Entrainment and Runout of Martian Pyroclastic Density Currents

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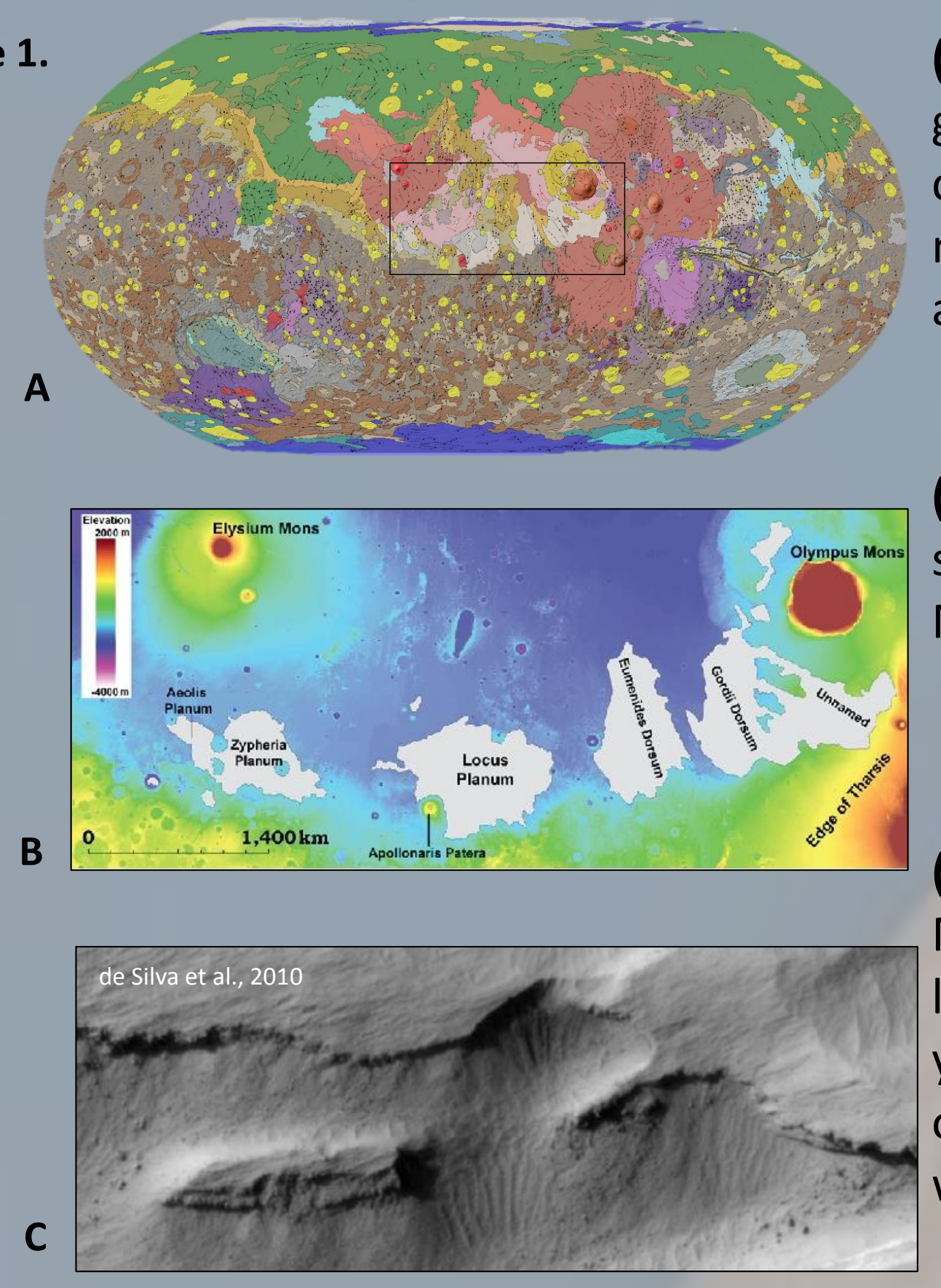
Motivation:

The large Martian deposit known as the **Medusae Fossae Formation** (MFF) was likely deposited through volcanic processes; i.e. deposition through pyroclastic fall or pyroclastic density currents (PDCs). This is based largely on the analysis of satellite images of the formation. Little has been done to test the feasibility of PDCs as the depositional mechanism of the MFF, or the effects of atmospheric pressure on PDC runout. One of the largest questions is if PDCs on Mars can travel far enough (>100s km) to make such a deposit from a small number of eruptive sources, or if, instead, PDCs travel short distances (<50 km) requiring many eruptive sources.

Figure 1.



(A) Global Martian geologic map centered on the 180° meridian (Tanaka, et al., 2014).

(B) Elevation map showing prominent MFF lobes in grey.

(C) HiRISE imaging of MFF showing layering and yardangs, features often associated with PDC deposits.

Background:

PDCs are dense mixtures of rock and gas generated during explosive eruptions. They travel laterally across the landscape until they become less dense than the atmosphere. Their density decreases as they mix (or **entrain**) air in through their surface area. The velocity of air being mixed into the current divided by the mean velocity of the current is called the **entrainment rate, ε**.

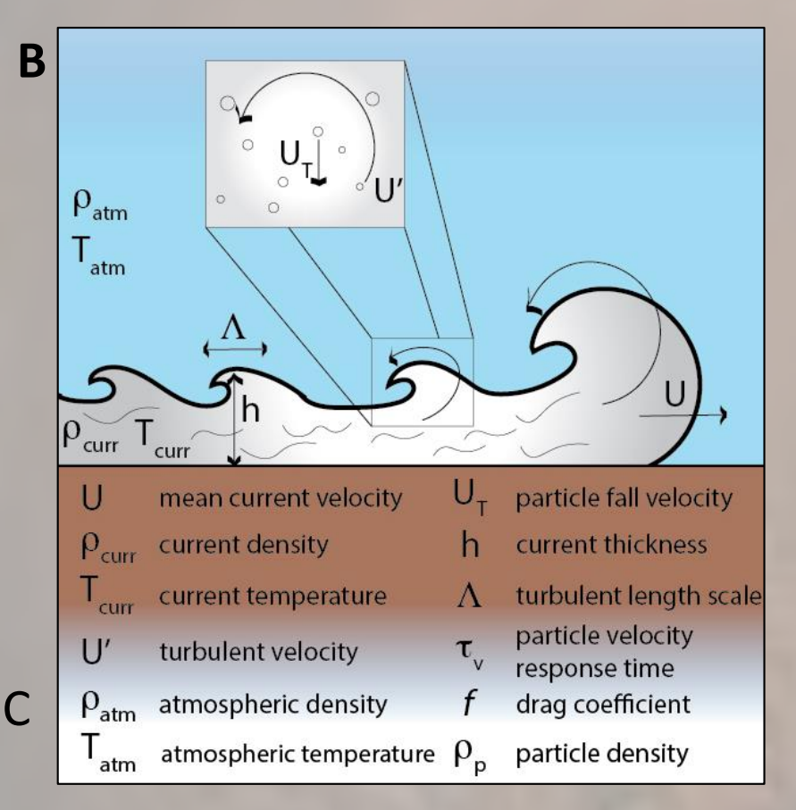


Figure 2.
(A) PDC from Soufrière Hills eruption in 1997. **(B)** Cartoon PDC illustrating main structures and parameters of the current.

Pressure:

Due to the low pressure of the atmosphere, PDCs are more likely to occur on Mars.

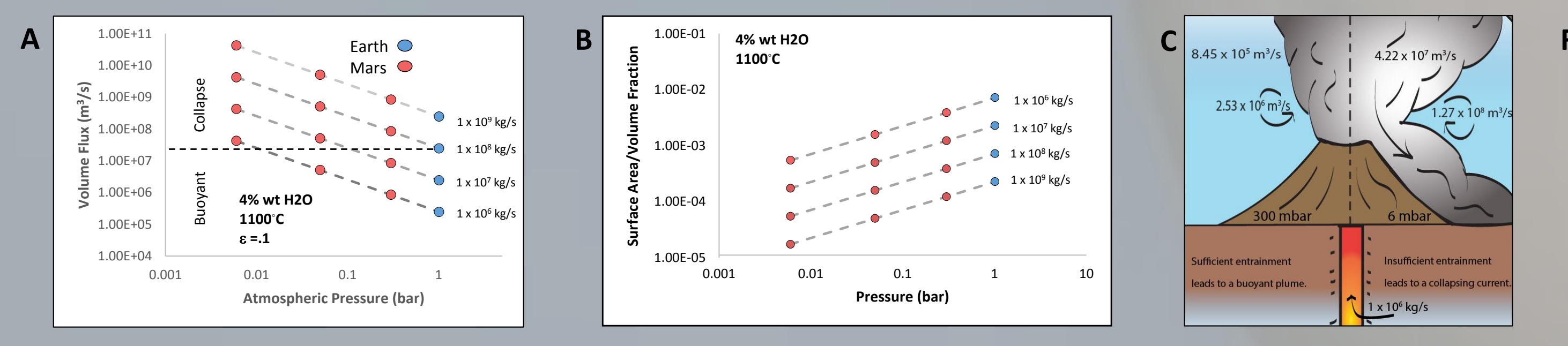


Figure 3.

(A) As pressure decreases for an eruption with a given mass flux (kg/s), the volume flux (m3/s) increases.

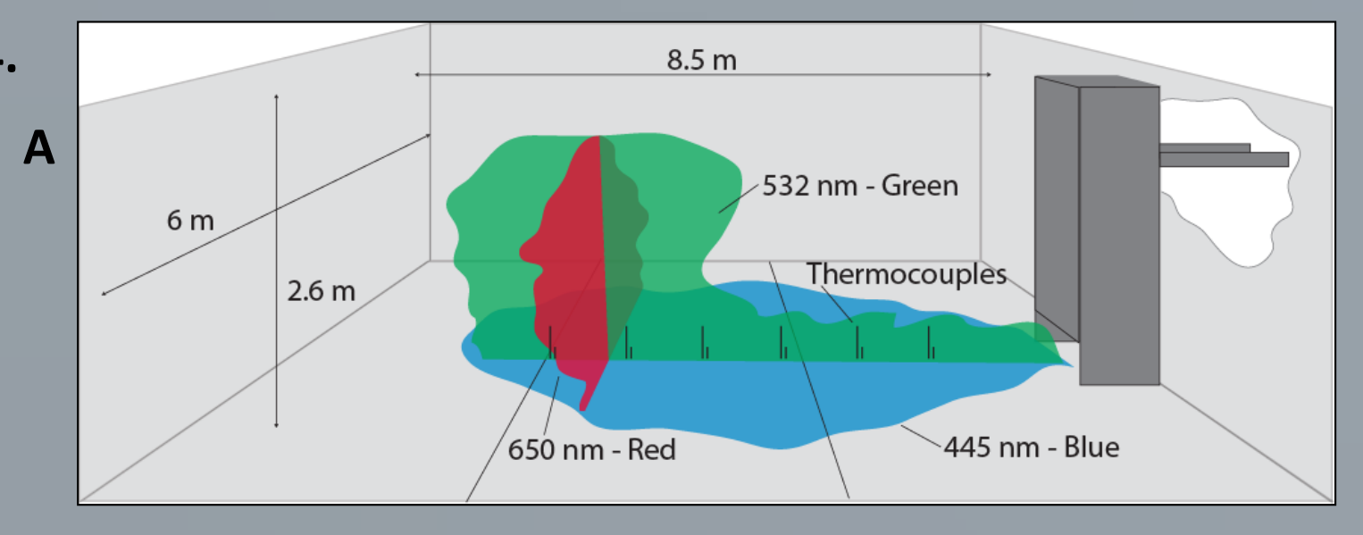
(B) Volume increases at a higher rate than surface area, reducing the plumes' entrainment capabilities.

(C) If a plume fails to mix in enough air to maintain it's buoyancy, it collapses and forms a current.

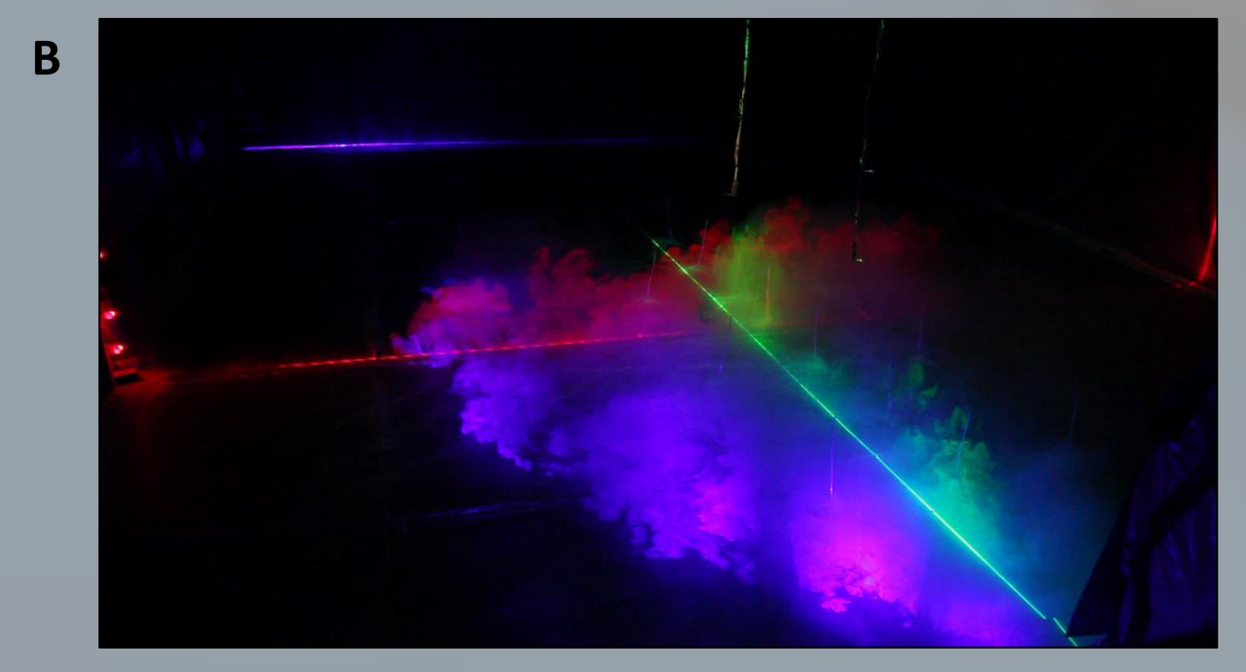
For a given mass flux, Martian eruptions yield plumes with larger volume fluxes that entrain air less efficiently than their Earth counterparts, resulting in column collapse and PDC generation. Those high volume flux PDCs should travel farther on Mars than on Earth.

Experimental Methods:

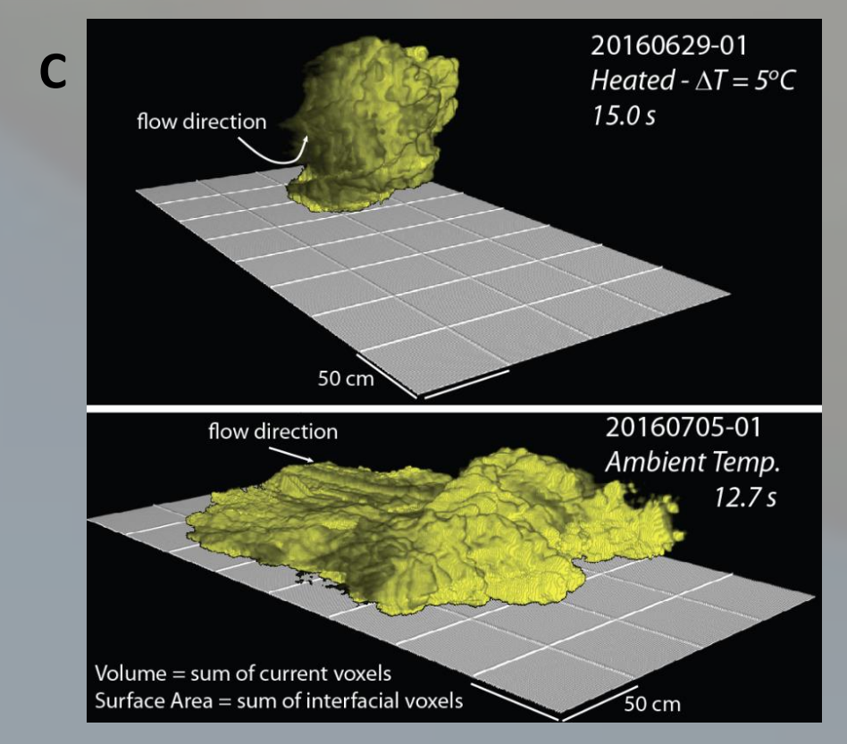
Figure 4.



(A) Schematic of the experimental PDC tank. Experiments are illuminated with orthogonal laser sheets (or a sweeping laser sheet), and temperatures are measured with thermocouples.



(B) Ambient temperature current spreading across the floor of the tank. Orthogonal illumination allows for feature tracking velocimetry (FTV) measurements.

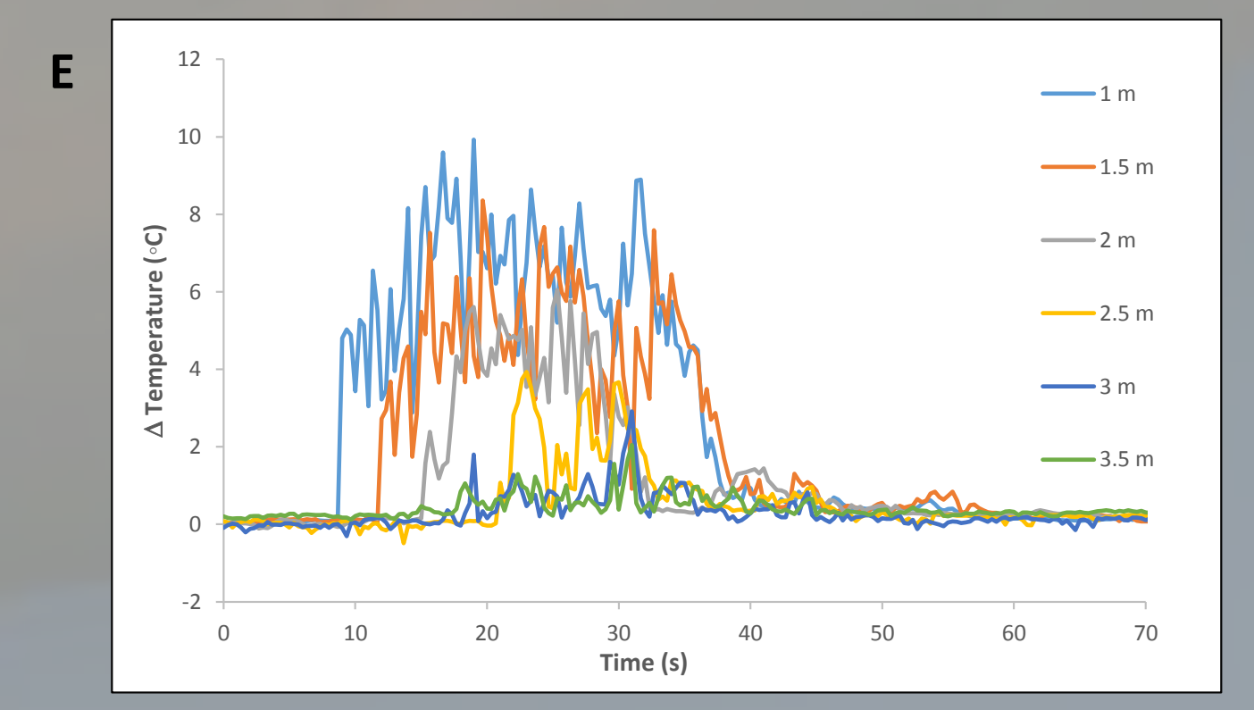


(C) Sweeping overhead lasers produce quantitative 3D renderings of currents.

D

		Natural PDCs	Experimental
Re	ρcUh/μair	10^8-10^{10}	10^6-10^7
Ri	ρcgh/ρatmU²	0-10	0.1-6
Ri_T	gΔTαh/U²	0-5	0-7
Fr	U/√g¹h	1	1
S_T	$\tau u'/f\Lambda(1+\rho c/2\rho_p)$	10^{-2}-10^2	10^{-4}
Σ_T	u_t/u'	10^{-6}-10^5	<1

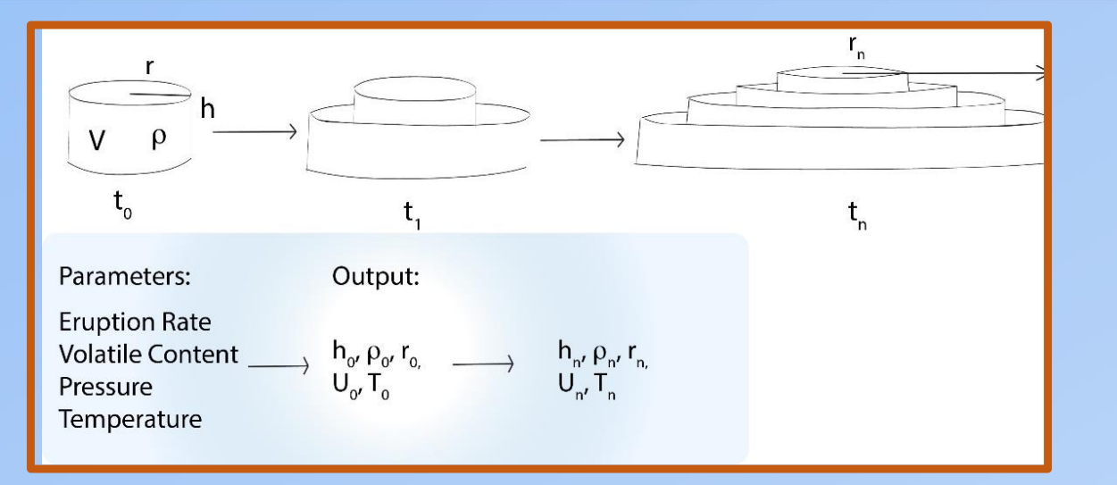
(D) Table with fluid dynamic scaling of natural and experimental currents.



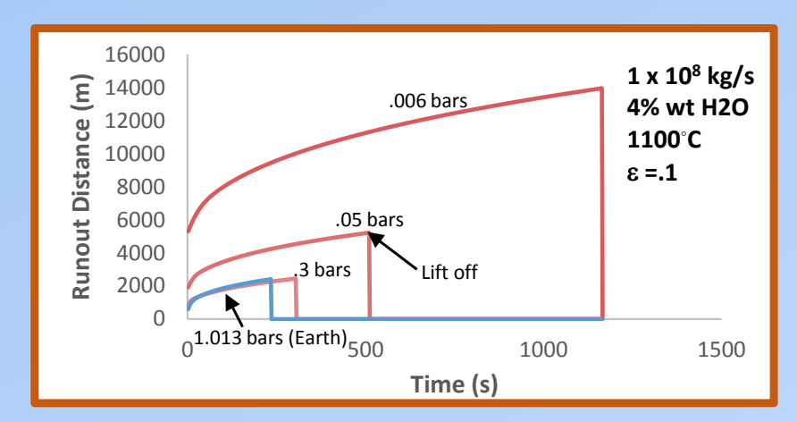
(E) Temperature recorded at 5 cm heights as a heated current travels downstream. Measurements taken three times per second.

Results:

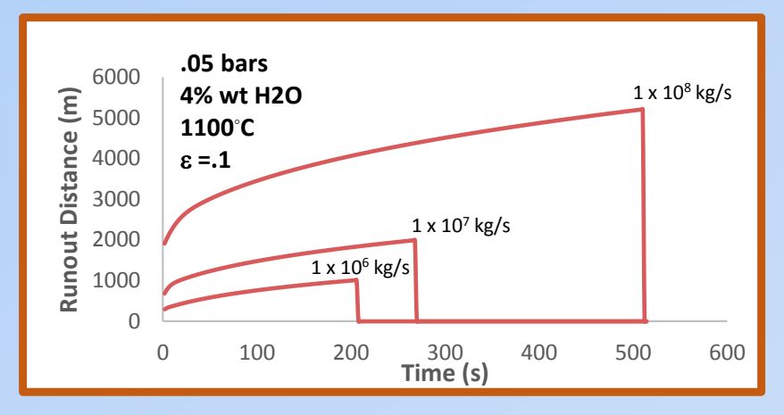
Numerical Model



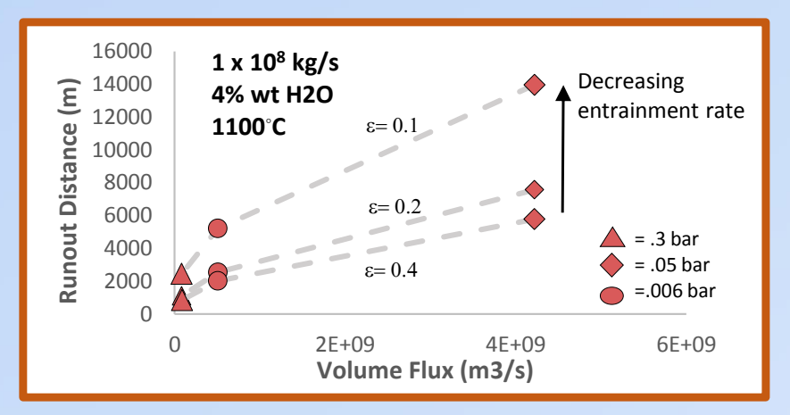
- Our numerical model treats currents as a sequence of axisymmetric cylinders growing over time.
- Various parameters such as eruption rate can be controlled to produce a data series that includes runout distance, density, and temperature.
- The model predicts when currents will lift off.



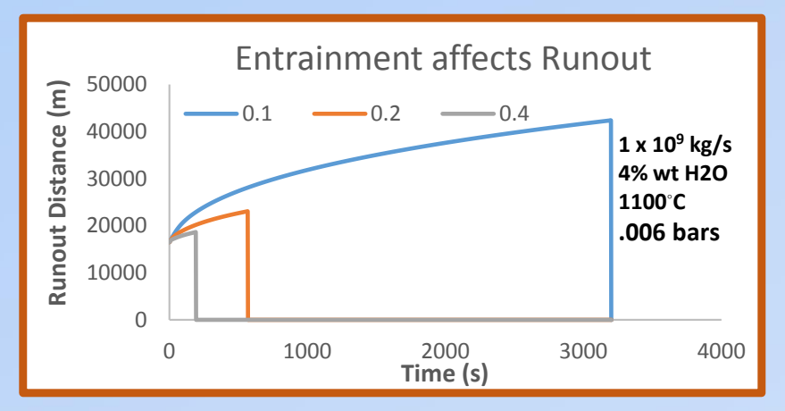
- Lower pressure results in farther runout distances.



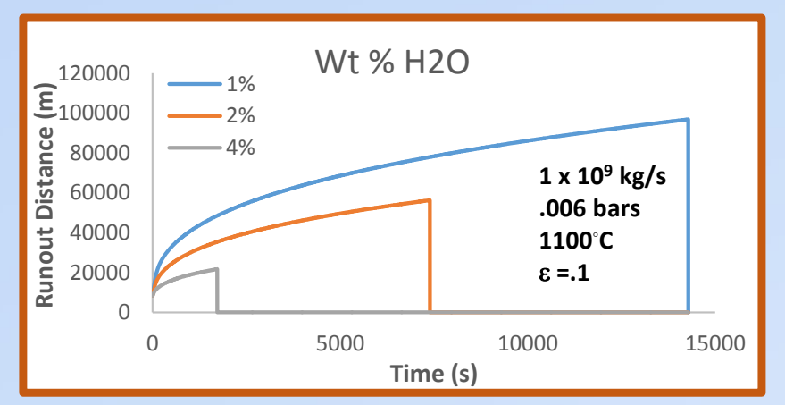
- Higher eruption rates (kg/s) result in farther runout distances.



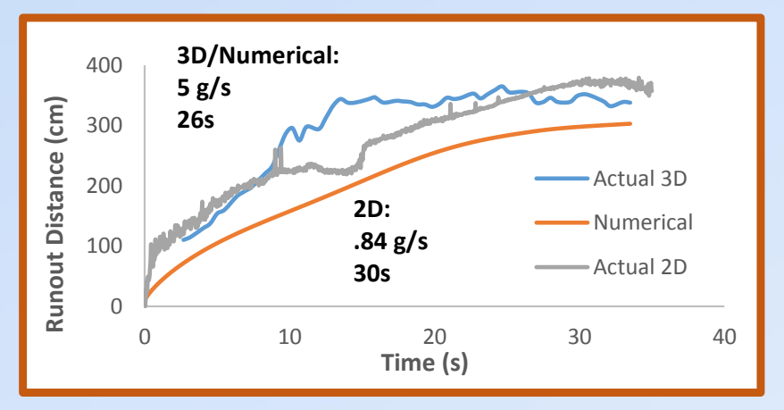
- Runout increases proportionally to volume flux and inversely with entrainment rate.



- As entrainment rate increases, runout decreases.

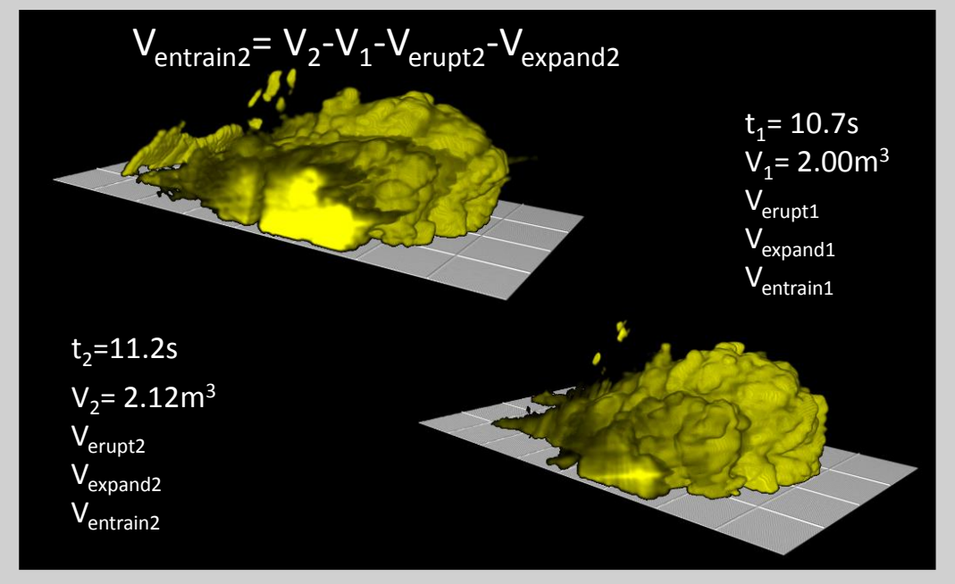


- Lower wt % H2O results in denser currents, increasing runout.



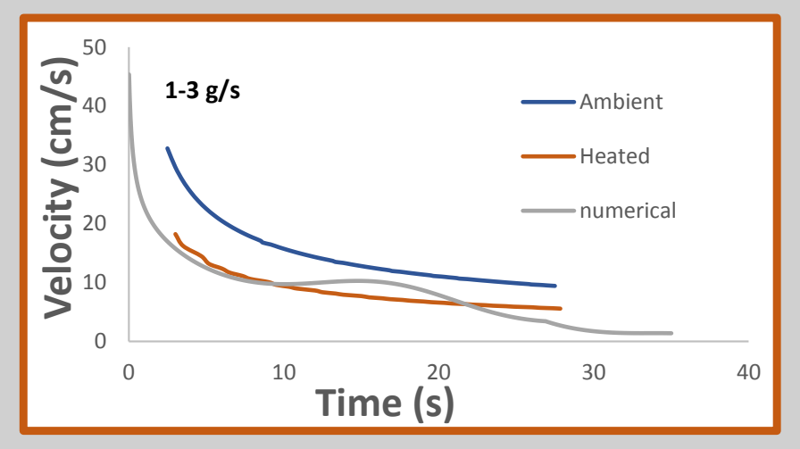
- Model predicts runout of experiments with a percent error of ~10%.

3D Experiments

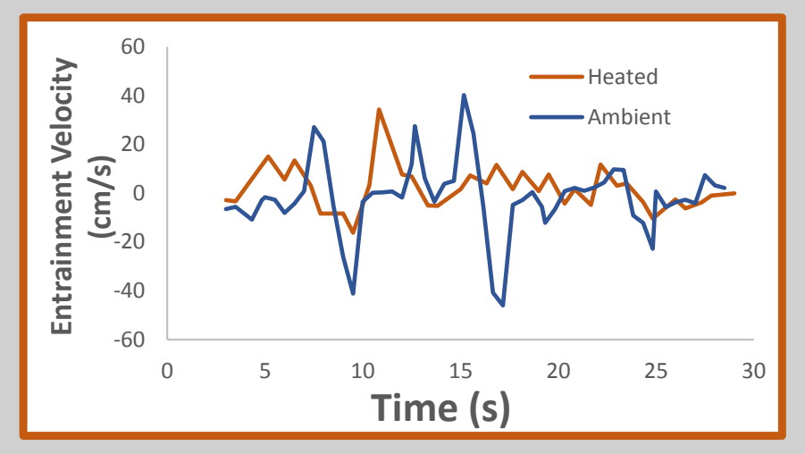


- Quantitative 3D renderings of currents accurately give us surface area and bulk volume measurements.
- Entrainment volume can be calculated and used to find entrainment velocity:

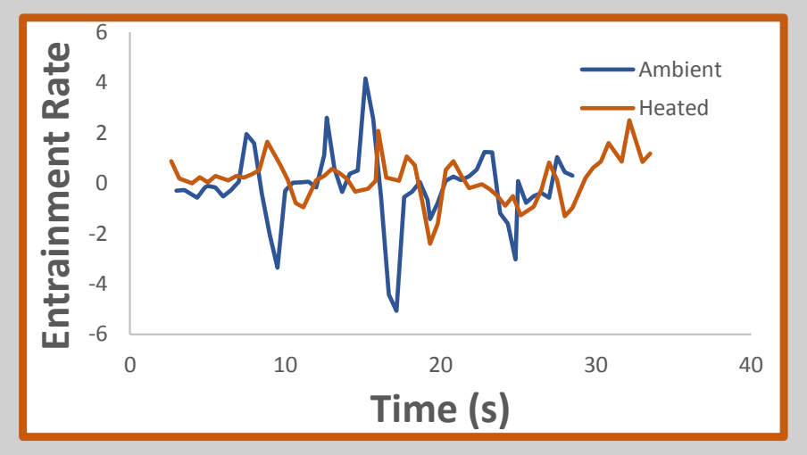
$$V_{entrain2}= V_2-V_1-V_{erupt2}-V_{expand2}$$
$$U_{entrain2}= V_{entrain2}/(Area_2 \times (t_2-t_1))$$



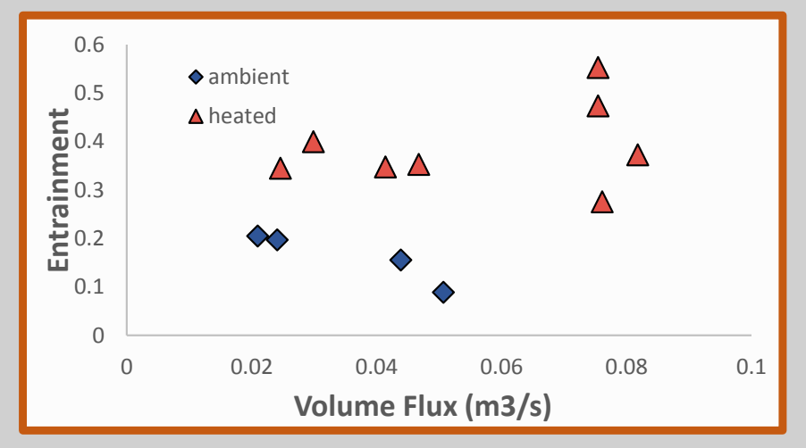
- Velocity graphs for experimental flows and numerical model show agreement.



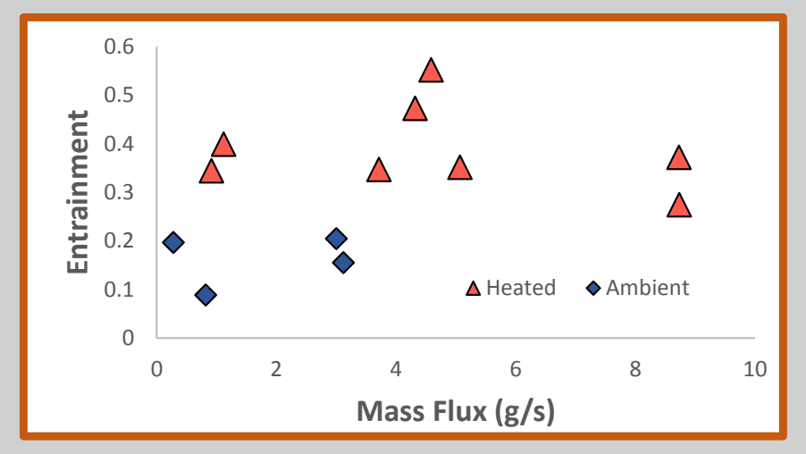
- Entrainment velocity fluctuates over time, contrary to previous models.



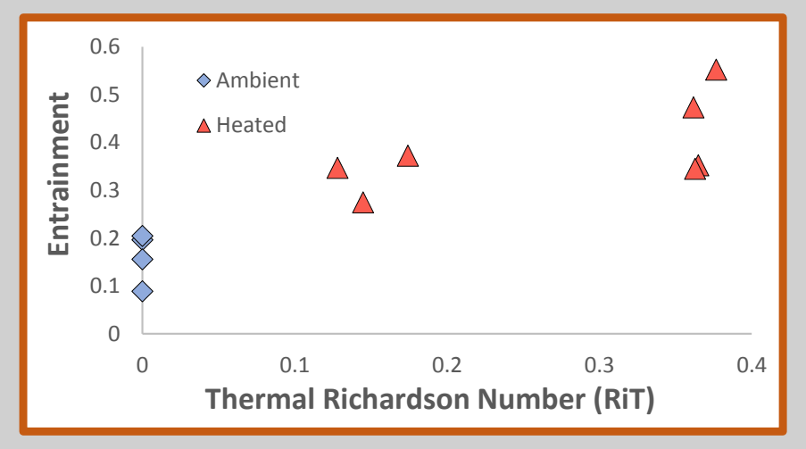
- Entrainment rate follows a similar trend as entrainment velocity.



- There is no relationship between volume flux and entrainment rate.



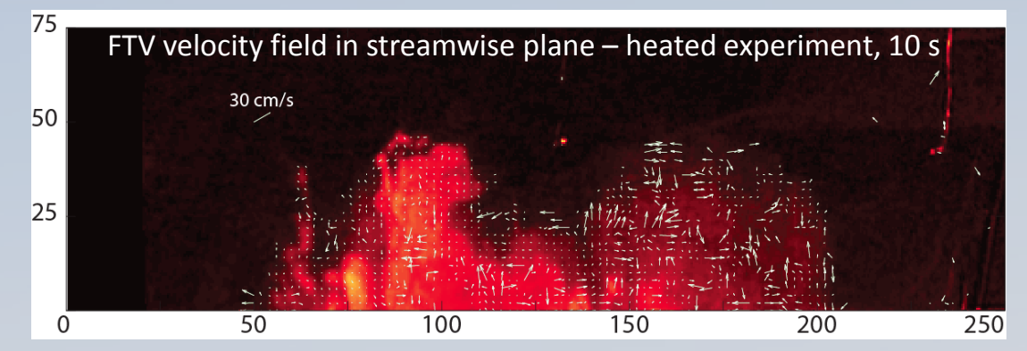
- There is no relationship between mass flux and entrainment rate.

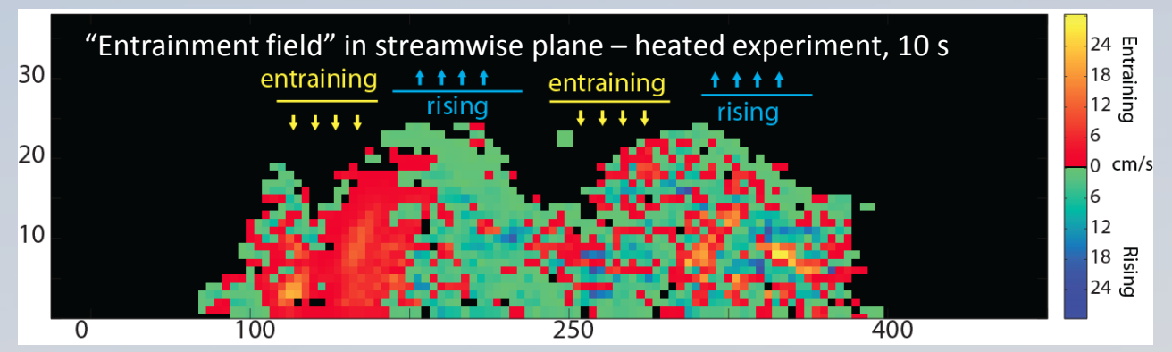


- Hotter currents entrain more efficiently.

2D Experiments

2D illumination shows turbulent velocity field; entrainment varies with space and time.





Discussion:

Validation of numerical model

- Numerical model recovers experiment runout to within ~10%.
- This difference likely results from axisymmetric dispersal (rather than directed), and because the model does not account for the deposition of pyroclasts.
- Variation in average entrainment rate strongly affects runout distance, but unsteadiness in entrainment rate does not. This relationship is demonstrated by experiments and numerical results.
- We assume entrainment of 0.2 for numerical simulations of Martian eruptions. This value agrees with that of Andrews (2014), but is higher than most previous estimates of entrainment, and has the effect of reducing runout.
- The model assumes no variation in entrainment with volume flux; this is supported by the experiments.

Entrainment varies with temperature, but not eruption rate

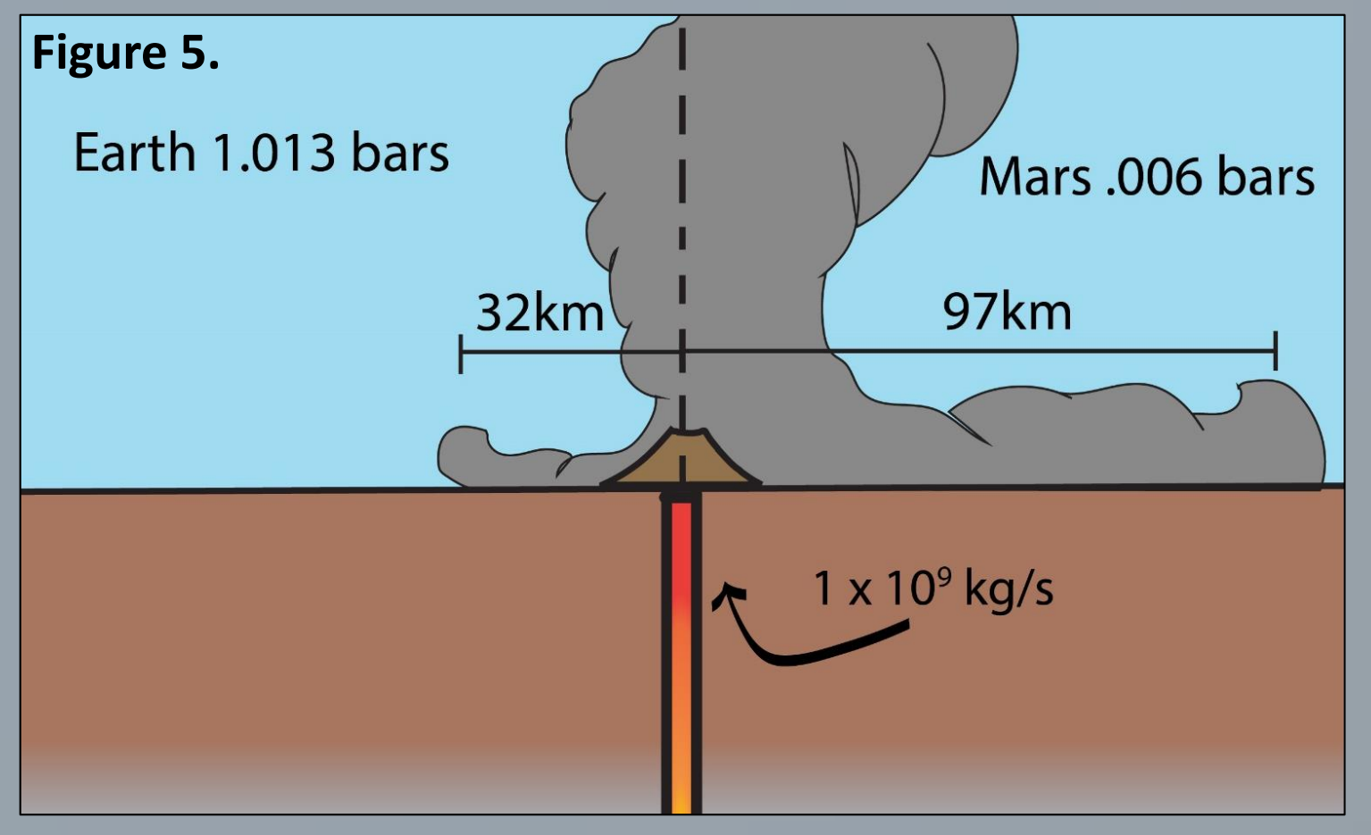
- Experiments show entrainment ranges from ~0.1-0.2 for ambient temperature currents to as high as 0.6 for heated currents.

Currents on Mars can travel up to 5.8 times farther than those on Earth

- For eruptions with equivalent parameters, runout distance increases as atmospheric pressure decreases.

PDCs provide a reasonable mechanism for the Medusae Fossae Formation

Figure 5.



- Explosive eruptions are increasingly likely at lower pressure (Wilson and Head, 1994).
- As pressure decreases, PDC generation becomes favored.
- PDCs can travel up to 100 km for "large" eruptions and >200 km for supereruptions.
- Our results do not say from where the MFF erupted, but they do suggest the potential extent of individual deposits.
- Future mapping efforts focused on describing the thickness of individual units within the MFF and mapping the extent of those units will provide constraints on atmospheric and eruptive conditions that led to the MFF.

References & Acknowledgements:

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