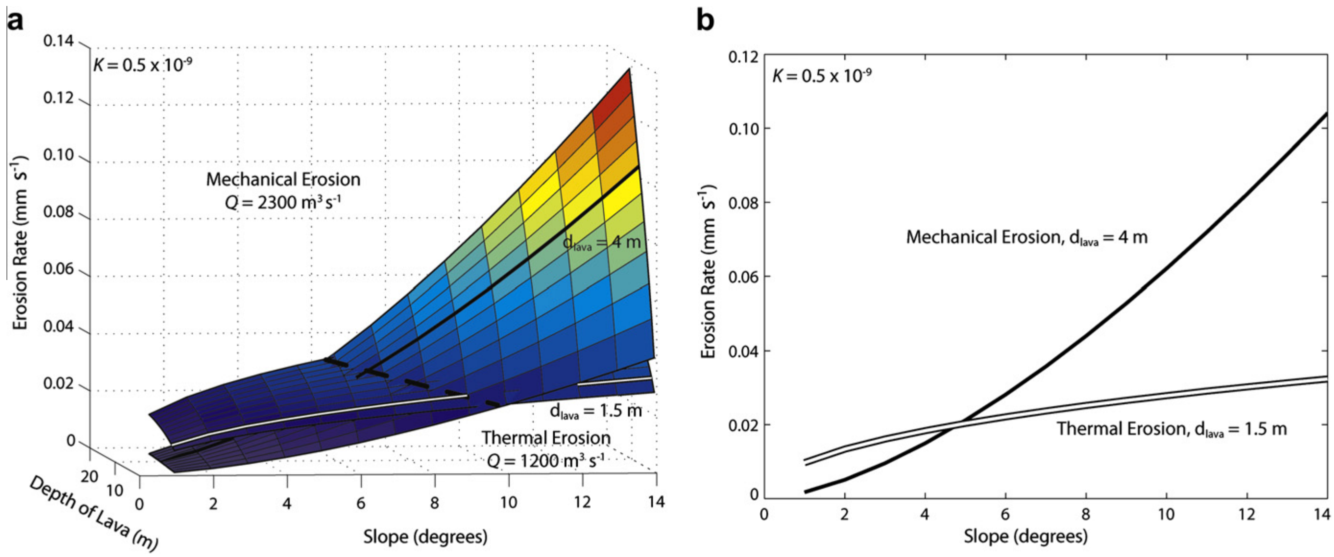

Fig. 4. Dependence of erosion rates in both mechanical and thermal regimes on slope and lava depth, assuming a constant lava flux and lava depth for each regime ($2300\ m^3\ s^{-1}$ and 4 m for mechanical erosion, $1200\ m^3\ s^{-1}$ and 1.5 m for thermal erosion consistent with conditions present for each erosion regime during the formation of the lower channel segment of the Elysium crater channel) that is required to erode to a depth of 150 m. (a) Erosion rate vs. slope vs. lava depth. As either slope or lava depth increases, mechanical erosion rates increase more significantly than thermal erosion rates. Both slope and lava depth contribute to the physical energy of a fluid flow, thus increasing the ability of the fluid to mechanically erode the substrate. At shallow slopes less than about 5°, thermal erosion is the more efficient erosion mechanism for lava channels forming on Mars. In contrast, mechanical erosion is the more efficient erosion mechanism at steeper slopes greater than about 5°. Erosion rates are similar for each erosion mechanism at slopes of about 5°, and therefore a combination of the two erosion regimes might be present during the formation of a channel under these conditions. (b) Erosion rate vs. channel slope for mechanical erosion and thermal erosion. Mechanical erosion is significantly more efficient than thermal erosion at the slope of the lower channel segment (13.5°), but thermal erosion rates are more similar to mechanical erosion rates at the slope of the middle channel segment (4.2°). This figure demonstrates that mechanical erosion was likely to be the dominant erosion regime present during the formation of the upper and lower Elysium crater channel segments but that thermal erosion might also play a significant role in the formation of the middle channel segment. Other calculations of channel depth discussed in the text indicate that mechanical erosion is likely the dominant erosion regime for the formation of the entire channel.

Elysium crater channel are typically greater than 5°, an observation that is consistent with the model results that indicate that mechanical erosion is expected to be the dominant erosion process present during the formation of this channel. Our results, showing the greater importance of mechanical erosion by lava over steeper, fragmental slopes, are consistent with observational and geochemical results supporting an enhanced role for mechanical erosion in the Cave Basalt lava tubes at Mount St. Helens, Washington (Williams et al., 2004).

The validity of the calculated duration of 30 Earth days for the mechanically eroded channel can be confirmed by considering the geologic context of the lava flow source. The lava flows that formed the observed crater channel have been identified to originate from a dike in Cerberus Fossae just north of Athabasca Valles (Jaeger et al., 2010). Analysis of high lava levels within Athabasca Valles using CTX DEMs indicates that these lava flows were locally as deep as 97 m, though the lava depth was likely an average of 30 m on the $250{,}000\ km^2$ lava plains (Jaeger et al., 2010). Calculations using Eqs. (3) and (4) indicate that this eruption was likely to have occurred at an average discharge rate of $1–2 \times 10^6\ m^3\ s^{-1}$ (peak discharge rate of $5–20 \times 10^6\ m^3\ s^{-1}$), indicating that it would take 1–6 months to erupt the entire $5000–7500\ km^3$ lava volume observed (Jaeger et al., 2010). Therefore, 30 Earth days is a reasonable duration for a channel forming from a lava flow with a flux of $\sim 2300\ m^3\ s^{-1}$ that originated from these erupted lavas.

5.2. Stream power and erosion

To further understand the conditions present in the Elysium channel, it is worth considering this channel in the context of other energetic flows. Baker and Kale (1998) examined several such flows which carved deep flood channels, typically in days to weeks. As discussed above (Eq. (1)), the mechanical erosion by lava can be modeled as proportional to unit stream power ($\Omega = \rho g Q \alpha$, the energy dissipated to the bed) multiplied by a constant of proportionality that reflects the resistance of the surface to erosion. The 'erodibility' proportionality constant K is uncertain, and so examining flows of similar energy expenditure can be used to independently assess whether mechanical erosion of the magnitude observed is reasonable.

Table 3 reproduces depths and unit energy expended (stream power per unit width) for several examples as given in Baker and Kale (1998), as well as for the Elysium volcanic channel using channel flux and width estimated in this study. These examples demonstrate that the energy expenditure by the fluid on the Elysium crater wall is directly comparable to extremely large terrestrial floods where erosion was obviously by mechanical means alone. Since there is less buoyancy contrast between lava and surface materials than between water and sediments as well as less resistance to transport because of a lower gravity on Mars than on Earth, less energy is required for a lava flow on Mars to attain similar erosion rates. Thus, the similarity in energy expenditure between the Elysium channel and the terrestrial floods carved by purely mechanical means suggests that our parameterization of surface erodibility is reasonable (and possibly conservative). This

Table 3
Unit stream powers and eroded depths for select channels.

Channel	Depth (m)	Stream power ($W\ m^{-2}$)
Chuja*	400	$10^5–10^6$
Rathdrum*	175	2×10^5
Grand Coulee*	100	3×10^5
Elysium volcanic channel (lower segment)	150	4×10^5

* Flood channels carved by water on Earth, from Baker and Kale (1998).