The Anatomy of the Blue Dragon:

Changes in **Lava Flow Morphology** and **Physical Properties** Observed in an Open Channel Lava Flow as a **Planetary Analogue**

SSERVI Seminar Series
NASA Museum Alliance and NASA Solar System Ambassadors
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Lava flows on the Moon

Hurwitz et al. (2013)
Lava flows on Mars

Flood lavas observed by MRO

Gusev rocks solidified from lava, taken by MER Spirit (2009)

Jaeger et al, 2010

NASA
Lava flows on Mars

Flood lavas in the ancient plains of Mars (Daedalia Planum). Image taken by Mars Express

Images: ESA
Lava flows on Mars

Olympus Mons, a shield volcano (Hawaii). Largest volcano in the solar system.
Lava flow features on Mercury
Lava flows on Mercury

Features observed on the Northern Volcanic Plains

Head et al. (2011)
Lava flows (?) on Vesta (asteroid)

Surface of Vesta resemble lava flow morphologies. Vesta was assumed to have had a magma ocean in its early history.
Lava flows on Io (Jupiter)

Only other planetary body where we currently observe volcanism. More volcanic activity than on Earth.

Top: Mosaic from images acquired by NASA’s Galileo spacecraft. USGS
Right: Amirani lava flow, with 23 new individual lava flows over the course of 173 days. JPL/NASA
Lava flows on Mercury

Features observed on the Northern Volcanic Plains

Head et al. (2011)
Hypothesis:

- **Morphology of lava flows corresponds to specific values in physical properties of the lava** (crystallinity, vesicularity, density, and temperature \(\rightarrow\) viscosity).

- Exploration: Use morphology to infer these properties.
Morphological transition from pahoehoe to `a`a lavas

Video 01a: Pahoehoe at PuuOo, Hawaii (overview)

https://youtu.be/9EfjzrqmuMU

Pahoehoe lava at PuuOo, Kilauea volcano (Hawaii), 2012
Morphological transition from *pahoehoe* to `a`a lavas

Video 01b: Pahoehoe at PuuOo, Hawaii (sampling)

https://youtu.be/mJv-lZqDpH4

Pahoehoe lava at PuuOo, Kilauea volcano (Hawaii), 2012
Morphological transition from pahoehoe to `a`a lavas

Video 2a: Lava at Pacaya (slope)

https://youtu.be/NQkdUxQ_drM


Pahoehoe to `a`a lava flow at flank of Pacaya volcano (Guatemala), 2014
Morphological transition from pahoehoe to `a`a lavas

Video 02b: Aa at Pacaya (terminus)

https://youtu.be/Oa8TYOVoow0

`A`a lava flow (terminus) at Pacaya volcano (Guatemala), 2014
Viscosity

- depends on temperature \((T)\)
- depends on composition \((X)\)
- depends on crystal \((\Phi_c)\) and bubble \((\Phi_b)\) fraction

As lavas cool, they will crystallize

- crystal fraction \((\Phi_c)\) increases
- changes residual liquid composition \((X)\)
- changes residual liquid viscosity \((\eta)\)

Lavas change their flow behavior throughout cooling
Morphological transition from pahoehoe to `a`a lavas

Whether pahoehoe or `a`a is formed appears to be a critical relationship involving both viscosity and rate of deformation:
- at high strain rates, low viscosity
- at low strain rates, high viscosity

Viscosity

• Resistance of a fluid to flow, in Pa s
• Ratio of applied shear stress ($\sigma$) to its rate of deformation ($\dot{\varepsilon}$)

\[ \eta = \frac{\sigma}{\dot{\varepsilon}} \]

• Flow curves illustrated in the diagram on the right

• Slope in these curves determines the viscosity ($\eta$)
Viscosity – viscous flow

- **Newtonian fluids**: slope is linear, therefore independent on the applied stress
- **Pseudoplastic fluids** are not linear. Deformation depends on the applied stress. Viscosity is lower at high strain rates
- Flow curves may not intersect in the origin. Deformation requires minimum stress that needs to be overcome

--> **Yield strength** ($\sigma_y$)
Viscosity – viscous flow

- **Newtonian fluid**  (Water, Oil)

- **Bingham fluid**  (Toothpaste)

- **Pseudoplastic fluid**

![Viscosity diagram](image)

Shear stress, \( \sigma \) (Pa)

Strain rate, \( \dot{\varepsilon} \) (s\(^{-1}\))

- \( \sigma_y \)
- \( \dot{\varepsilon} \)
- \( d\sigma \)
- \( d\dot{\varepsilon} \)

<table>
<thead>
<tr>
<th>Type</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newtonian fluid</td>
<td>Water, Oil</td>
</tr>
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Rheological transition from pahoehoe to `a`a lavas
For Hawaiian lava: Morphology and physical properties quantified. Coincidence? Needs to be checked for other flow of different lava type.
Craters of the Moon National Monument and Preserve, Idaho
Video 03: Blue Dragon Flow (COTM)

https://youtu.be/jyiKsEBk2b0
Near spatter cones (volcanic vents)
Direction of flow (east)

South rim of lava lake (looking south)
SE of lava lake
(white patches disappeared)
Near terminus
Digital Terrain Model (DTM)
High resolution (~ 5 cm per pixel)

Mapped flow from near vent to toe,
Sampled over ~2.75 km length (Summer 2016)
Additional levee and depth samples (Summer 2017)
Total of 35 samples

Spatter cones

Terminus
Down flow changes in sample texture

Spatter bomb (vent):
- highly vesicular
- Rounded bubbles
- Low crystallinity, random order
Down flow changes in sample texture

Pahoehoe lobe:
- vesicular
- Rounded bubbles
- Low crystallinity, random order
Down flow changes in sample texture

Pahoehoe lobe:
- Less vesicular
- Rounded/irregular bubbles
- Low crystallinity, aligned
Down flow changes in sample texture

Pahoehoe slab:
• Vesicular
• Rounded bubbles
• Low crystallinity, aligned
Down flow changes in sample texture

COMBD-14
Distance: 1.40 km

Pahoehoe rubble:
• Vesicular
• Rounded/irregular bubbles
• High crystallinity, aligned
Down flow changes in sample texture

Pahoehoe rubble:
- Vesicular
- Rounded/ bubbles
- high crystallinity, random order
Down flow changes in sample texture

`A`a rubble:
- Vesicular
- Irregular bubbles
- Very high crystallinity, random order
Seeing trends with flow distance in
- Crystallinity
- Bulk density
- Pore space
Height profile through center of lava flow extracted from DTM
Height/elevation between each adjacent pixel averaged over length 50 meter. Based on center line profile.

- Correlation between flow distance and roughness exists.
- Correlation between flow distance and density and vesicularity exists.
Roughness vs Density

Based on a single line profile: biased (directional view!). Use the 2D/3D ratio instead.
Surface roughness classification
Currently developed by Mallonee and Kobs Nawotniak at Idaho State University

- RMS (root-mean-square) height, below
- Area ratio (2D/3D), left
Thermo-Physical Properties of Lava Flows
Looking at the morphology and estimate a temperature?
Not impossible!
Viscosity measurements

High temp.
1600ºC – 1150ºC

low viscosity
0.1 – 10^5 Pa s

Low temp.
1000ºC – 500ºC

high viscosity
10^8 – 10^{13} Pa s
Viscosity of crystal-free lavas across the Solar System

Viscosity of crystal-free lavas across the Solar System

N = 494

Craters of the Moon Blue Dragon Lava (crystal-free)

- Crystal-free lavas = Melts
- Newtonian fluids

Rheology measurements at:
1310 °C
1275 °C
1256 °C
1237 °C
1202 °C
1186 °C
1181 °C

increase in crystal fraction ($\Phi_c$) during cooling with change in residual melt composition ($\lambda$)
$T < 1150^\circ C$

$T > 1250^\circ C$

$T \sim 1200^\circ C$
Take home message:

- Lava flow morphology can be correlated to viscosity, observed for two different lava types (HI and ESRP basalt)
  - Viscosity depends on physical properties of the lava
  - Physical properties are correlated to morphology
  - Should be true for any type of lava (further testing to confirm)
  - Classify morphology mathematically, and tie to physical properties

- Remote sensing tool for physical properties

- Rheology experiments to estimate eruption and emplacement temperature