Table 1
Model parameters and constant.

Parameter	Symbol	Value	Units	Certainty/value range	Model sensitivity
Martian gravity	g	3.7	m s^{-2}	Very certain	
Density of basalt	ρ	2800	kg m^{-3}	Fairly certain	Not sensitive from 2600 to 3000 kg m^{-3}
Viscosity of basalt[a]	μ	10	Pa s	0.1–1000 Pa s	Not sensitive over three orders of magnitude
Strength of substrate[b]	Y_s	1×10^6	Pa	l kPa–25 MPa	Very sensitive, constrained by observations, discharge (Q), or duration
Erodibility factor[c]	b	10^{-3}	–	10^{-4}–10^{-1}	Extremely sensitive, not well constrained, most reasonable results for $b = 10^{-3}$
Proportionality constant for the erodibility of the substrate	K	1×10^{-9}	Pa^{-1}	10^{-10}–10^{-4}	A ratio of b/Y_s, dependent on these factors
Thermal conductivity of basalt[d]	k	2	W m^{-1}K^{-1}	Fairly certain	
Specific heat capacity of basalt	c	837	J kg^{-1}K^{-1}	Very certain	
Latent heat of basalt	λ	5×10^5	J kg^{-1}	Very certain	
Fraction of rock melted prior to mechanical erosion	q	0.4	–	0–1	Not sensitive
Erupted lava temperature	T_e	1450	K	1335–1450 K	A 100 K change in T changes thermal erosion rate by one order of magnitude
Substrate temperature	T_s	200	K	Fairly certain	
Melting temperature of substrate	T_m	1335	K	Fairly certain	
Experimentally derived reference temperature[e]	A	1635	K	Experimentally derived	

[a] Value range compiled from Murase and McBirney (1970) and Keszthelyi and Self (1998).
[b] Value range compiled from Arvidson et al. (2004) and Tanaka and Golombek (1989).
[c] Value range defined in Zum Gahr (1998).
[d] Values for the following constants (k, c, λ, q, T_e, T_s, T_m, and A) are presented in Wilson and Head (2010, in preparation).
[e] Value derived in Hulme (1973).

v of material flowing through the channel. The rate of change in channel depth d_{chan} under a mechanical erosion regime is given by

$$\left(\frac{d(d_{chan})}{dt}\right)_{mech} = K\rho g Q \sin\alpha, \tag{1}$$

where Q is the average lava volume flux per unit width through the channel in m^2 s^{-1}, ρ is the lava density (see Table 1 for parameter values), g is the acceleration due to gravity on Mars, α is the ground slope, and K is a dimensional ratio (units of Pa^{-1}) between the erodibility of the substrate b and the strength of the substrate Y_s that represents the efficiency of incision into the substrate (Sklar and Dietrich, 1998). Eq. (1) can be thought of conceptually as erosion rate as a function of the erodibility of the substrate and unit stream power Ω, where $\Omega = \rho g Q \sin\alpha$ (Sklar and Dietrich, 1998). The erodibility of the substrate is significantly dependent on substrate composition; for example, a regolith substrate that contains a pore-water ice cement would be expected to be more erodible than a substrate of pure basalt. An alternative approach has been employed previously by Siewert and Ferlito (2008), where the erosion rate is taken to be proportional to the vertical load of the lava on the substrate ($\rho g \cos\alpha$) as opposed to the shear stress of the lava on the bed as used by Sklar and Dietrich (1998). Siewert and Ferlito (2008) predict that mechanical erosion will be most efficient when the regional slope is at a minimum, or when the vertical load is greatest. Erosion rates predicted by the Siewert and Ferlito (2008) model overestimate the amount of erosion observed in the upper and middle segments of the Elysium channel as described in Section 3, and thus the Sklar and Dietrich (1998) stream power formulation that assumes that shear stress is the dominant force responsible for erosion is preferred in this study. Eq. (1) indicates that a mechanically eroded channel will increase in depth faster as a higher flux of lava flows over a more poorly consolidated substrate.

The erosion rate of a channel formed under a thermal erosion regime also depends on the flux of lava through the channel. However, the erosion rate under this regime also depends on the temperature T and viscosity μ of the lava. A frequently cited model for the rate of change in channel depth in a thermal erosion regime and a turbulent flow regime (Hulme, 1973) is given by

$$\left(\frac{d(d_{chan})}{dt}\right)_{th} = \frac{0.017k^{0.6}c^{0.4}\rho^{0.8}Q^{2/15}}{\rho_s[q\lambda + c_s(T_e - T_s)]}\left(\frac{2g\sin\alpha}{C_f}\right)^{1/3}\left(\frac{T_e}{A}\right)^6 (T_e - T_m), \tag{2}$$

where the subscript s denotes the substrate, k is the thermal conductivity of lava (parameter values as used in Wilson and Head (in preparation); see Table 1), c is the specific heat of the lava and substrate, q is the volume fraction of rock which must be melted before structural integrity is lost, λ is the latent heat of fusion required to melt the substrate, T_s is the average temperature of the surface of Mars, T_e is the temperature of the erupted lava, T_m is the melting temperature of a primarily basaltic surface, A is a reference temperature determined experimentally, and C_f is a friction factor that is dependent on Re and is defined in Keszthelyi and Self (1998) by

$$C_f = \left(\frac{1}{32}\right)\left(\log_{10}\left[6.15\left(\left(\frac{2Re + 800}{41}\right)^{0.92}\right)\right]\right)^{-2}. \tag{3}$$

This friction factor formulation is valid only for moderately turbulent lava flows, where $10^3 < Re < 10^5$ (Keszthelyi and Self, 1998). A thermally eroded channel is expected to increase in depth faster as a larger flux of hotter and less viscous lava flows over the substrate. It should be noted that the Hulme (1973) model presented in Eq. (2) probably predicts somewhat greater erosion rates than other models of thermal erosion developed because it underestimates the thickness of the thermal boundary layer and thus overestimates heat flux to the ground (i.e., Williams et al., 2000). It should also be noted that the original formulation for thermal erosion rate presented in Hulme (1973) uses an independent friction factor (developed by McAdams (1954)) that represents flow through an enclosed tube and must be solved iteratively to arrive at a solution. The current study employs the friction coefficient shown in Eq. (3) (developed by Goncharov (1964) and used by Shaw and Swanson (1970) and Keszthelyi and Self (1998)) because it represents sheet flow and open channel flow, a more relevant representation of the