Planetary pyroclastic fall eruptions and the origin of the Nili Fossae olivine-rich unit on Mars

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Background: The Nili Fossae olivine-rich unit

- The Nili Fossae olivine-rich unit (NFOU) has been suggested to result from pyroclastic fall processes (i.e., the settling of tephra from a volcanic plume) [1].
- The Perseverance rover encountered a possible exposure of the NFOU named the Séitah formation, but this was determined to be an olivine cumulate and therefore not derived from explosive volcanic processes. The relationship between Séitah and the regional NFOU remains unclear.
- To better understand the plausibility of pyroclastic fall processes in producing this and other widespread deposits on Mars, we have constructed a settling model for ash particles in planetary atmospheres.

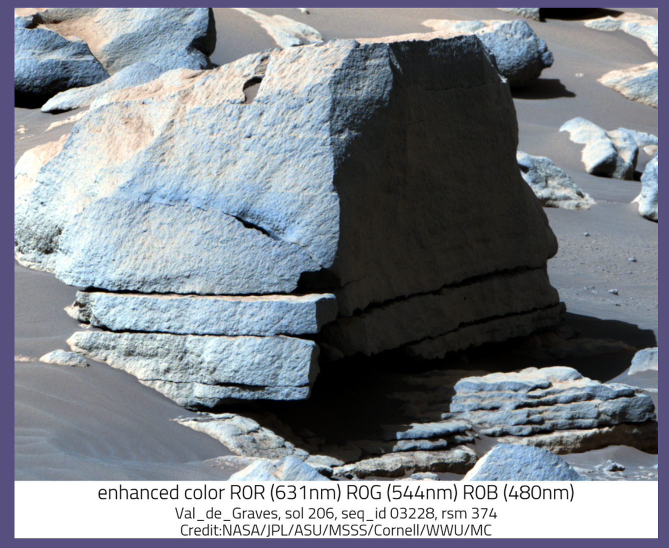


Figure 1: *Enhanced color right-eye Mastcam-Z image of Val de Graves, part of Séitah, taken on sol 206. Sequence ID zcam03228.*

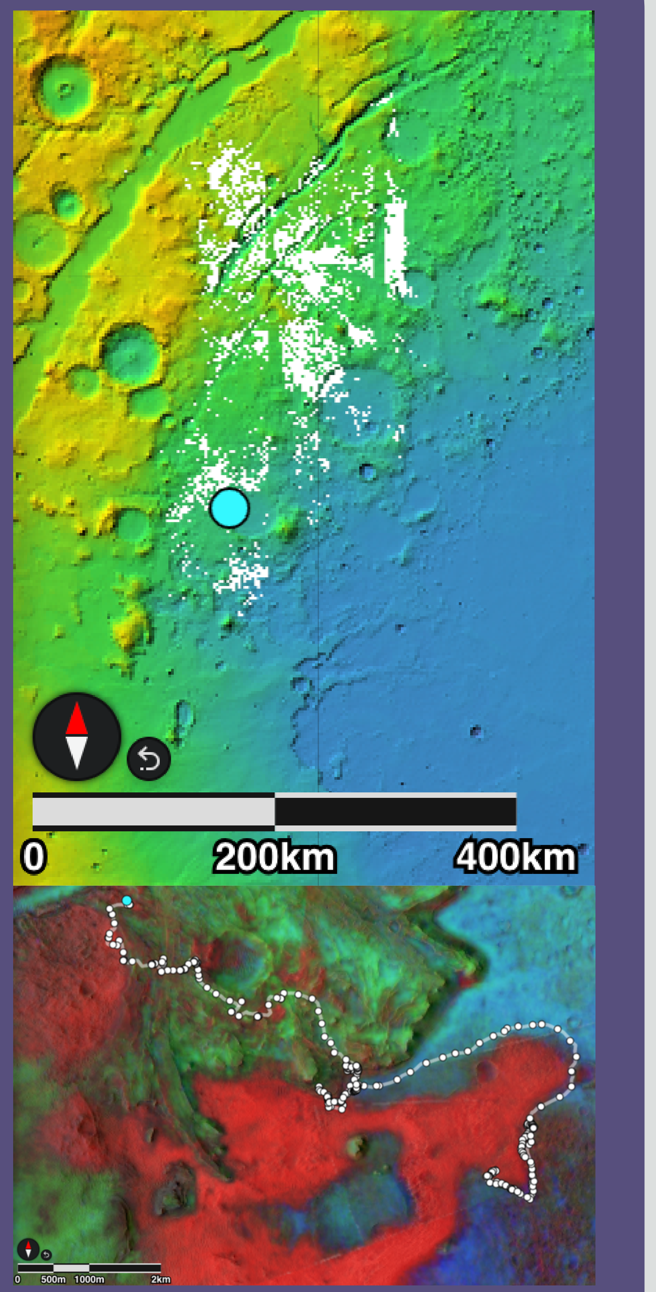


Figure 2: *Top: the olivine-rich unit, as mapped in Mandon et al. 2020 [22], shown in white, overlain on MOLA elevation data. Bottom: the Séitah formation as shown in a CRISM mafic band map (BD1300 / LCPINDEX/ HCPINDEX) where areas high in olivine show up as red. Rover traverse is in white with current position shown as a cyan dot.*

Pyroclastic fall eruptions on Mars and ash settling models

- Previous modeling of pyroclastic fall on Mars was based on the finest ash size fractions [2], [3], [4] whereas the NFOU is relatively coarse-grained (≥500 μm).
- Recent terrestrial investigations of the density of tephra grains have revealed a sigmoidal density distribution with particle size [5], [6], which we account for in our modeling.
- We developed an ash settling model that uses atmospheric properties and windfield output from Global Circulation Models (GCMs), and draw on terrestrial volcanological studies to inform the assumptions used within our modeling.

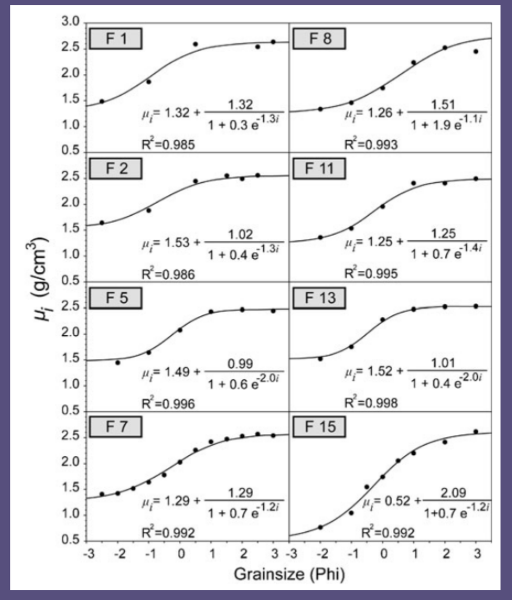
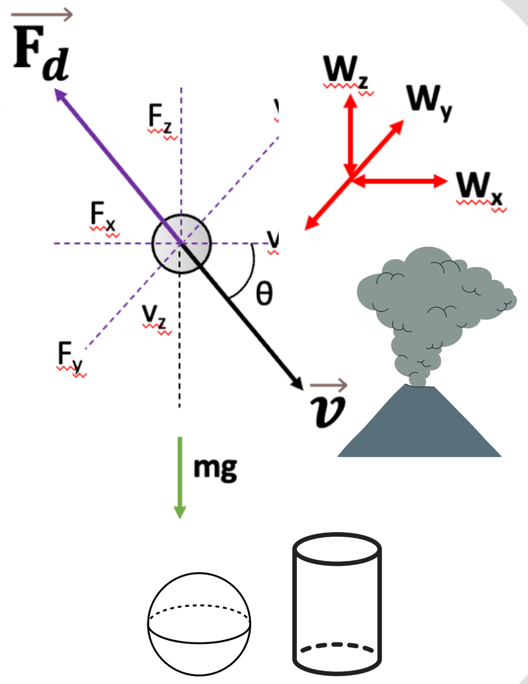


Figure 3: *The sigmoidal density distribution with grain size fractions measured by pycnometry from deposits of the 2006 subplinian eruption of Tungurahua volcano in Ecuador. From Eychenne & Le Pennec, 2012, Fig. 4 [5].*

Methodology

- Our numerical model calculates the trajectories of particles falling from the top of an eruptive plume in three dimensions. We are treating advection in the wind field only, not using a full advection-diffusion formulation, to calculate the maximum downwind dispersal.
- The lateral translation of the particles in the ambient wind, temperature, and density fields (derived from a relevant use case GCM) is used to calculate resultant ash dispersal distances for a given particle size, shape and density.
- We can choose to compute trajectories of particles treated as spheres or cylinders [7],[8], using empirical fits for the drag coefficient C_d of [9] and [10], respectively.



Model validation: Earth data

- To test that our model produces reasonable results, we used grain size data [11] as a function of distance from vent, plume, heights, and wind profiles for three contemporary eruptions:

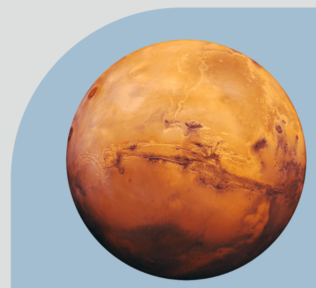
1. *2010 Eyjafjallajökull eruption, Iceland [12]*
2. *2008–2013 Chaitén eruption, Chile [13]*
3. *17–25 May 2016 eruption of Etna Volcano, Italy [14]*

Results:

- Treating particles as cylinders results in greater settling times and dispersal distances than for spherical particles.
- We are able to reproduce observed MdΦ grain size of deposits accounting for plume height, wind velocity and offset from dispersal axis of field sites.
- Assumed plume height has a significant effect on dispersal distance.

Image of Chaitén volcano on Sept 3, 2008, taken by MODIS on NASA Aqua satellite.

Mars: Using MarsWRF outputs



- MarsWRF is a GCM that can be run as a global 2° model with five "nested" higher resolution regions for more local investigations. We take MarsWRF outputs as inputs for our ash settling model, use plume height assumptions based on [15] and interpolate the data in the three spatial dimensions.

Results

- Cylindrical particles travel farther than spheres. Particle density is also significant, particularly for the low atmospheric pressure of current Mars.
- We are also investigating the dispersal of different particle sizes from a given vent, e.g. Syrtis Major, under higher pressure conditions (60, 600 and 1200 mb). We find that under the conditions explored so far, we are unable to disperse coarse grained (500 micron) ash particles across the area of the Nili Fossae olivine-rich unit from a single eruptive center.

Future Work

- We intend to further investigate the parameter space, including the effects of obliquity and seasonality. We also intend to integrate time interpolation, which may require the use of additional computing resources.

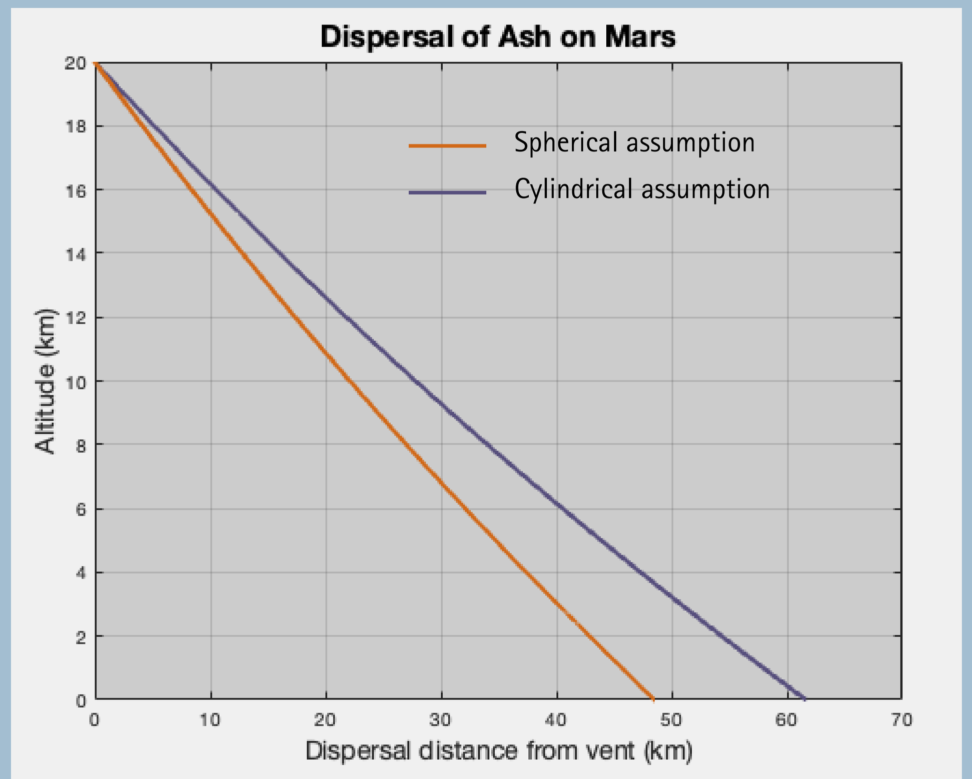
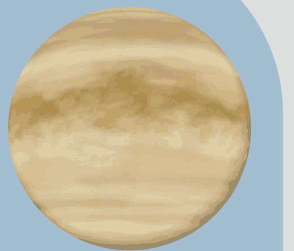


Figure 4: *Dispersal of a 500 micron particle from a 20 km height plume on Mars under current atmospheric conditions. Density of the particle is assumed to be 2300 kg/m^3.*

Pyroclastic fall eruptions on Venus



- Explosive volcanism on Venus has been suggested to explain patterns of increase and decrease in S02 observed at cloud tops [16], [17]. Recent results using Magellan data from 1990-1992 have also suggested that Venus is potentially still volcanically active [18].
- Certain conditions can produce buoyant plumes that plausibly explain the SO2 detection, such as at Maat Mons where a buoyant plume 9 km above the mean planetary radius is plausible [19]. We model the settling of ash from such a theoretical plume.
- We utilize temperature and pressure values from the Venus International Reference Atmosphere [20], [21] to calculate atmospheric density, and we assume low wind speeds of 2 m/s.
- We show that a 500 micron particle could be dispersed ~39 km.

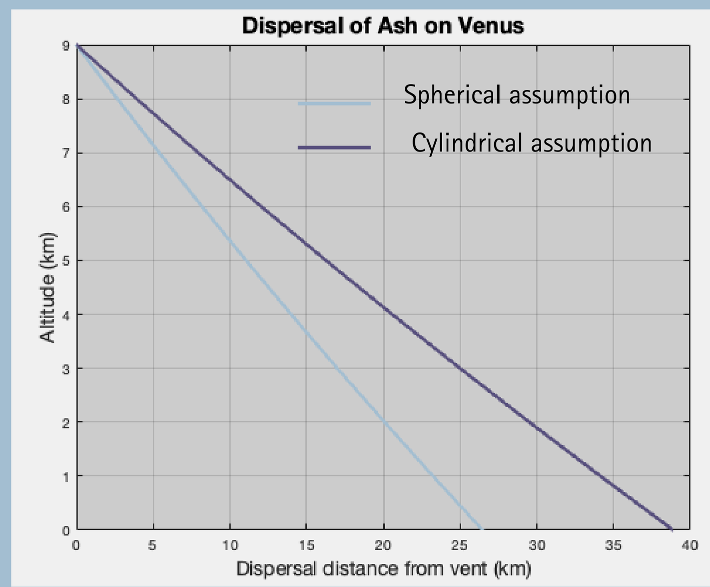


Figure 5: *Dispersal of a 500 micron particle from a 9 km height plume on Venus. Density of the particle is assumed to be 2300 kg/m^3.*

Discussion

- For ash settling trajectories explored for Earth, Mars and Venus, the particle shape assumption has a significant effect on dispersal distance, with cylindrical particles travelling farther than spheres. Particle density also affects dispersal distances.
- In the parameter space we have thus far explored, coarse grain sizes inferred for the Nili Fossae olivine-rich unit on Mars are unlikely to be derived from a single source vent.
- If significant portions of the olivine-rich unit were deposited as pyroclastic fall, then we hypothesize that eruptions occured from multiple vents.
- Alternatively, the unit may have formed through one or more other processes. A mix of formation mechanisms may also help explain the cumulate rocks of Séitah versus the orbitally-derived characteristics of the regional olivine-rich unit. Future in-situ exploration of the unit with the *Perseverance* rover will further elucidate its origin/s.

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