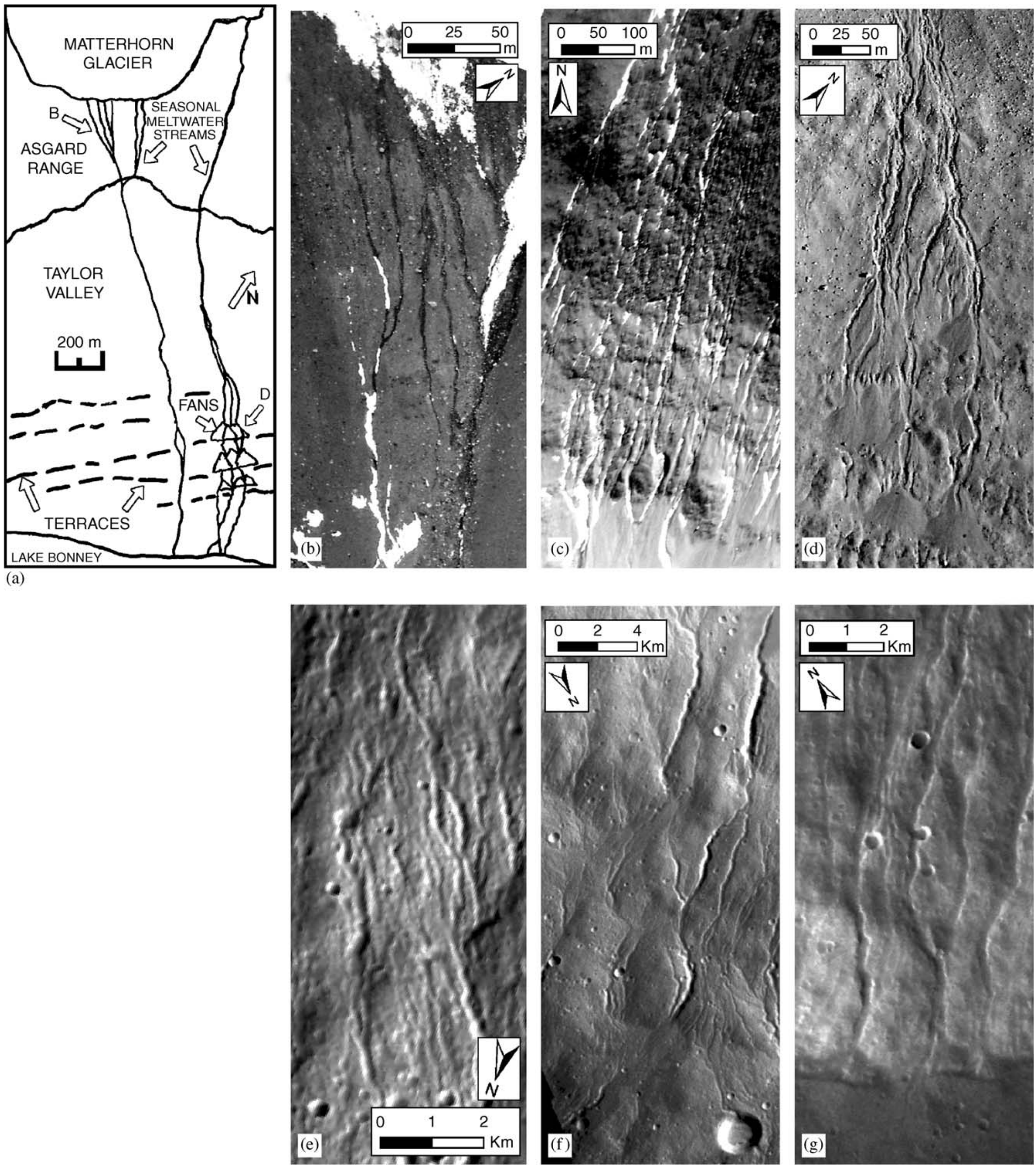

Fig. 4. Antarctic analogs and Hecates Tholus. (a) Map of the Matterhorn Glacier in the southern Asgard Range, Antarctic Dry Valleys. Seasonal meltwater streams emerge from the glacier and flow down the northern wall of Taylor Valley to ice-covered Lake Bonney. In the upper part of the sketch map, meltwater streams emerging from the glacier (Fig. 4b; see also Fig. 4c) are parallel and sometimes branching. Further down slope, (lower right; Fig. 4d) the parallel and braided meltwater streams give way to larger channels, and depositional fans are formed on terraces at breaks in slope. Note that snow is preferentially trapped in the small channels (Figs. 4b, c) and represents an additional meltwater source. On Hecates Tholus (see map and synoptic images in Fig. 3), radial valleys (Fig. 4e) are interpreted to be formed by melting of summit snowpack, and lateral runoff and incision. Parallel and braided channels often lie in lows between relatively undissected terrain (Figs. 4f, g). In several cases parallel and braided channels are deeply incised (compare to Fig. 4d); the enhanced width of deeper channels appears to be related to local slopes over which the channels are forming (see the slope map in Fig. 3). Channels also form depositional fans (see the lower part of Fig. 4g). Comparison of b–d and e–g suggests that the Hecates channels could have formed from drainage of meltwater from summit snowpack. Antarctic images courtesy: NASA ATM-CAMBOT; Hecates images are THEMIS/VIS.

manner. These valleys have higher drainage densities than those found in other dissected regions of the highlands (Gulick and Baker, 1989, 1990). Gulick and Baker (1990) classify these valley networks on the basis of evidence for runoff (shallow, more widely distributed valleys), groundwater sapping (deeper, less abundant valleys, theater-headed), or both. They proposed an evolutionary sequence of processes, where valleys are initiated by runoff and later modified by sapping that takes advantage of pre-existing depressions to act as focal points for groundwater.

Mapping using new THEMIS and MOC data together with high-resolution Viking images show that the valleys on Hecates can be classified into the following zones and trends: (1) a ~25 km-radius zone at the summit that contains few fluvial valleys, (2) a downslope zone in which systems of small predominantly parallel valleys dominate, (3) an intermediate zone in which the systems of parallel (occasionally braided) valleys begin combining into larger valleys, and (4) a lower zone in which these valleys deposit small debris fans that dominate at breaks in slope; the valleys either cut through, or are diverted by, the fans. Valleys tend to coalesce and increase in width downslope (Figs. 4e–g). Many of the larger valleys form debris fans at the base of the edifice (Fig. 4g). The valleys which enter the large depression on the northwest flank of Hecates may have been enlarged by recent ice-related processes related to the lobate fan deposits at their base (Hauber et al., 2005).

As illustrated in Fig. 3, the variations in the size of valleys are correlated with local slope variations at the ~500 m scale, derived from the MOLA 128 pixel per degree gridded dataset (Smith et al., 2003). In terrestrial streams this is commonly observed where streamflow occurs across undulating topography. This correlation supports a scenario where the morphology of the Hecates Tholus fluvial valleys is primarily due to the surface flow of water. Observations of valley morphology on the basis of Viking data led Gulick and Baker (1990) to suggest that the valleys on Hecates were initiated by surface runoff, then later enlarged by groundwater sapping. Although such a sequence may have occurred locally (such as for the largest valleys on Hecates' northwest flank), we believe that the new data that indicate a correlation of slopes with degree of incision largely obviates the need to invoke significant groundwater sapping. Differential erosion on steep and more shallowly sloping surfaces by overland flow appears to have been the primary control on valley morphology.

What terrestrial analogs exist for valleys formed in a non-pluvial, non-sapping, overland meltwater regime? Strikingly similar features and relationships are observed in valley systems that form from seasonal meltwater drainage of snowpack and glaciers in the Antarctic Dry Valleys (Figs. 4a–d) (Fountain et al., 1998; Conovitz et al., 1998; Dana et al., 1998), a cold polar desert analog to Mars (e.g., Marchant and Head, 2004). Although the Dry Valleys are dominated by sub-freezing temperatures analogous to Mars for the vast majority of the year, in the austral summer, parts of the coastal and mixed microenvironment zones become sufficiently warm that melting can occur on the surface of snowpack and the faces of glaciers (Marchant and Head, 2004). Thus, despite the lack of pluvial activity throughout the year, during parts of the austral summer, glacial meltwater is generated and transported down the sides of valleys in streams, eroding and redepositing sediments, and eventually flowing into the Dry Valley lakes (McKnight et al., 1998). A subset of these Antarctic Dry Valley ephemeral streams is shown in Fig. 4. In these examples, summer melting of the Matterhorn Glacier in the Asgard Range produces meltwater which drains from the glacial margins and flows down the steep $5-10^{\circ}$ slopes of the Taylor Valley wall to Lake Bonney, occupying the valley floor. This transient drainage drives the formation of small, localized systems of parallel channels that erode immature till surfaces (Figs. 4a–d). Initially parallel channels increasingly intersect and braid downstream, and larger channels begin to dominate (compare Figs. 4b and d). The seasonal water input forms relatively low-volume, low-velocity streams that erode and preferentially transport the finer-grained portions of the till and slope debris. On shallower slopes, channels are parallel-to-braided and are relatively shallow. On steeper sections, water velocity increases and individual channels deepen and often widen. Channel-fed fans and small deltas are formed at breaks in slope (Fig. 4d). Meltwater flow both filters into the fans and is channelized, diverted by or eroding into the fans and their margins (Fig. 4d).

These transient Antarctic Dry Valley valleys drain meltwater from snowpack and glaciers in non-pluvial, non-sapping stream systems, and show morphological changes related to changes in topographic slope and erosional efficiency similar to those on Hecates Tholus. The Antarctic streams occur on comparable slopes but are smaller than the Hecates channels, perhaps enabled by the longer time interval over which the martian channels likely formed. In summary, the striking similarities between the flank valleys on Hecates and transient valleys adjacent to melting glaciers/snowpack in the Antarctic Dry Valleys (Fig. 4) strengthens the possibility that the Hecates channels could have formed by melting of summit snowpack.

If the martian atmosphere was not significantly warmer than it is today when the Hecates Tholus valleys formed, pluvial activity (rainfall) would be precluded as their cause. Recent GCM simulations show that during enhanced obliquity, water will be mobilized from the poles and redeposited equatorward as snow and ice (Richardson and Wilson, 2002; Mischna et al., 2003). Gulick et al. (1997) and Haberle et al. (2004) found that volcanic edifices are likely to be preferential sites of snow deposition. Moreover, Hecates Tholus and Ceraunius Tholus are both poleward of 25°N, at higher latitudes than the Tharsis Montes and Olympus Mons, the sites of tropical mountain glaciers (e.g., Head and Marchant, 2003). During the Hesperian when these edifices and valley networks appear to have been formed, outflow channels provided a possible source of water to the adjacent northern lowlands (e.g., Gulick et al., 1997 and references therein; Carr, 1996). Thus, these edifices occur at latitudes that are plausible sites for (1) water-rich atmospheric adiabatic upwelling and snow deposition from mobilized polar volatiles (Haberle et al., 2004) during periods of high obliquity (Laskar et al., 2004), or (2) emplacement during sublimation and redeposition of abundant water ice in the adjacent northern lowlands during outflow channel activity.

Why would valley networks form on some volcanic edifices and not on others? The most probable explanation is that the formation of valley networks on these edifices requires a combination of two factors, a thick accumulation of snow and an enhanced geothermal gradient, as earlier noted by Gulick (2001) and Gulick et al. (1997). Thus, snow might accumulate and then sublimate without forming valleys if the volcano was inactive during a period of enhanced snow accumulation. Furthermore, the large tropical mountain glaciers observed on the Tharsis rise appear to have accumulated at substantial distances from the summit region, perhaps too far to have experienced much enhanced heating by local magmatic heat flux. This is consistent with the interpretation that these glaciers are cold based, implying little or no basal melting (e.g., Head and Marchant, 2003).

In summary, the deposition and melting of snow contemporaneous with magmatic intrusive activity is a plausible mechanism for forming the enigmatic valleys observed on several martian volcanoes. Recent work by Carr and Head (2003) presented a model of the depth of snowpack that must exist for melting to occur at a given basal heat flow and snowpack surface temperature. The numerical modeling of diffusive heat flow away from a cooling magma reservoir described above suggests that more than enough heat would be conducted to the summit to melt snow and form the valleys.

4. Discussion and conclusions

We find that under atmospheric conditions similar to those of today, significant snow accumulation on the summits of active volcanoes could create an environment conducive to valley network formation. Given appropriate snow accumulation, conductive and advective heat loss from magma reservoirs are sufficient sources of heat to melt ice at the base of the snowpack. This model is consistent with the observed radial distribution of valleys surrounding the summit area and evidence that runoff largely controlled valley development. Although there is no clear morphological evidence for glaciation on the summit of Hecates Tholus, this does not preclude the basal melting hypothesis. Indeed, younger ice accumulation and flow have been observed in depressions at the base of Hecates Tholus (Hauber et al., 2005).

Finally, it is worth exploring whether the snowpack-melting model for valley formation on small volcanic edifices is applicable to the valley networks in the martian highlands. Invoking the existence of abnormal local heat flow as a source of melting is clearly more plausible for the volcanoes than it is for terrain throughout the cratered highlands. However, the likelihood of higher heat flux in earlier Mars history may permit this explanation to be applied to broader regions of the highlands (Carr and Head, 2003; Gulick, 2001; Zent, 1999; Gulick et al., 1997), particularly if regional subsurface groundwater convection causes heterogeneous regional surface heat flux (e.g., Travis et al., 2003). Melting either ground ice or surface snow by geothermal heating remains a viable mechanism for valley formation that needs to be further explored.

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