Erosion by Flowing Martian Lava: Insights from Modeling Constrained by *Mars Express* and MER Data

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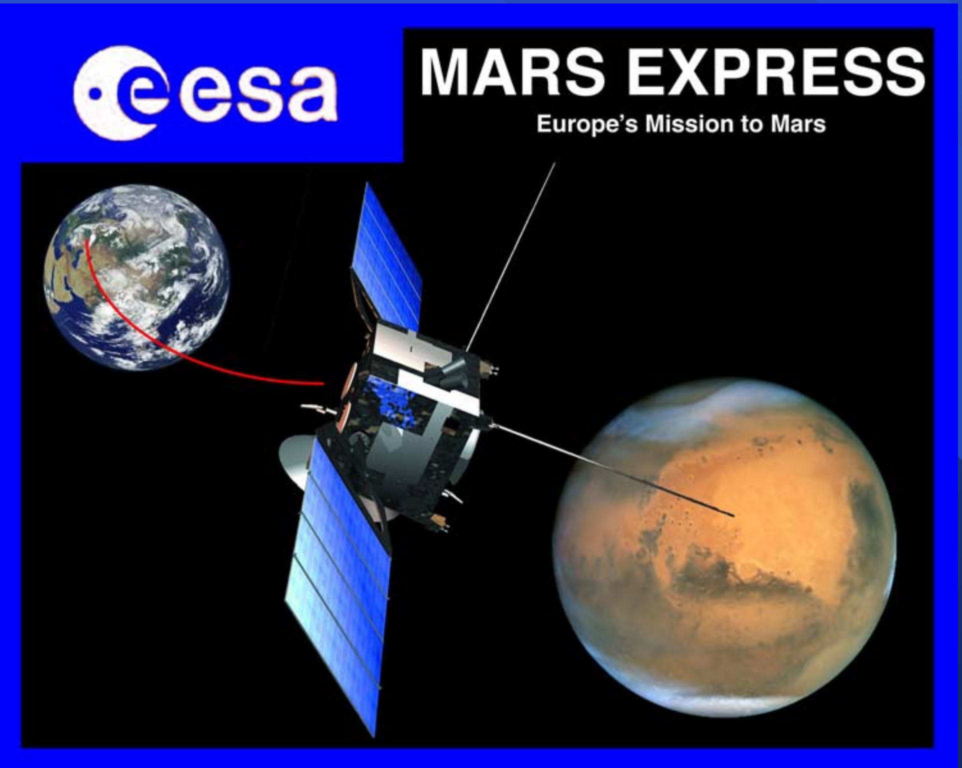

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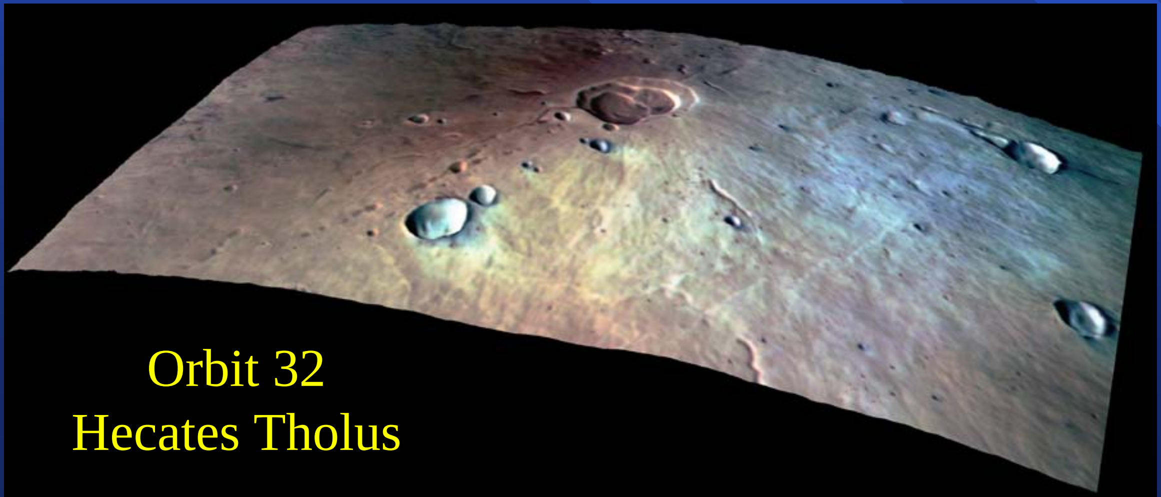
Outline

- Background and objectives: Why study erosion by flowing lava?
- Data from MER *Spirit*: Compositional data on Martian lavas
- Data from MEx HRSC: Slopes, flow heights, channel depths
- Description of analytical-numerical model
- Results

Orbit 32
Hecates Tholus



Orbit 32
Hecates Tholus

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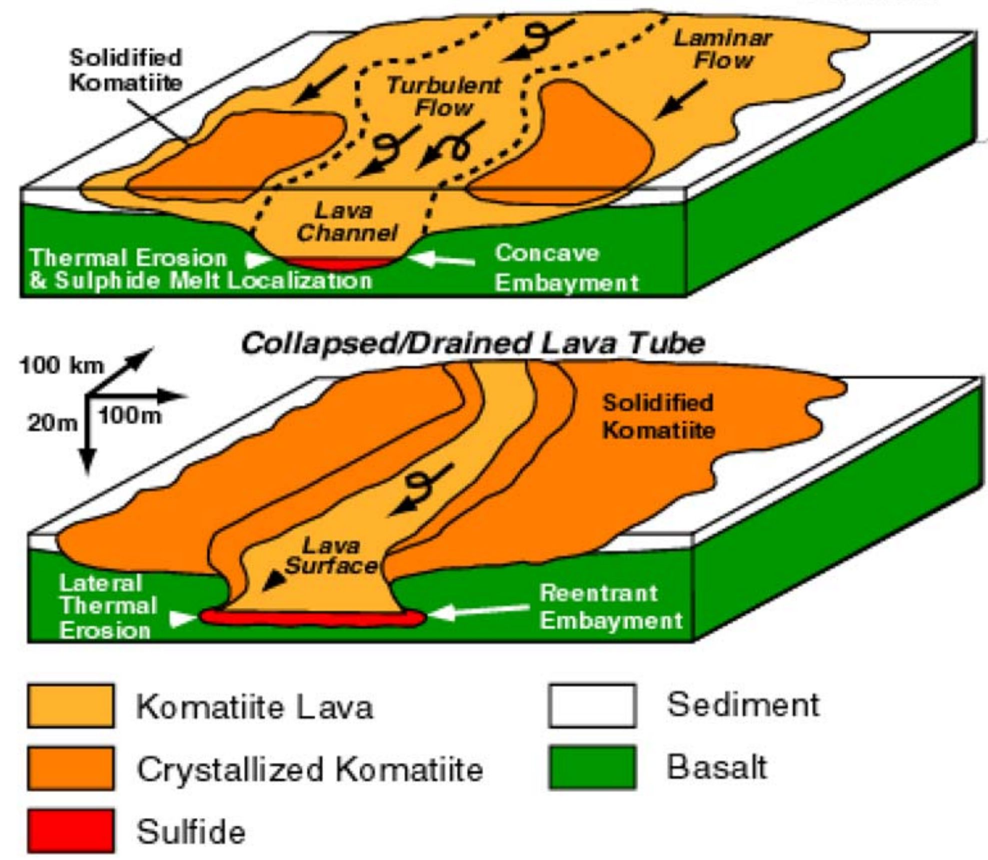
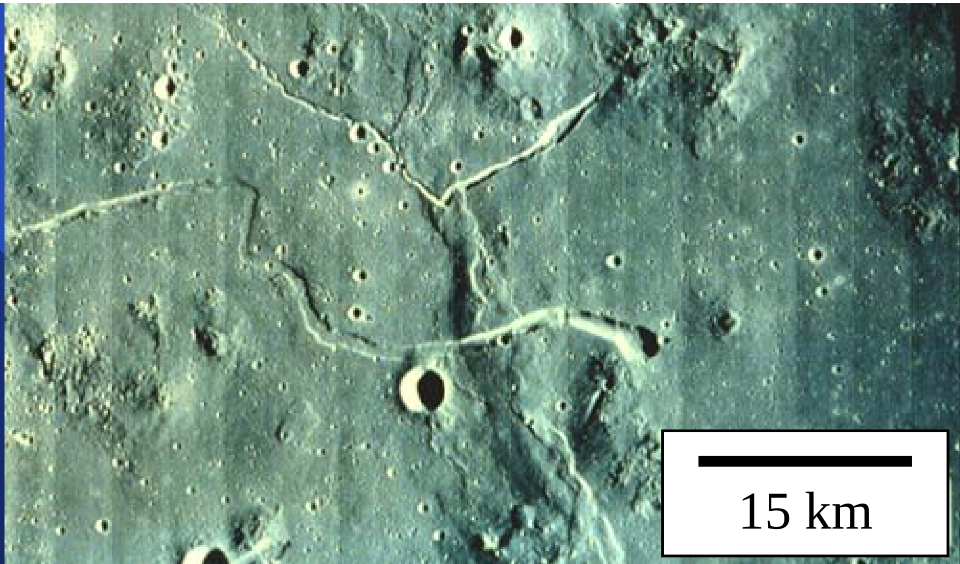
Background: Erosion by Flowing Lava

- Components
  - Thermal Erosion
  - Mechanical Erosion
  - Combination of both
- Why Important?
  - Formation of terrestrial magmatic Fe-Ni-Cu-(PGE) sulfide ore deposits
  - Formation of some extra-terrestrial lava channels
- Evidence
  - Terrestrial field studies
  - Computer modeling
  - Analog experiments





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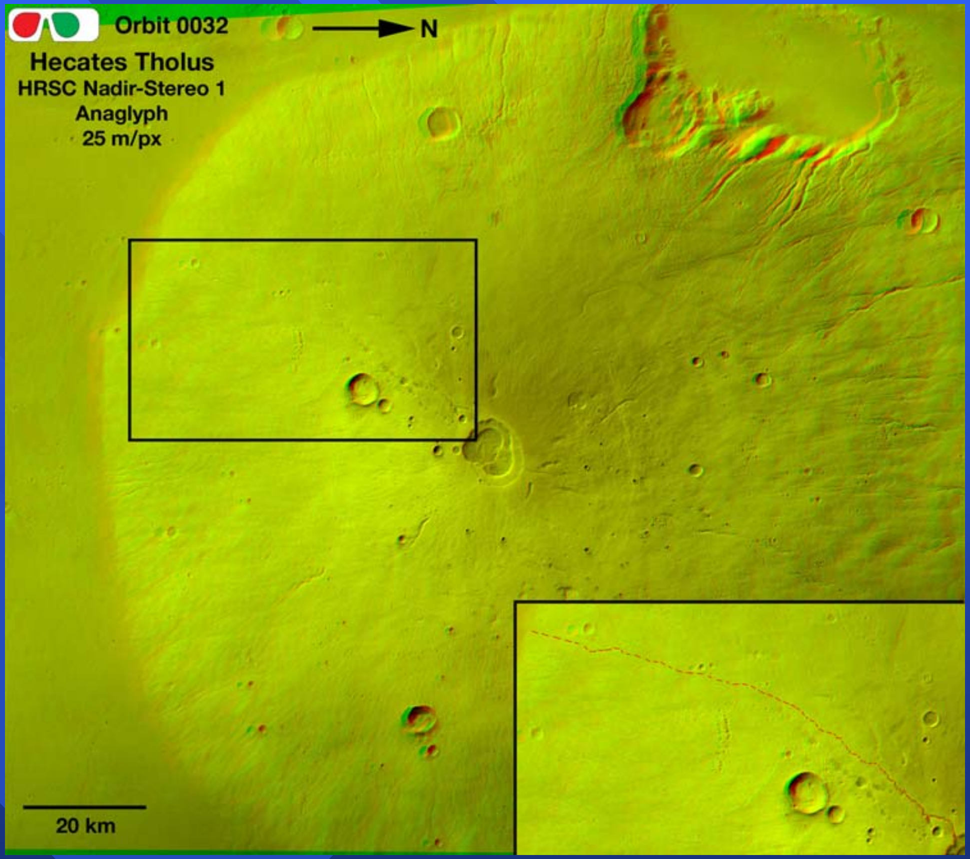
Why Study on Mars Now?

- New data from current missions provide additional constraints for modeling
  - MEx HRSC provides high-resolution stereo data on slopes (DTMs), lava flow thicknesses, and channel depths
  - MER provides *in situ* measurements of volcanic rock compositions
- Inspiration: Some channels on Hecates Tholus (Orbit 32)
  - Most channels likely fluvial in origin: *Fassett & Head*, 2004
  - Some resemble collapsed lava tubes or sinuous rilles



From MER *Spirit*: Basaltic Compositions at Gusev

	Earth Komatiite	Io U-mafic	Moon Mare Bas	Earth Kom. Basalt	Mars* Basalt	Earth Thol. Basalt
SiO_2	45.0	49.8	47.9	46.9	45.4	50.9
TiO_2	0.3	0.1	2.6	0.6	0.5	1.7
Al_2O_3	5.6	7.9	7.9	9.8	10.9	14.6
FeO_{tot}	10.6	5.3	21.7	14.4	18.2	14.6
MgO	32.0	30.9	14.9	18.9	12.8	4.8
CaO	5.3	5.2	8.3	8.6	7.5	8.7
Na_2O	0.6	0.4	0.2	0.3	2.8	3.1
T_{liq} (˚C)	1640	1610	1440	1420	1270	1160
ρ (kg/m^3)	2770	2680	2900	2800	2820	2750
μ (Pa s)	0.08	0.2	0.4	0.8	2.3	90
Re (-)	1.7E+06	5.7E+5	3.1E+5	1.4E+5	2.3E+5	5.5E+2

- Mars basalts could have been emplaced as ***turbulent flows***

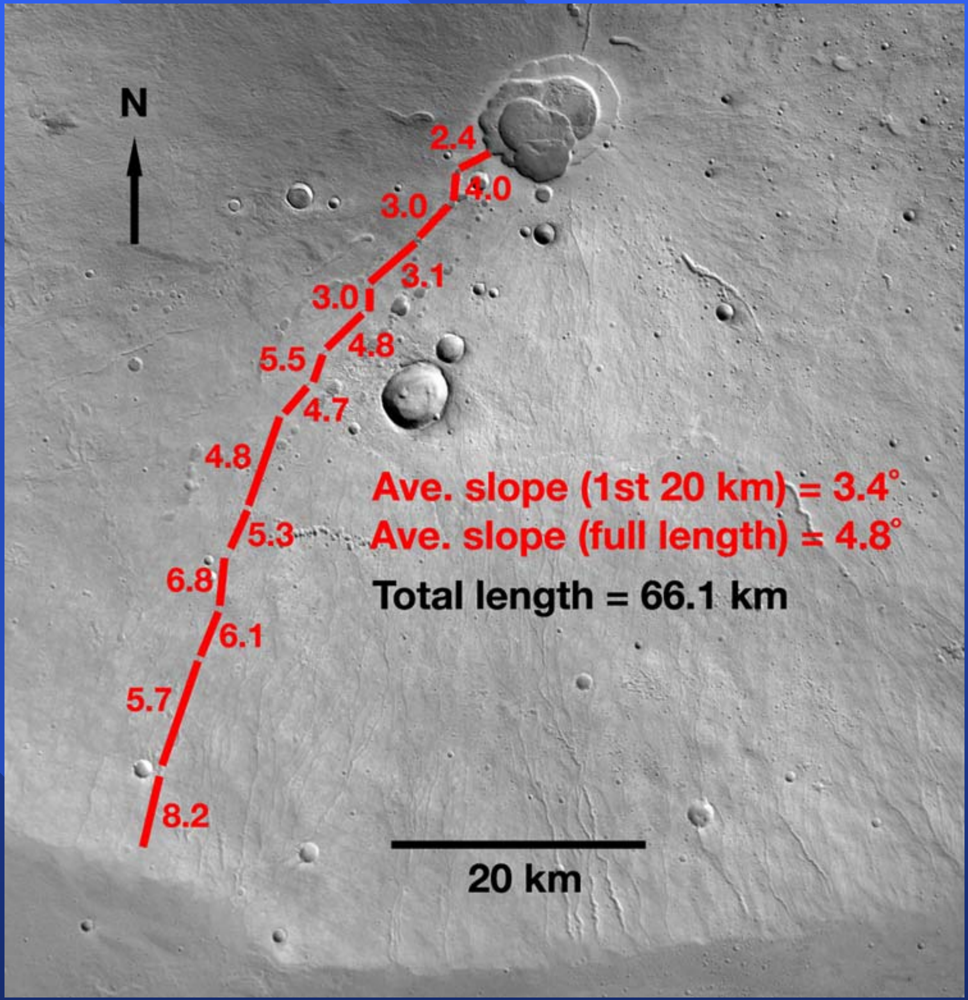
*** Extrapolated from RAT-abraded APXS data, MER *Spirit*, *McSween et al.*, 2004**

From HRSC: Slopes under Lava Channel

- Determine underlying slopes using existing 100 m HRSC DTM
  - Slope at caldera = 2.4°
  - 3-5° on upper flanks
  - 5-6° on lower flanks
  - >8° at base of shield

  - Average slope near vent = 3.4°
  - Overall average slope = 4.8°

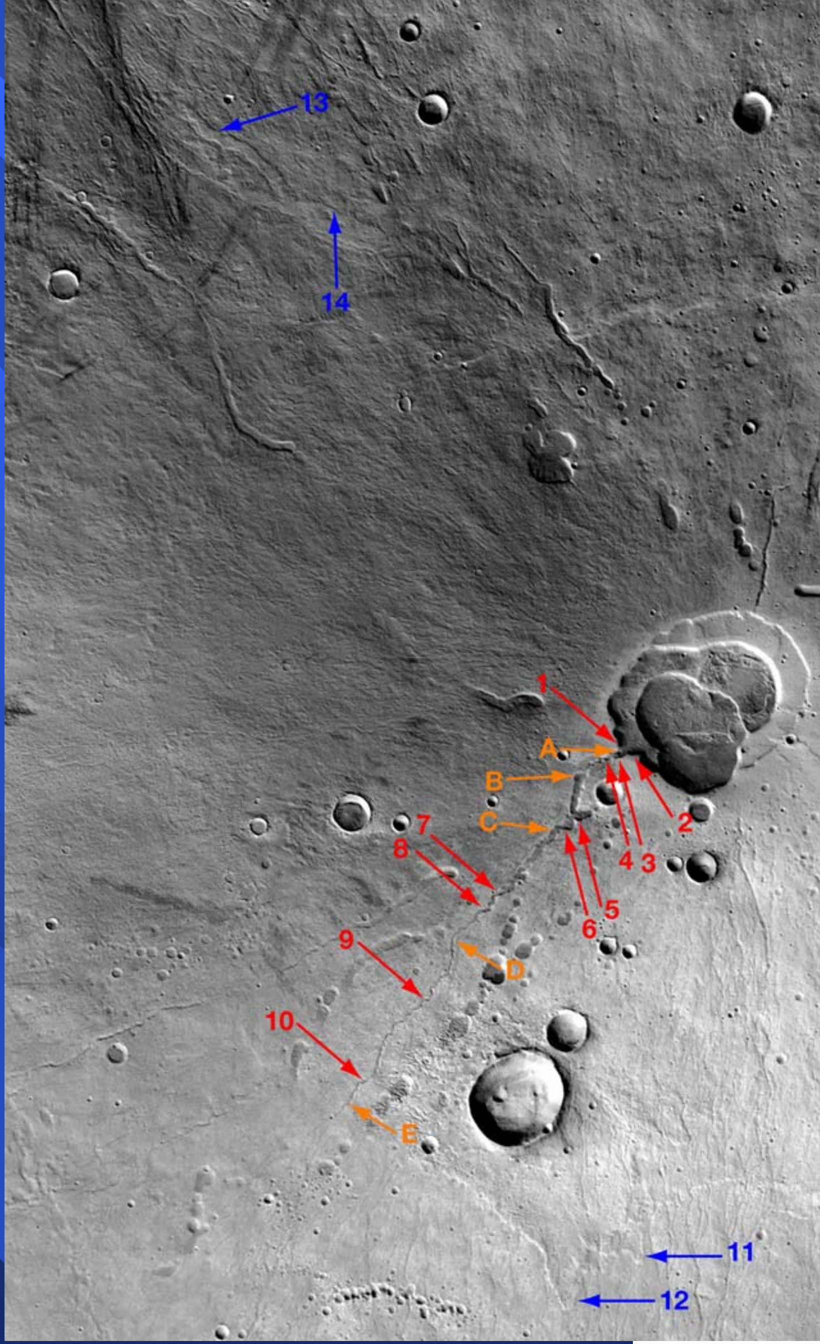
Slope Measurements from HRSC DTM:



From HRSC: Estimate Channel Depth

- Method 1: Shadow Measurements
  - MOC-NA coverage not good, no useful shadows
  - Use HRSC Level 3 nadir image
  - Depths: ~100 m neat caldera wall,

    ~30 m at ~20 km downstream, average ~40-60 m in channel
- Method 2: Stereo comparator: Consistent Results
- Estimate flow lobe thicknesses
  - Shadow measurements off of HRSC image
  - Thicknesses: ~20-60 m



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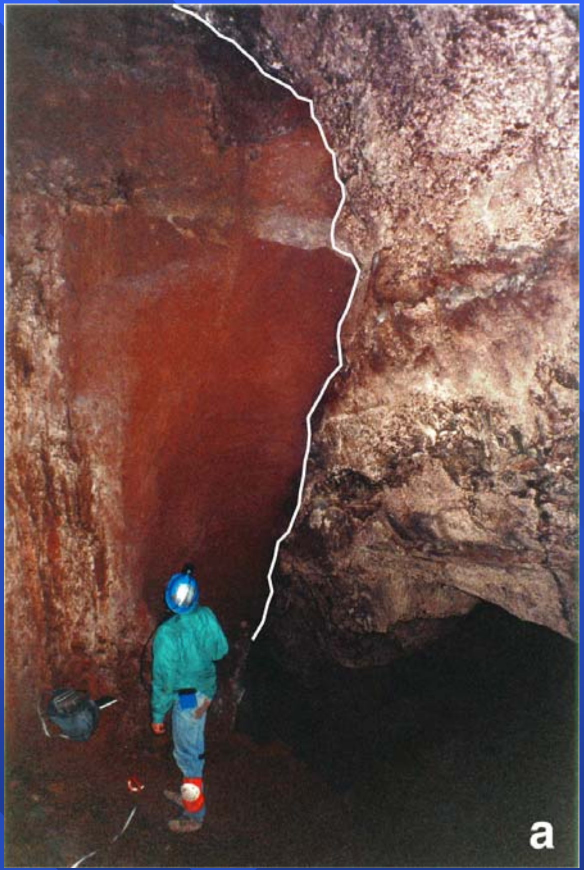
Numerical Modeling of Erosion by Lava

- Types of questions we can address:
  - How erosive are Martian lavas?
  - Are Martian lavas capable of eroding channels of given size?

- Nature of model: Simulates thermal - fluid dynamic - geochemical evolution of lava

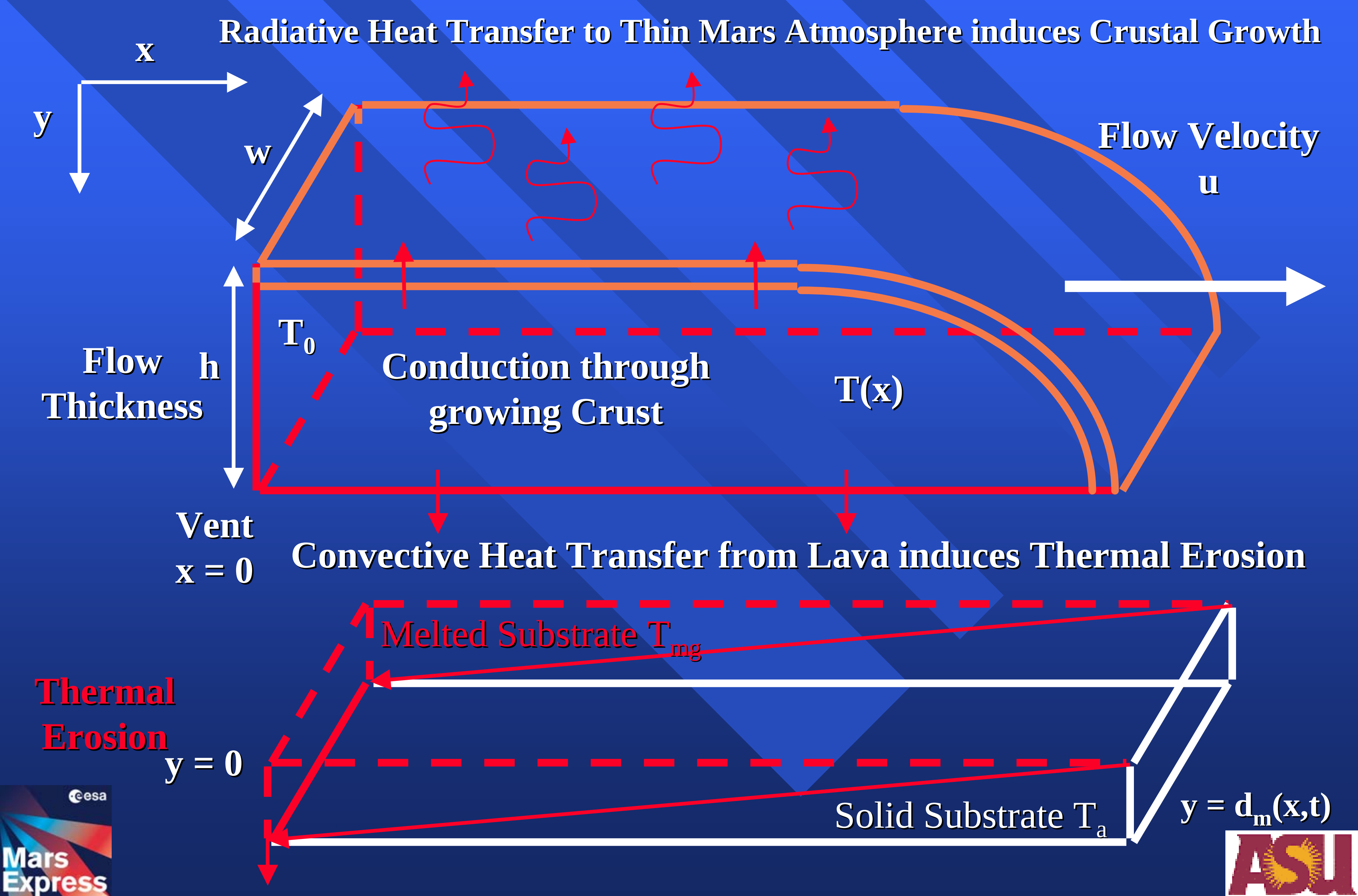
- Input parameters
  - Lava and substrate major oxide composition, lava liquidus, solidus, and eruption temperatures, substrate melting temperature
  - Initial flow thickness (flow rate), slope of ground, fraction of ice in ground, ambient temperature & pressure, environment of emplacement (vacuum, subaerial, or submarine)



Constrained by MER *Spirit*

Constrained by HRSC on *Mars Express*

Modeling Flow Emplacement & Erosion



Cooling-Limited Lava Emplacement

Conservation of Energy: Heat gains = heat losses

$$\rho_l c_l h u \frac{dT}{dx} = -2\tilde{h}_T\left(T - T_{mg}\right) + \tilde{h}_T\left(T_{Sol} - T_{mg}\right) - \frac{\rho_l c_l \tilde{h}_T\left(T - T_{mg}\right)^2}{EMG}$$

$$\tilde{h}_T = \frac{h_T}{1 - \frac{L_l x'(T)}{c_l}}$$

Heat Transfer w/Latent Heat, turbulent pipe flows:

$$h_T = \frac{0.027 k_{eff} Re^{0.8} Pr^{0.33}}{h}\left(\frac{\mu_l}{\mu_g}\right)^{0.14}$$

Energy to Remove Ice & Rock Substrate:

$$EMG = (1-f_i)\{\rho_g[(T_{mg}-T_a)+L_g]\} + f_i\{\rho_i[c_i(T_{mi}-T_a)+L_i]\}$$

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Erosion and Assimilation

Substrate Melting Rate:

$$u_m = \frac{\tilde{h}_T \left(T - T_{mg} \right)}{EMG}$$

Erosion Depth after Elapsed Time t:

$$d_m = u_m t$$

Amount of Assimilated Substrate as Volume Fraction of Lava:

$$S = 1 - \frac{Q_0}{Q_0 + \int_0^x u_m dx}$$

- Lava temp > ground melting temp => Thermal Erosion
- Thermal erosion measured in laminarly-flowing lavas in Hawaii (<10 cm/day: basalt over basalt: Kauahikaua et al., 1998)

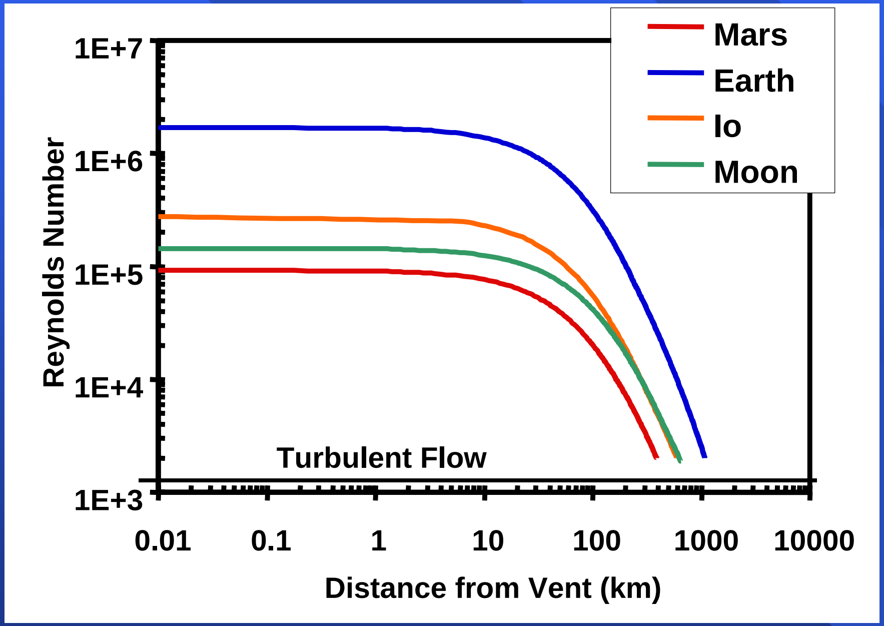
Model Lava Physical Properties

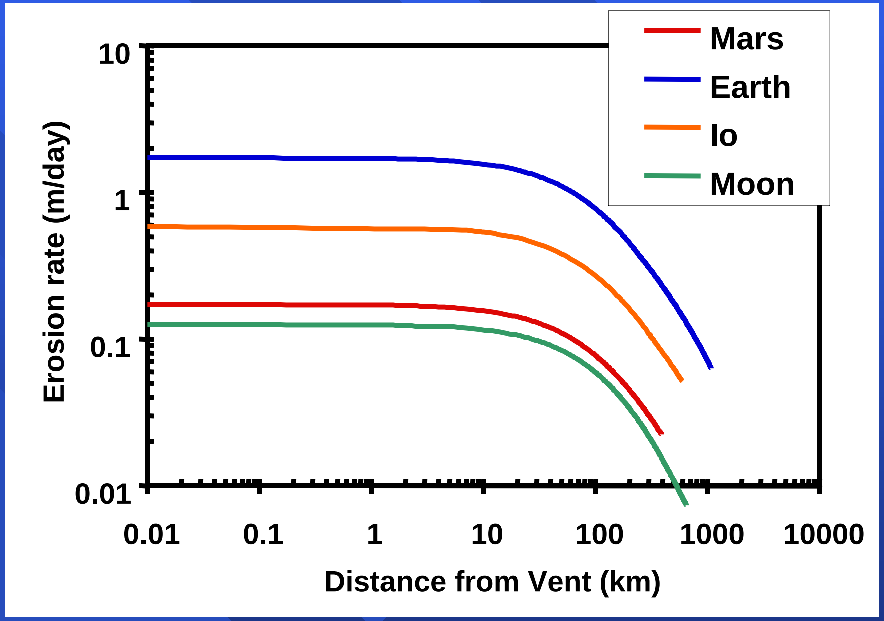
- Vary with temperature and composition
  - ☞ Lava/Substrate Density (*Bottinga & Weill*, 1970)
  - ☞ Lava/Substrate Specific Heat (*Lange & Navrotsky*, 1992)
  - ☞ Lava Viscosity (*Shaw*, 1972)
  - ☞ Lava/Substrate Heat of Fusion (*Navrotsky*, 1995)
  - ☞ Lava Thermal Conductivity (*Snyder et al.*, 1994)
  - ☞ Lava Reynolds Number (assuming specific flow rate)
  - ☞ Lava Convective Heat Transfer Coefficient (*Kakaç et al.*, 1987)
  - ☞ Lava Thermal Erosion Rate

Results I

Question: How erosive are Martian lavas compared to other planets?

Assumptions: Initially 10 m thick flow, erupted at liquidus, slope = 0.1˚, dry substrate same composition as lava (except Earth: komatiite over basalt)





Answer: As expected, Martian lavas are the least mafic and thus least turbulent (all else equal). Erosion rate less on the Moon due to higher heat transfer rate to ground on Mars (higher Prandtl number due to higher dynamic viscosity).

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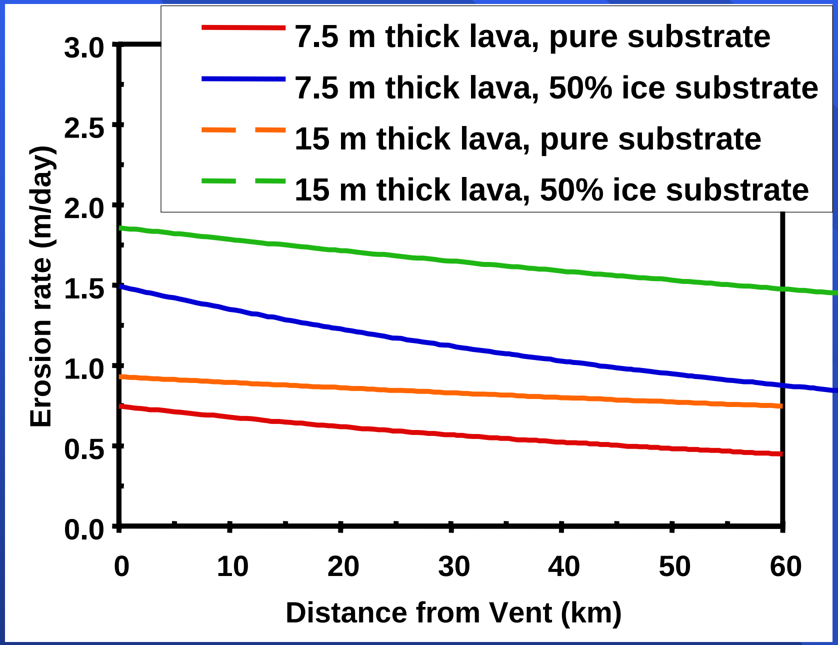
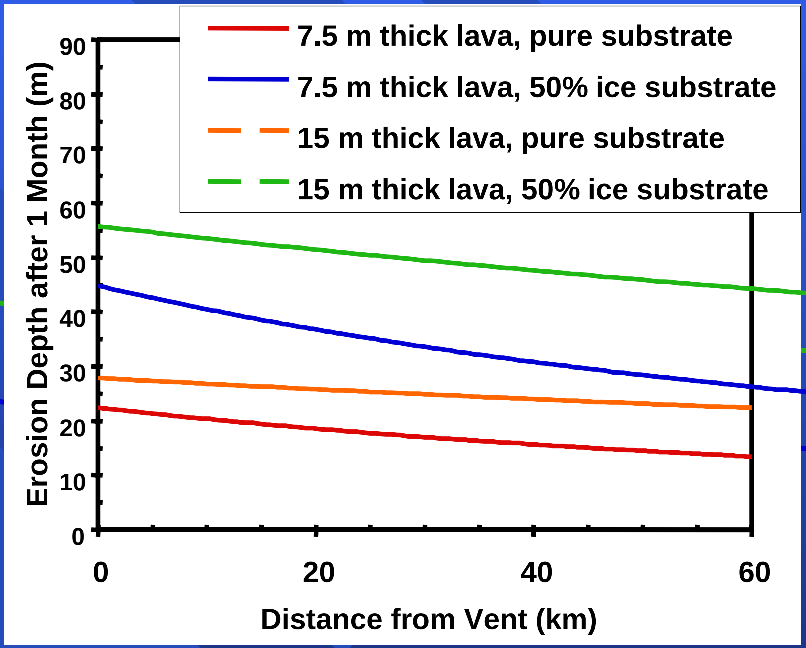
Results II

Question: Could Martian lavas have eroded the large channel on Hecates Tholus?

Assumptions: Initially 7.5 m thick flow, erupted at liquidus, slope = 3.1˚, substrate same composition as lava (with & without ice), ambient T = -59˚C





Answer: Yes, if sustained flow (weeks to months) occurred. Maximum erosion rates ~70-90 cm/day for 7.5 & 15 m thick flows, respectively. Erodability of substrate enhanced if fragmental & contains ice (~150-190 cm/day). This does not include the mechanical force of the now liquid water.

Conclusions

- Current Mars missions are providing excellent basic information on Mars for various modeling studies
  - MER: Compositions of rocks and soils, rock textures from MI, aeolian & atmospheric measurements from cameras
  - MEx: Regional coverage at high resolutions, color, & stereo (HRSC); high-res data on surface relief (DTMs); VNIR spectroscopy (OMEGA)
- These data enable a more rigorous investigation of the role of erosion by lava in the genesis of Martian channels
  - Hecates channel first candidate for modeling
  - Other candidates should be studied
- Assuming Hecates lavas similar in composition to Gusev lavas, then they could have eroded channels or formed tubes on Hecates Tholus
  - Erosion enhanced if substrate is pyroclastic material, or contains large fraction of ice
  - Erosional channels could have been deepened by later fluvial activity ala *Fassett and Head* (2004)