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

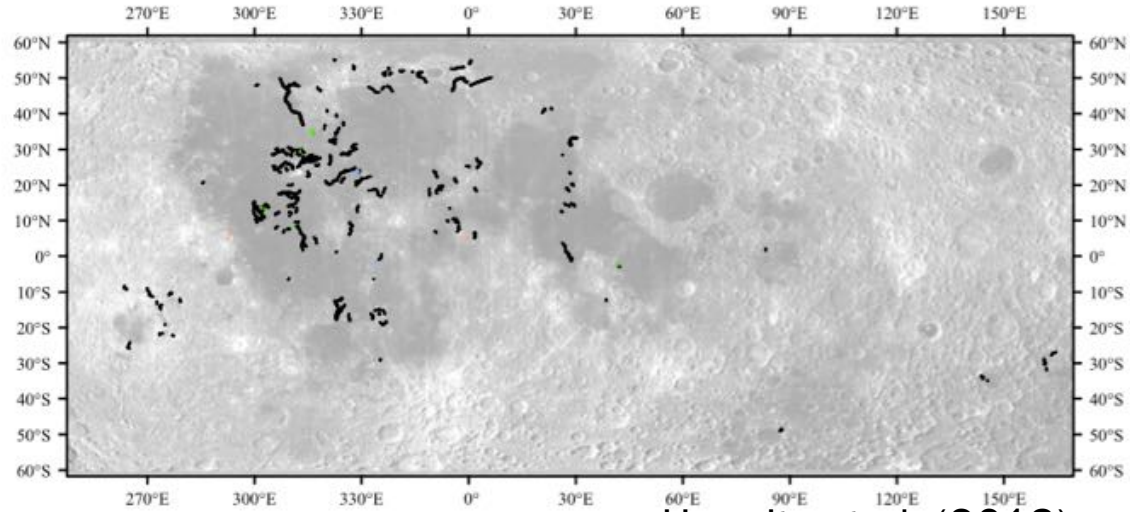
NASA Museum Alliance and NASA Solar System Ambassadors

12 Sep 2017

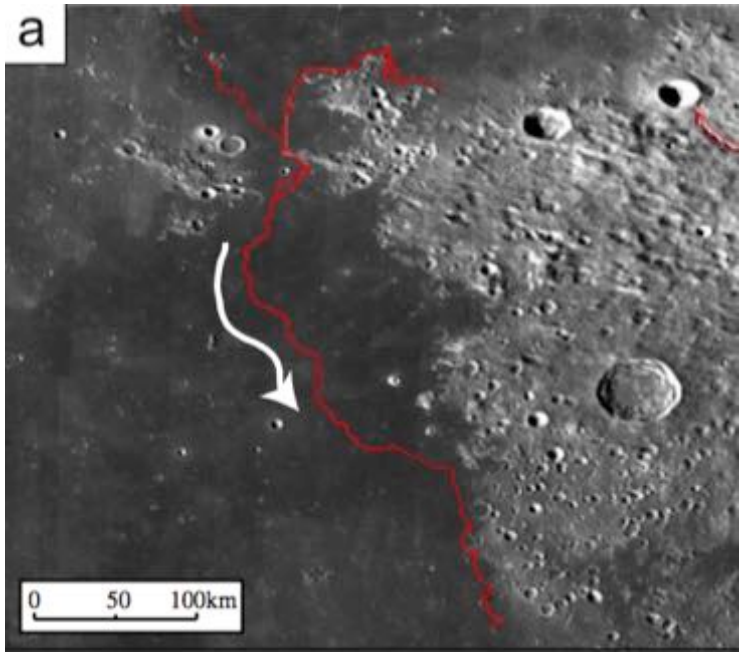
Alexander Sehlke, NPP fellow

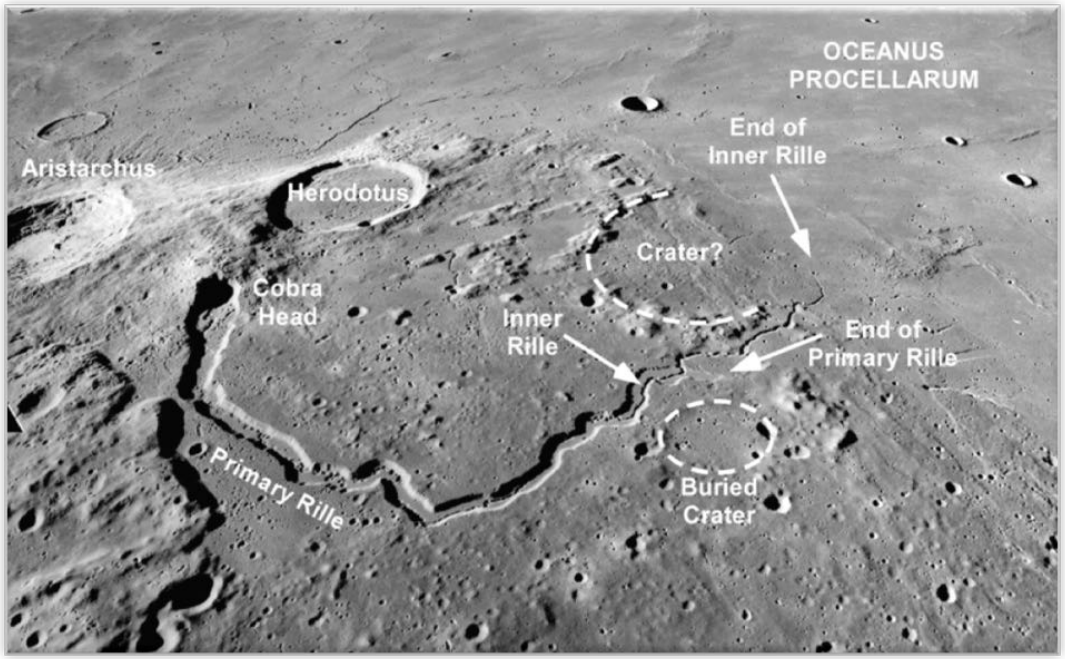
NASA Ames Research Center, CA

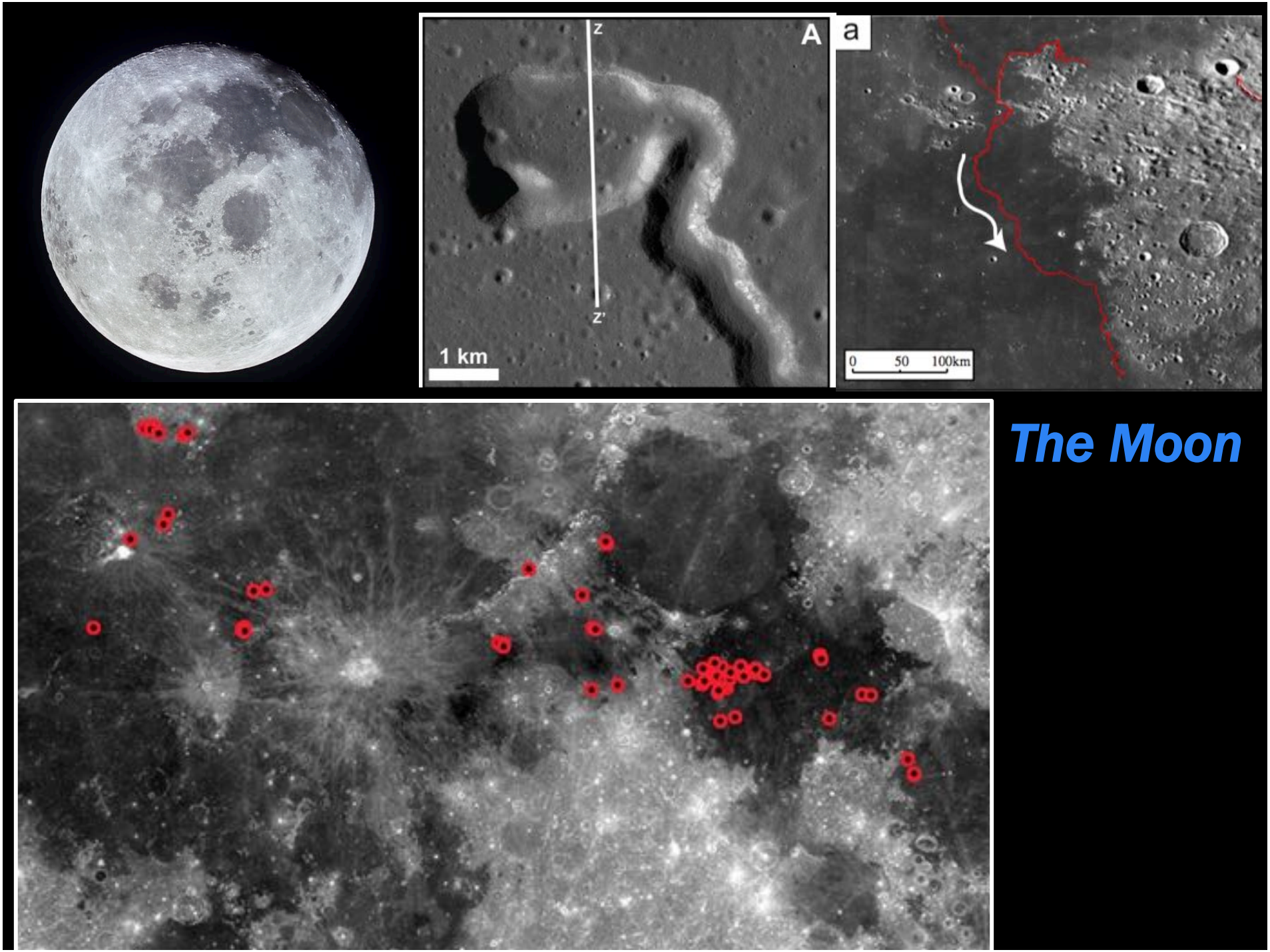
Lava flows on the Moon



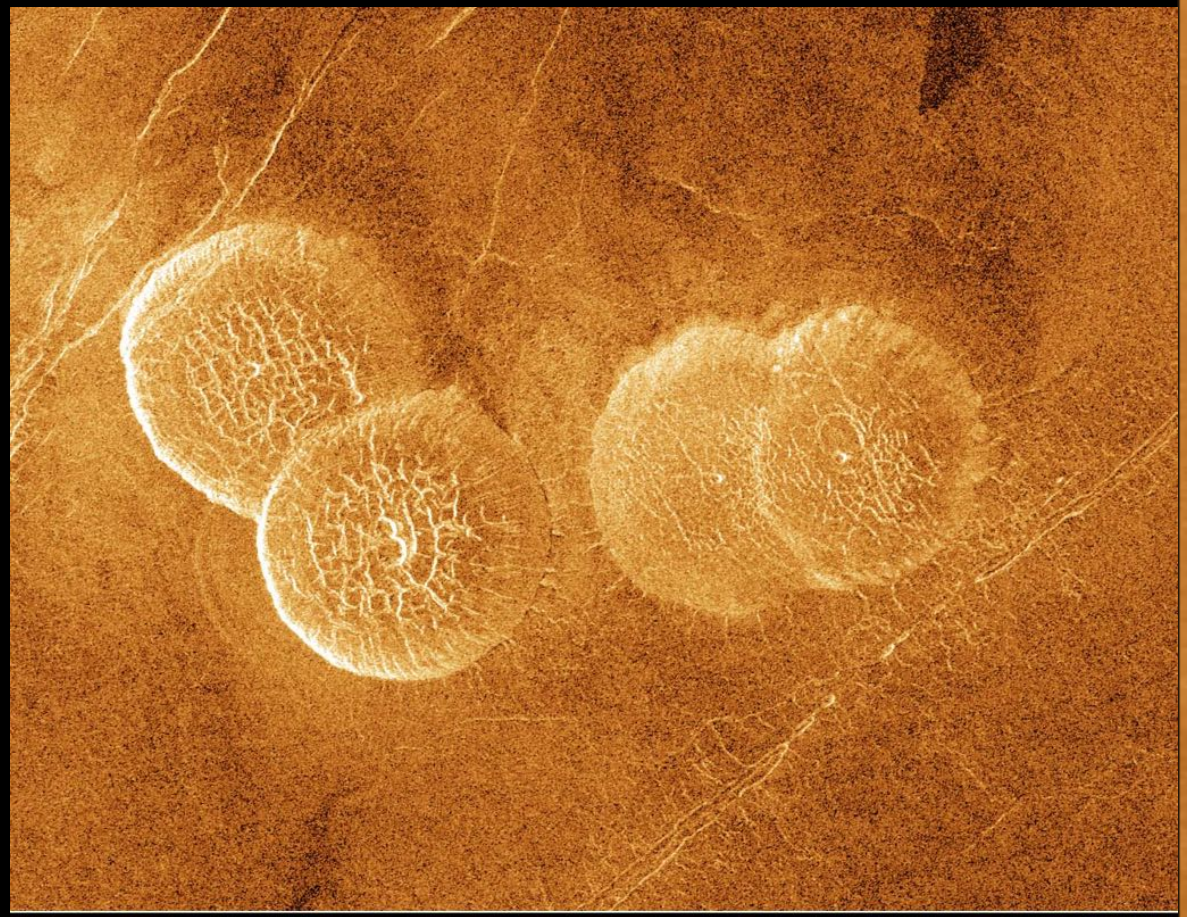
Hurwitz et al. (2013)






A
z
z'
1 km
a
0 50 100km
The Moon

Venus



Venus • Pancake Volcanoes

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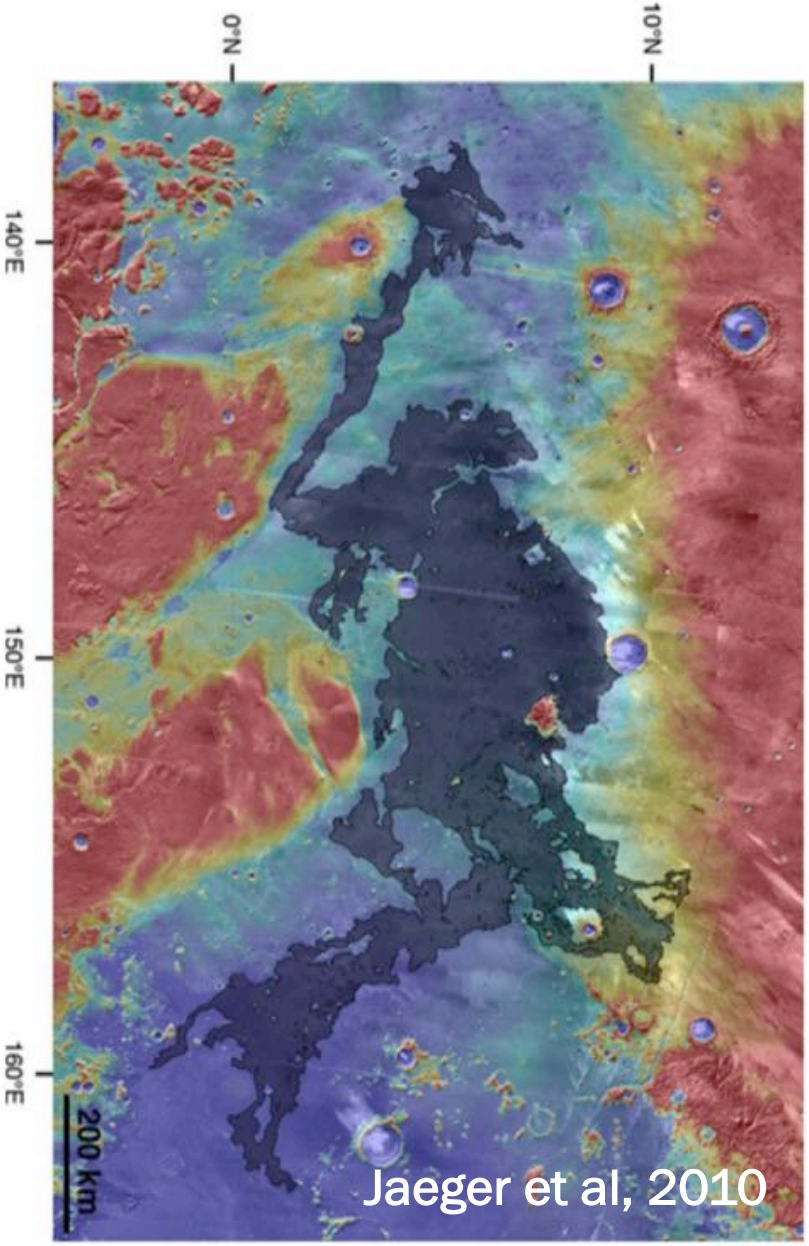
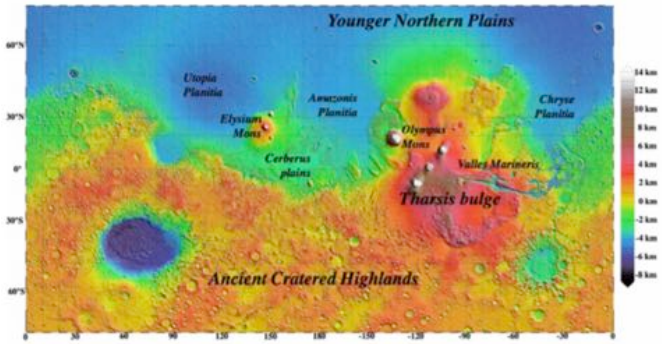
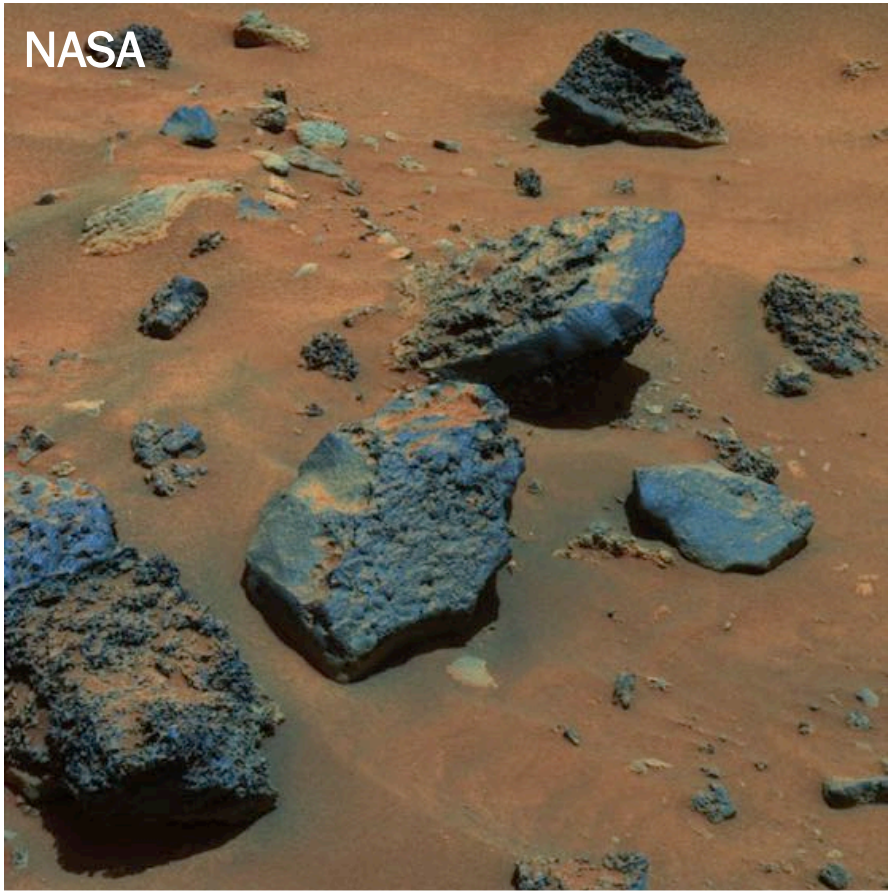
Lava flows on Mars



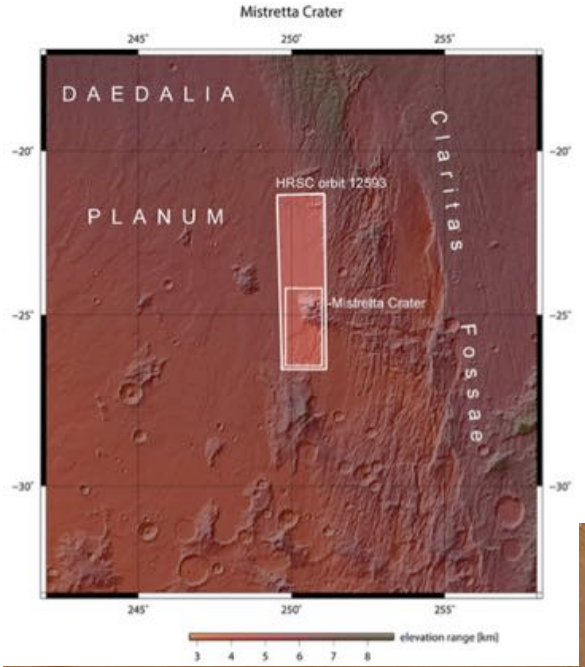
Jaeger et al, 2010

Flood lavas observed by MRO

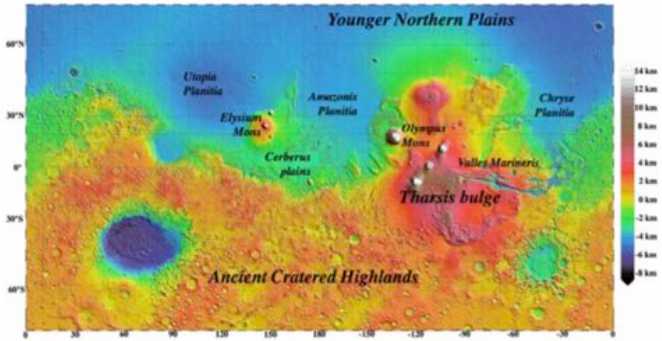




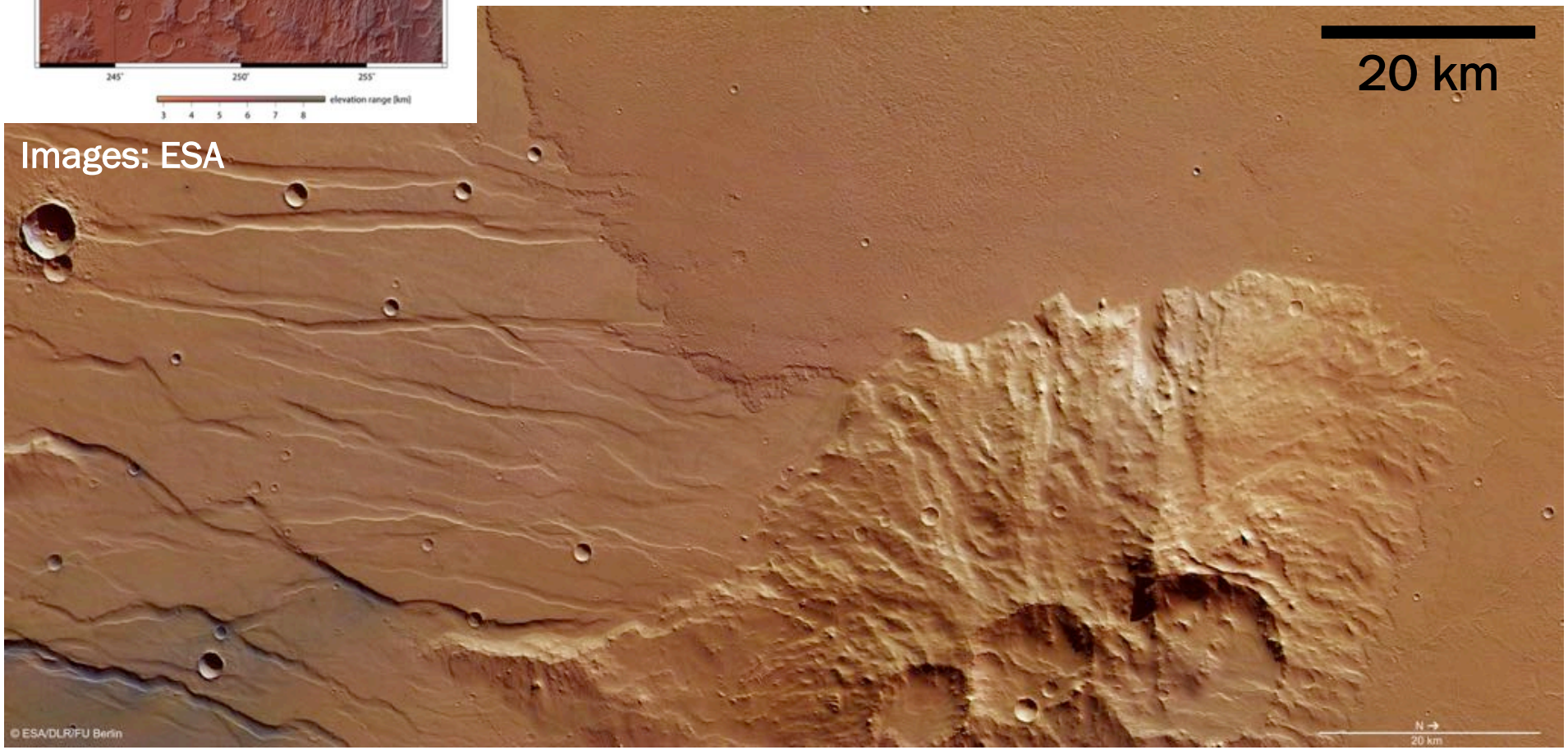
Gusev rocks solidified from lava, taken by MER *Spirit* (2009)



Lava flows on Mars

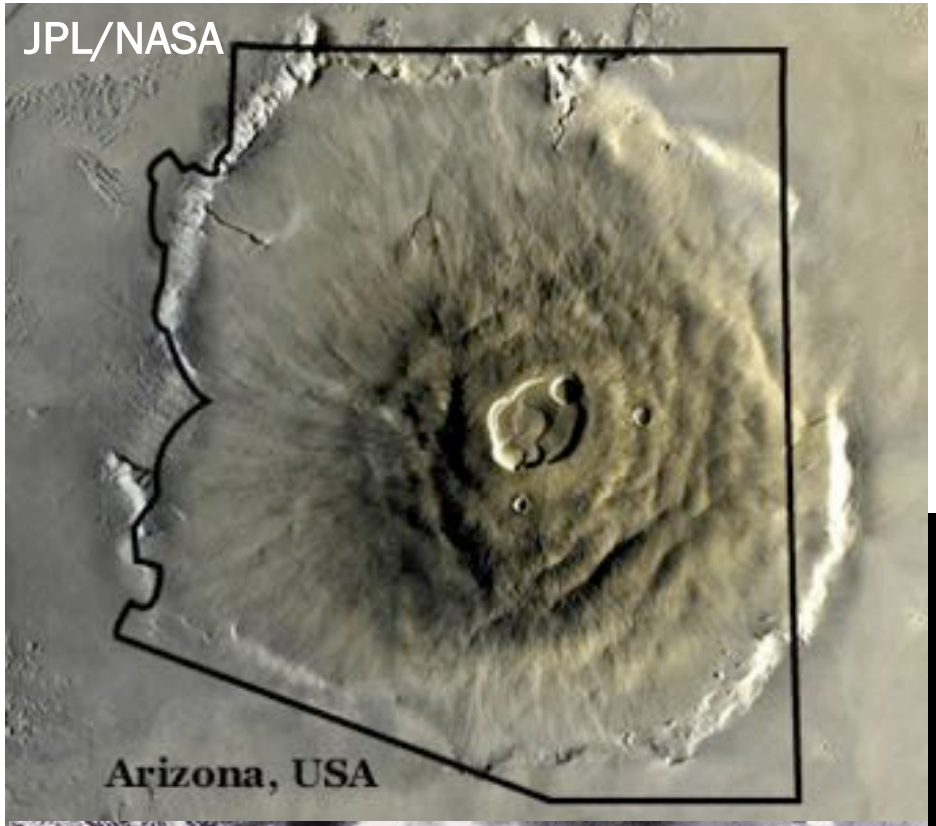


Flood lavas in the ancient plains of Mars (Daedalia Planum). Image taken by Mars Express

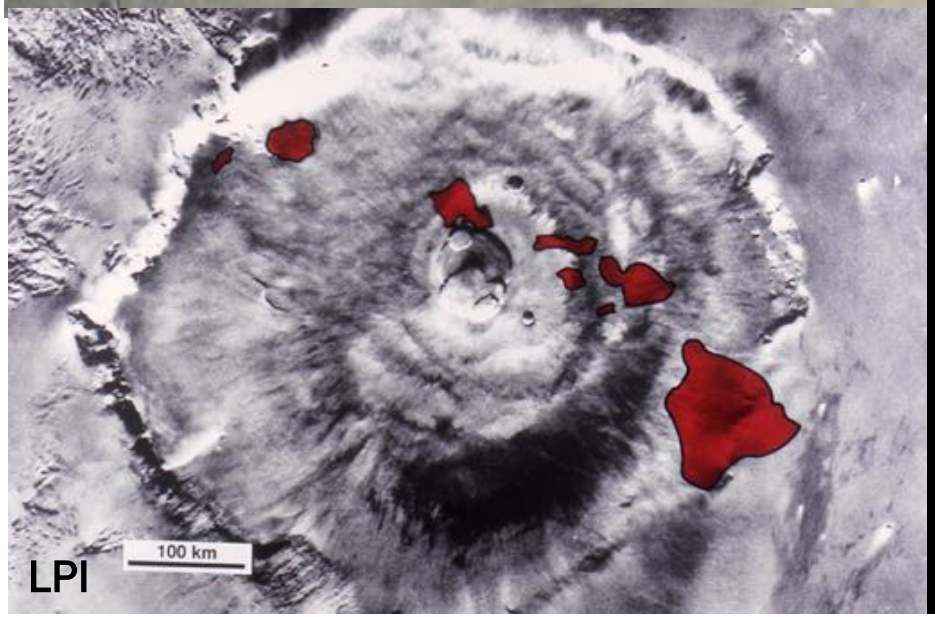


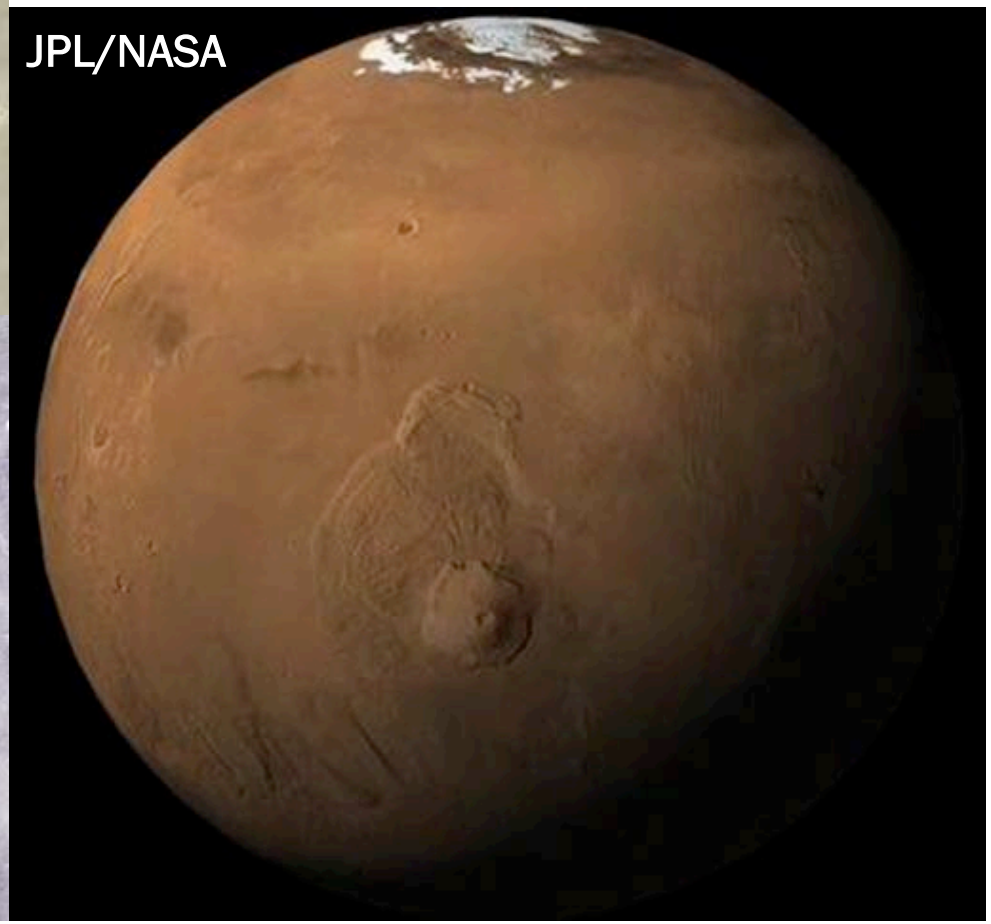
Images: ESA

Lava flows on Mars



Olympus Mons, a shield volcano (Hawaii).
Largest volcano in the solar system





Lava flow features on Mercury

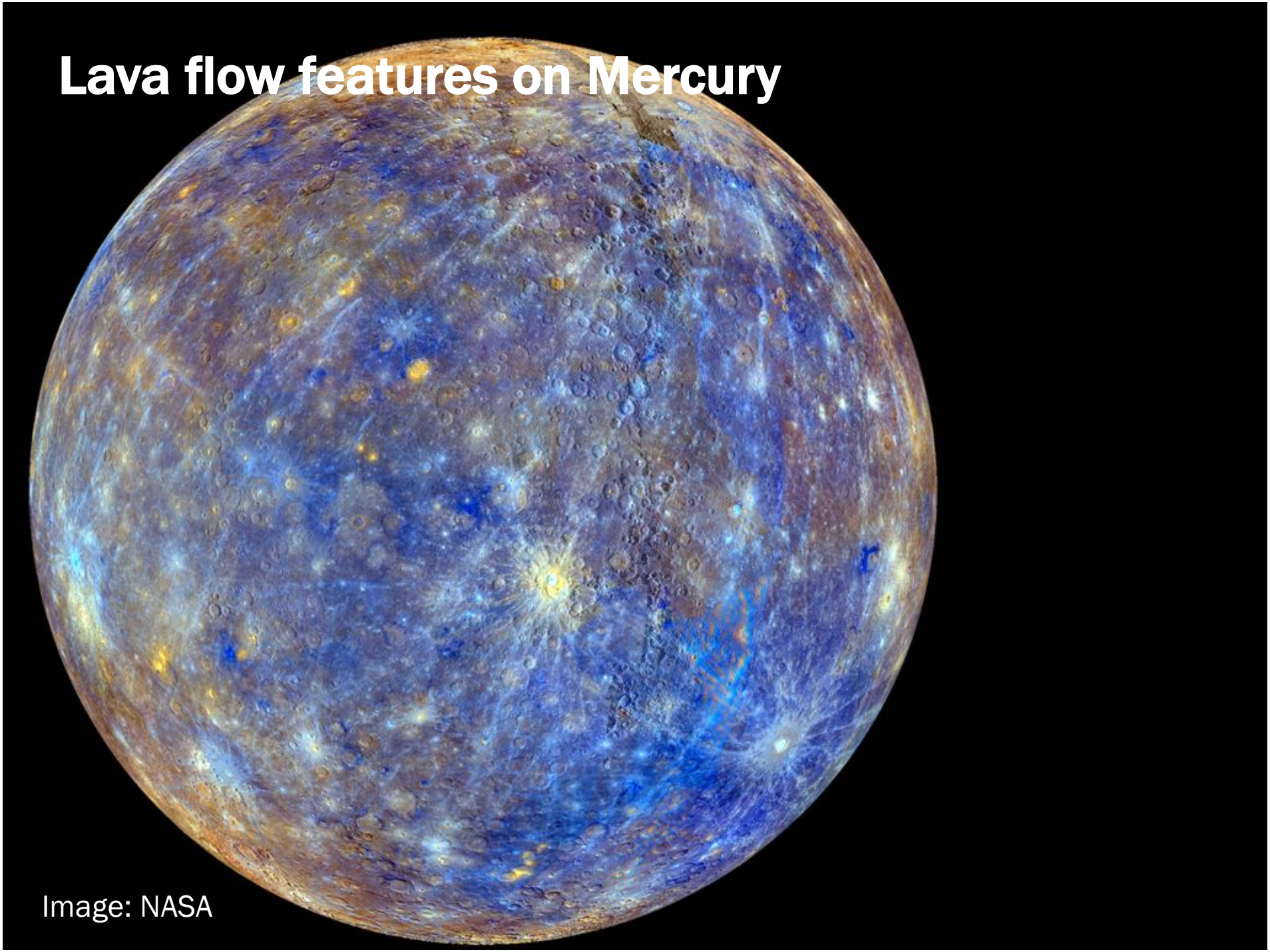
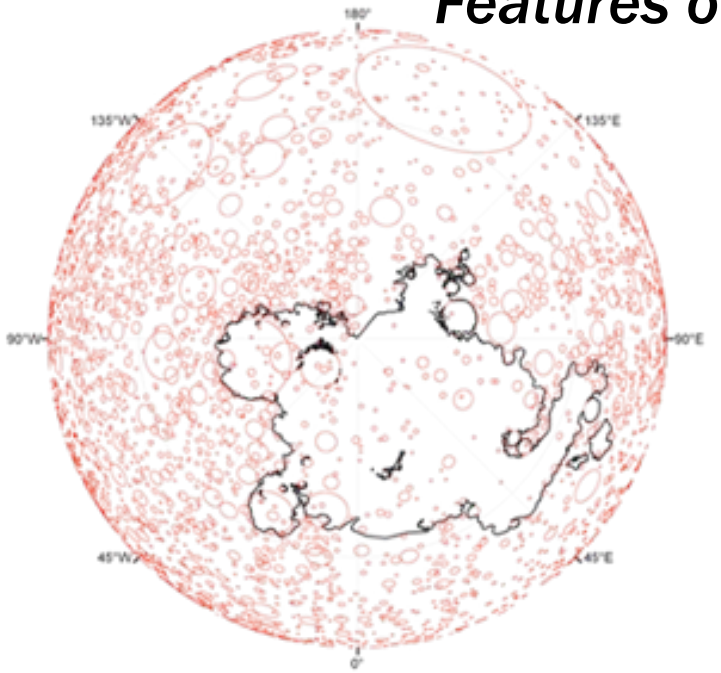


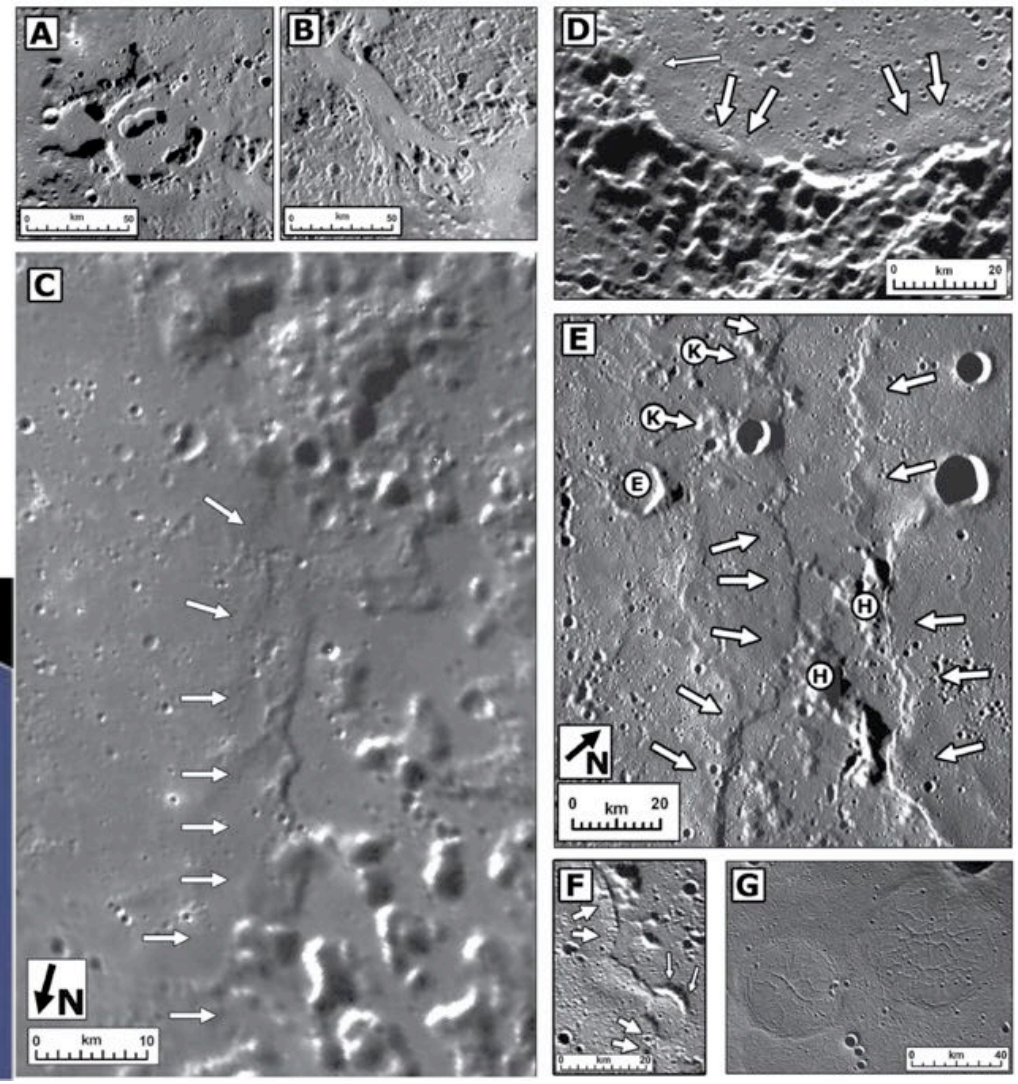
Image: NASA

Lava flows on Mercury

Features observed on the Northern Volcanic Plains

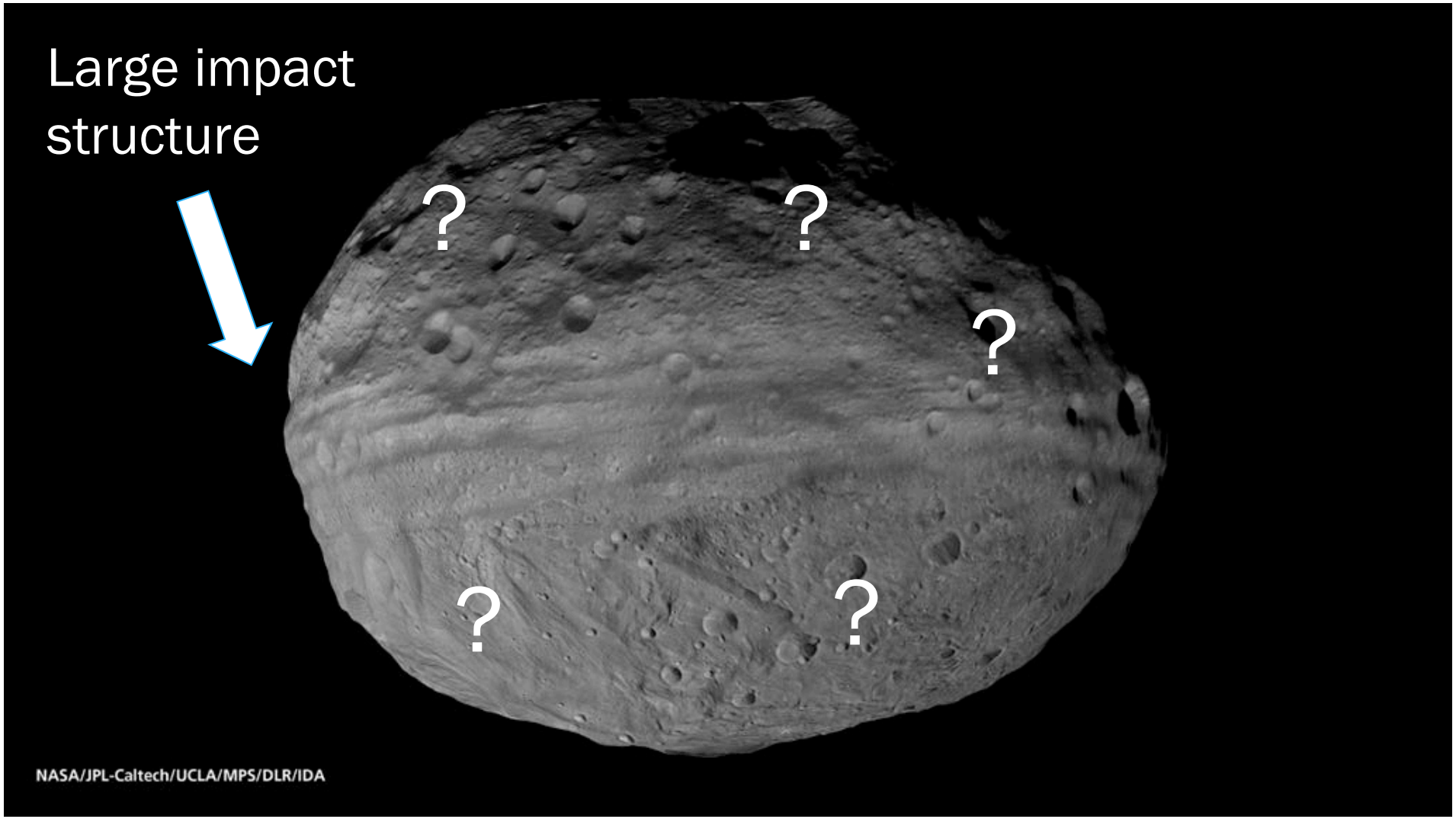
Head et al. (2011)





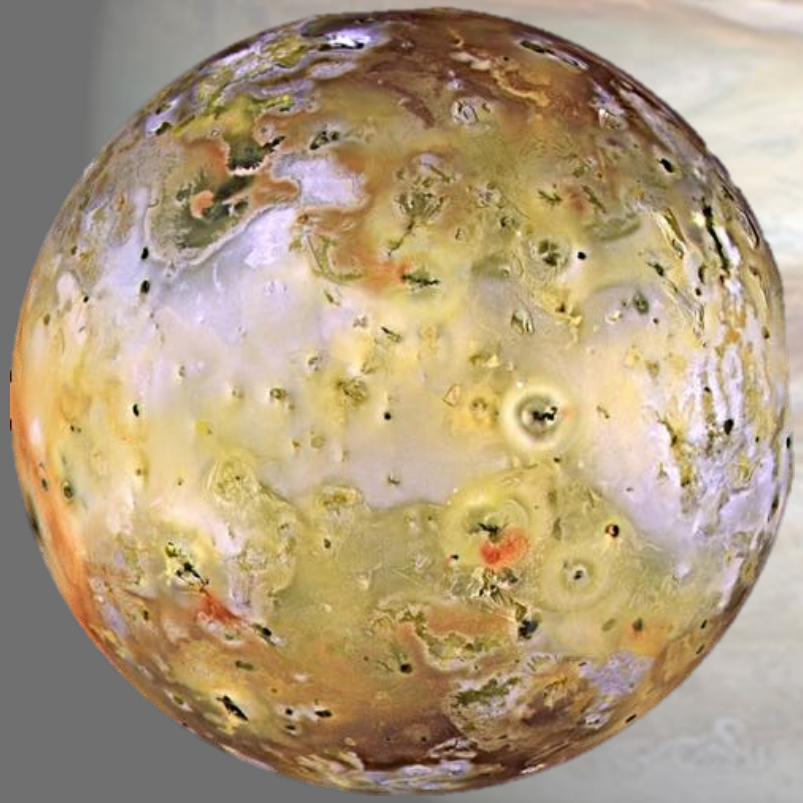
Lava flows (?) on Vesta (asteroid)

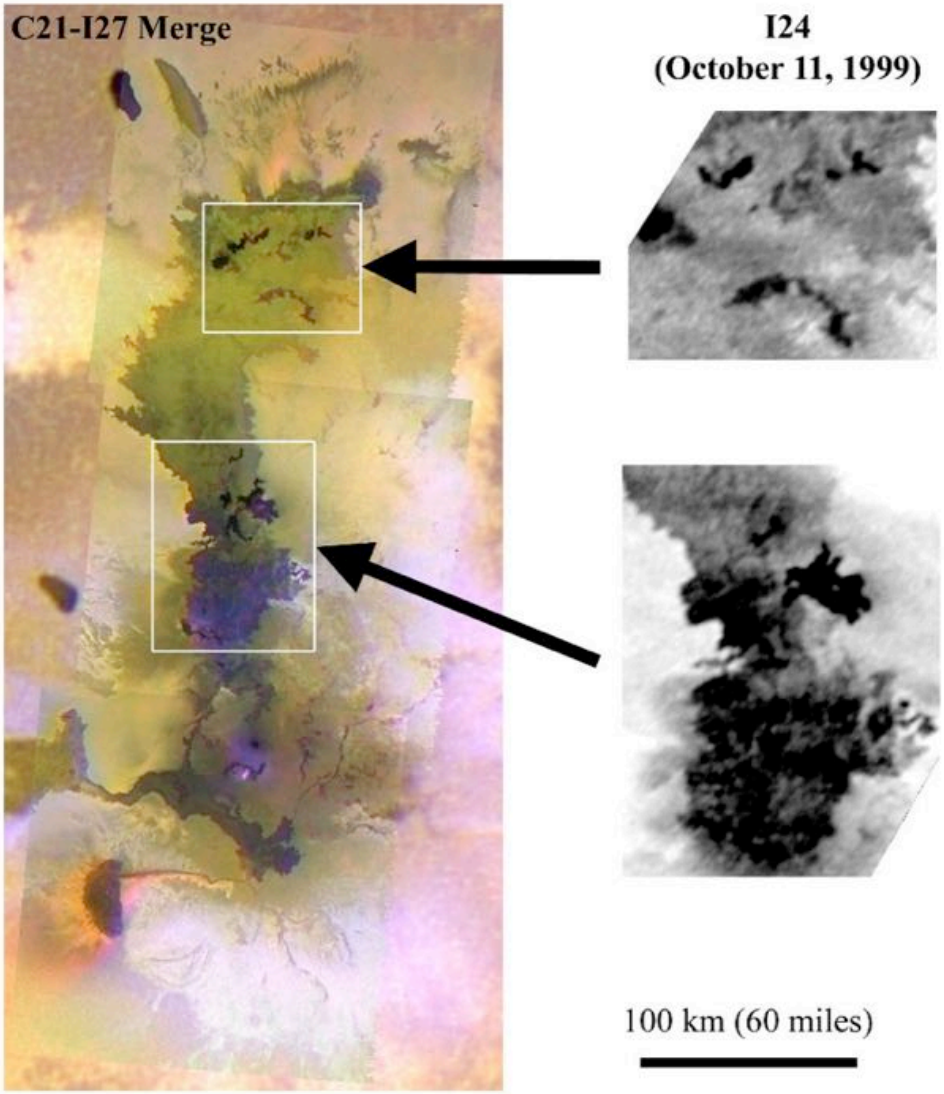
Surface of Vesta resemble lava flow morphologies. Vesta was assumed to have had a magma ocean in its early history.



Lava flows on Io (Jupiter)

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



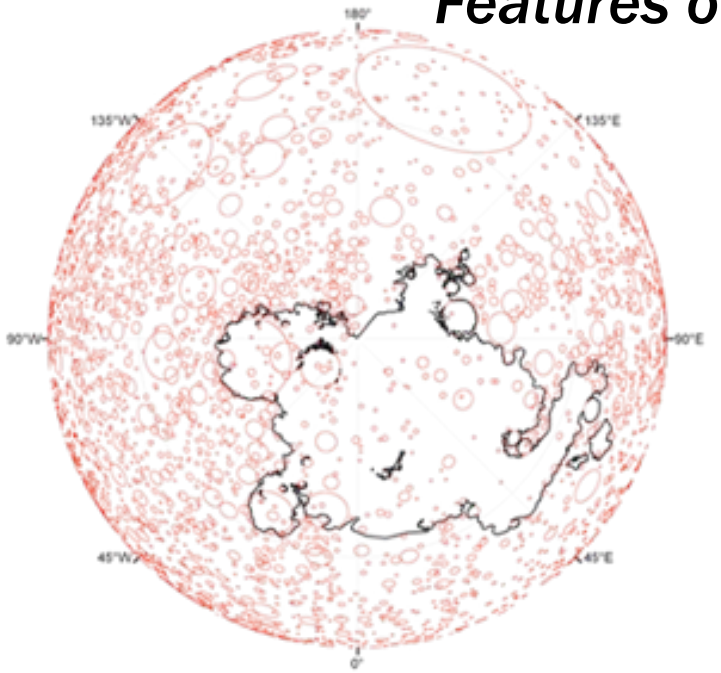


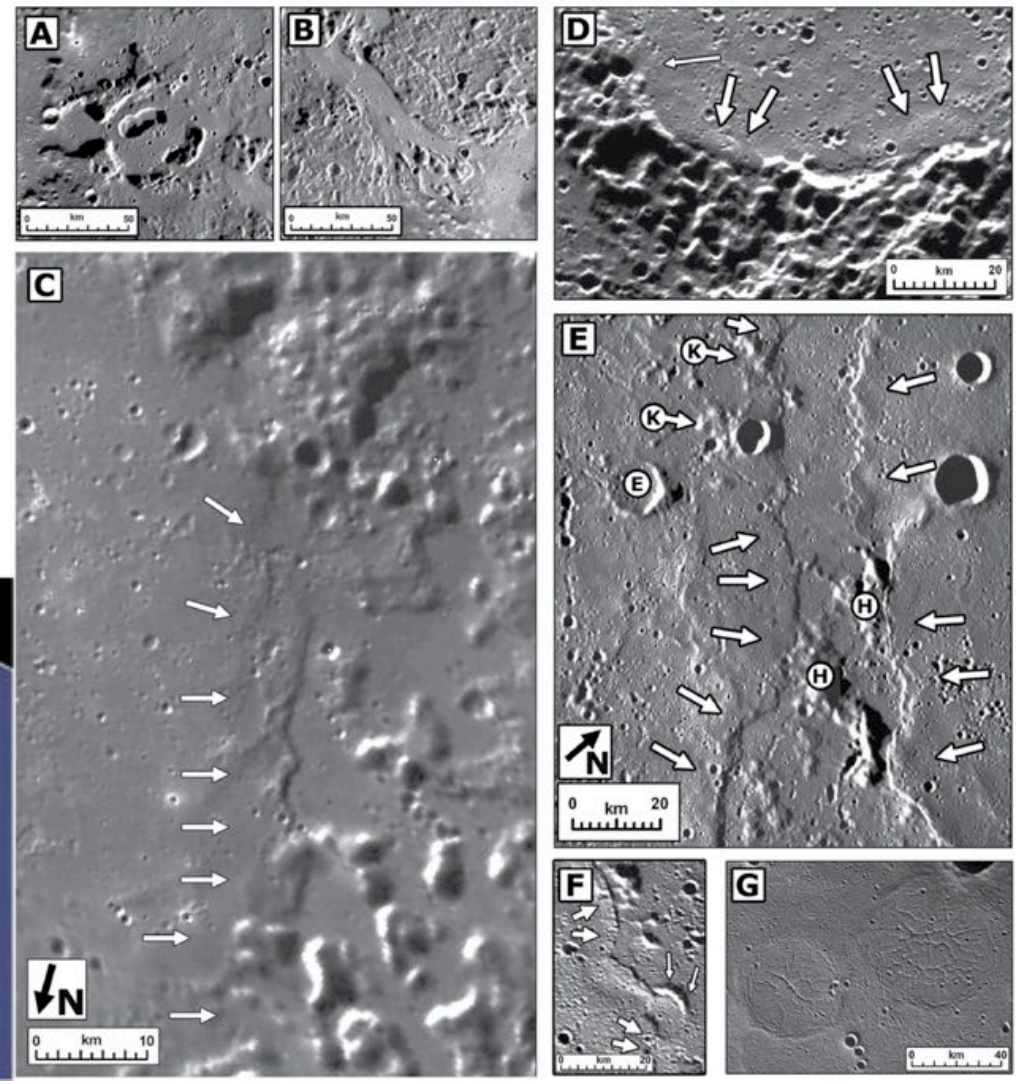
Top: Mosaic from images acquired by NASA's Galileo spacecraft. USGS
Right: Amirani lava flow, with 23 new individual lava flows over the course of 173 days. JPL/NASA

Lava flows on Mercury

Features observed on the Northern Volcanic Plains

Head et al. (2011)

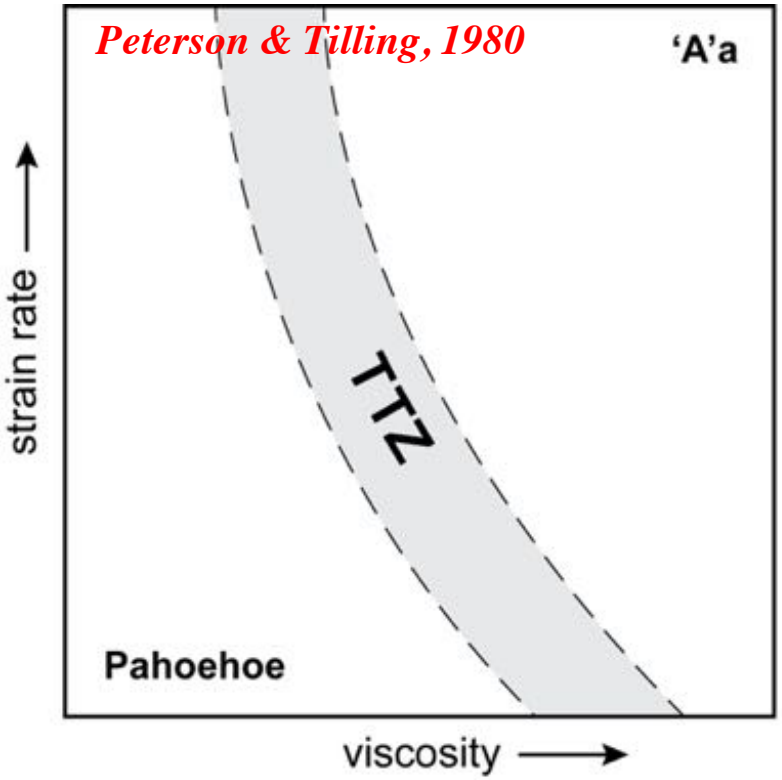


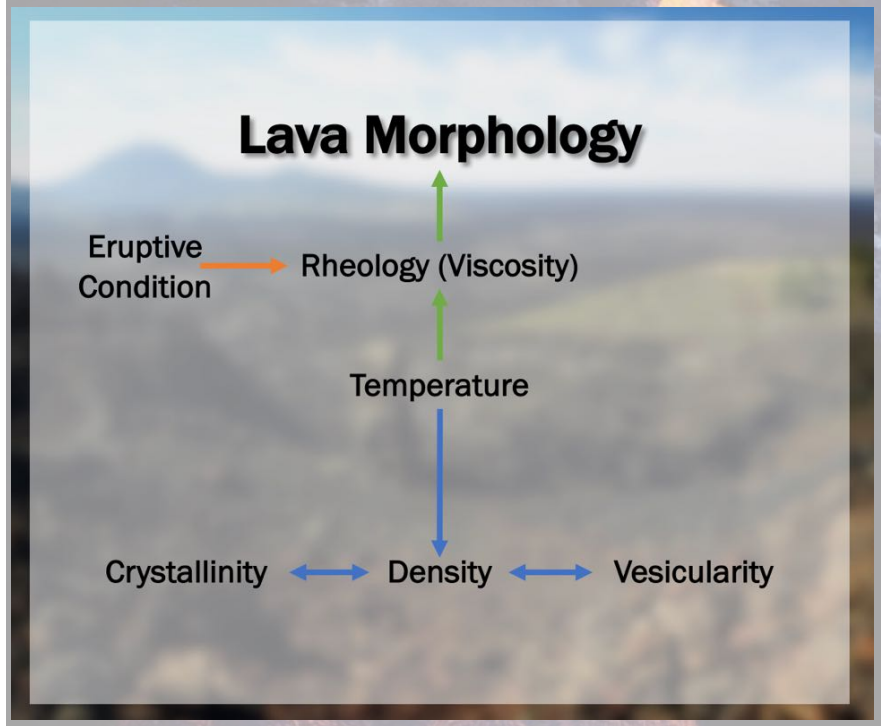


Hypothesis:

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

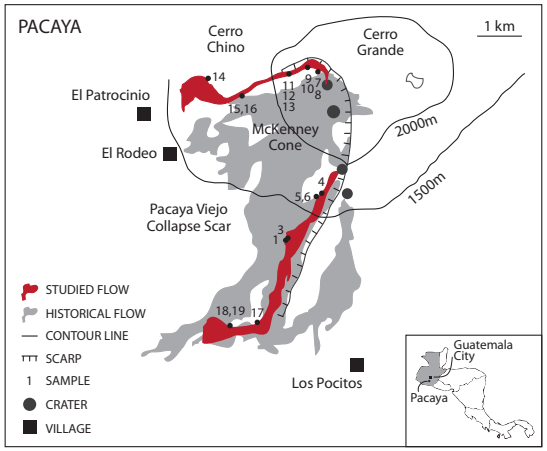
https://youtu.be/mJv-lZqDpH4

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



Soldati et al. 2014. Bull Volc.

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/0a8TY0Voow0

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

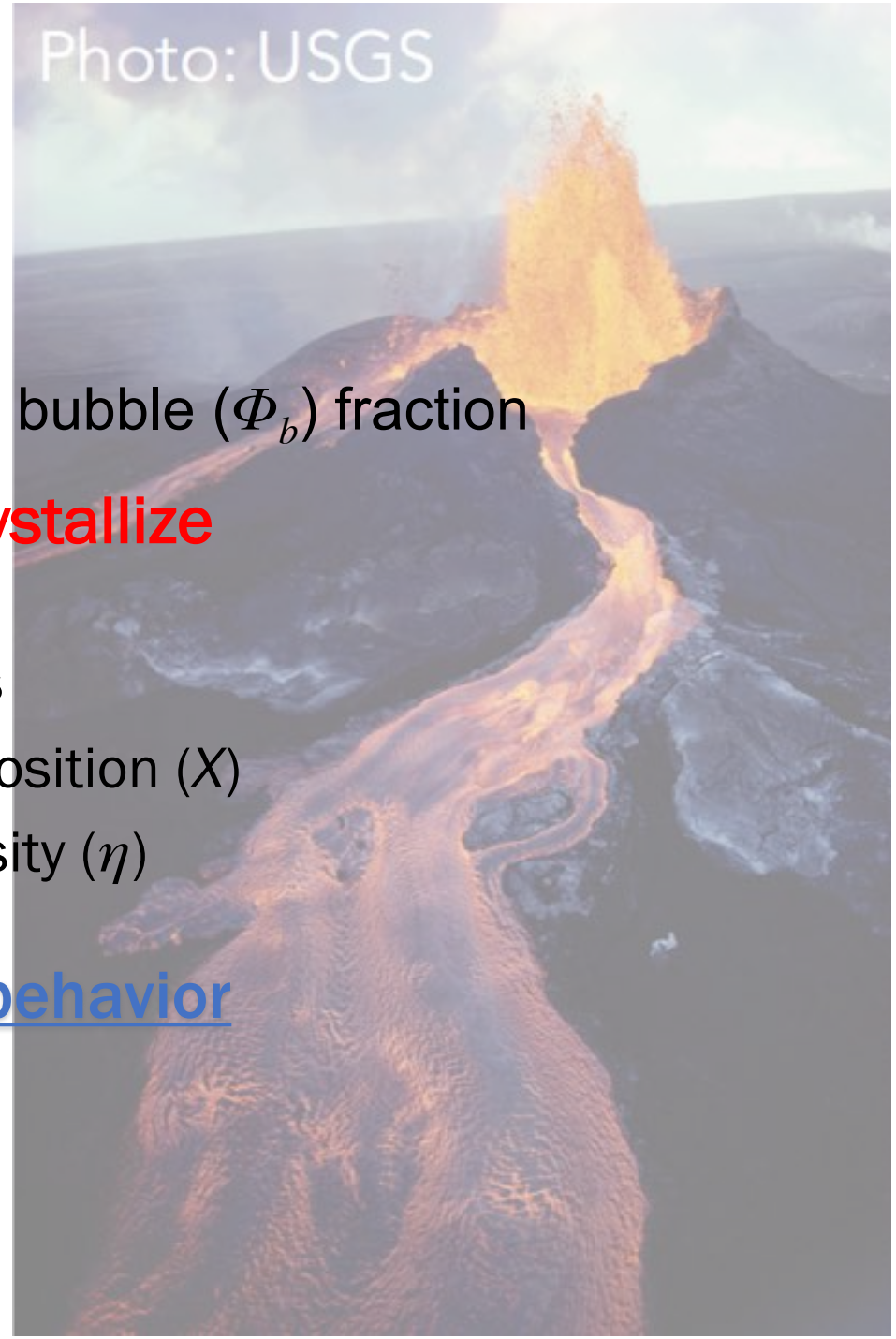
Viscosity

- ❑ depends on temperature (T)
- ❑ depends on composition (X)
- ❑ depends on crystal (Φ_c) and bubble (Φ_b) fraction

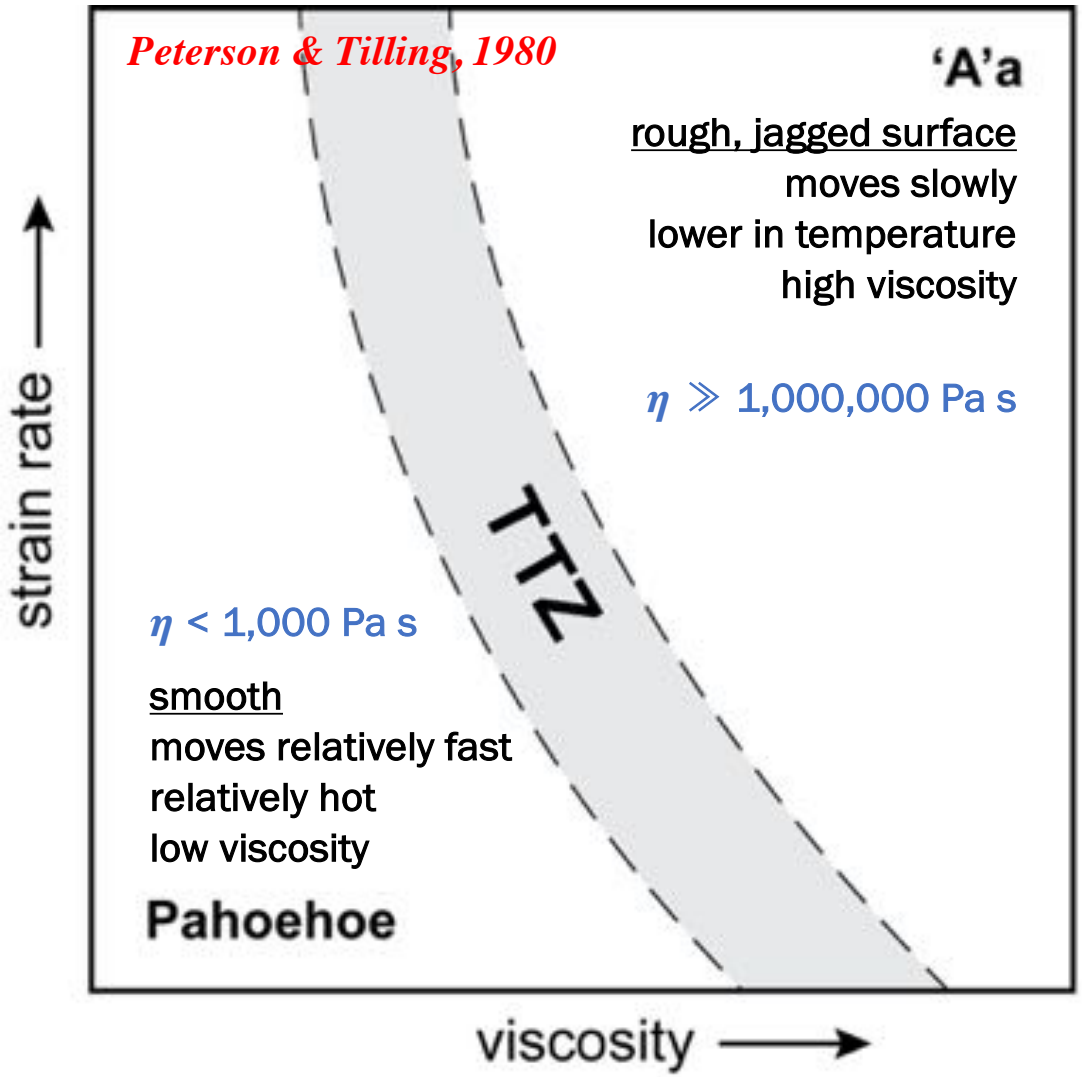
As lavas cool, they will crystallize

- ❑ crystal fraction (Φ_c) increases
- ❑ changes residual liquid composition (X)
- ➢ changes residual liquid viscosity (η)

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
  -> pseudo-plastic

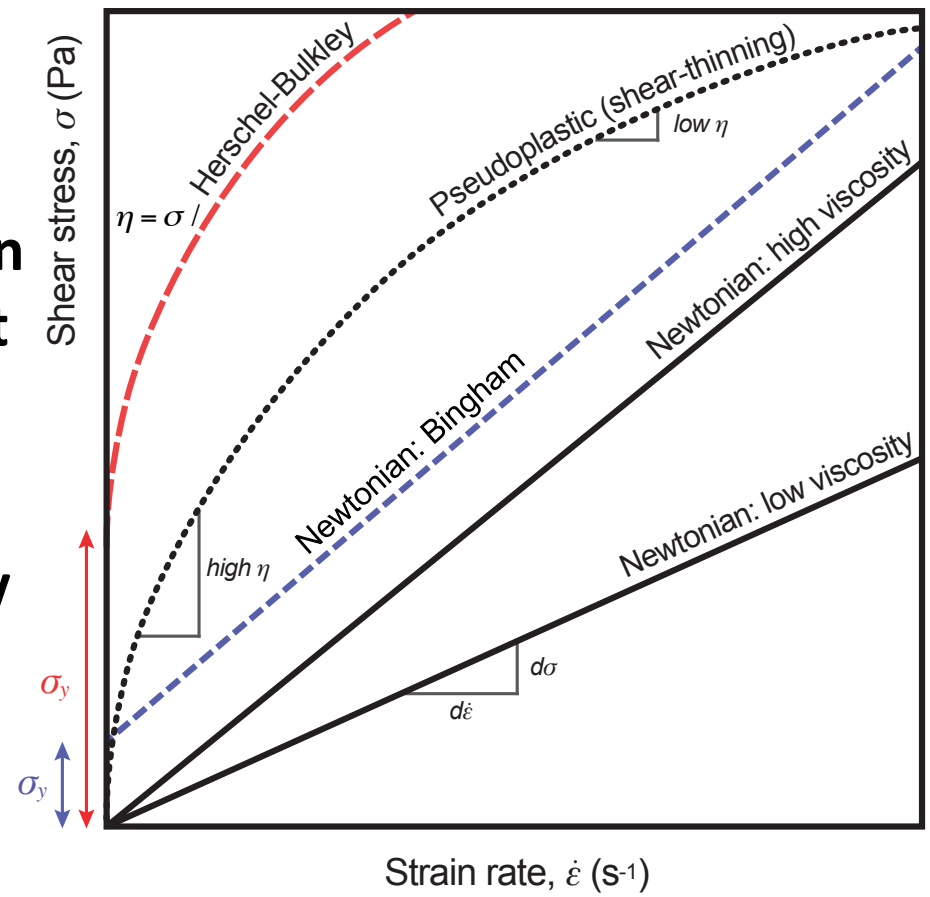
Viscosity and strain rate relationship of pahoehoe to `a`a transition determined by Robert et al. 2014. Bull Volc. Sehlke et al. 2014. Bull. Volc.

Viscosity

- **Resistance of a fluid to flow, in Pa s**
- **Ratio of applied shear stress (σ) to its rate of deformation (ε)**

$$\eta = \frac{\sigma}{\dot{\varepsilon}}$$

- **Flow curves illustrated in the diagram on the right**
- **Slope in these curves determines the viscosity (η)**

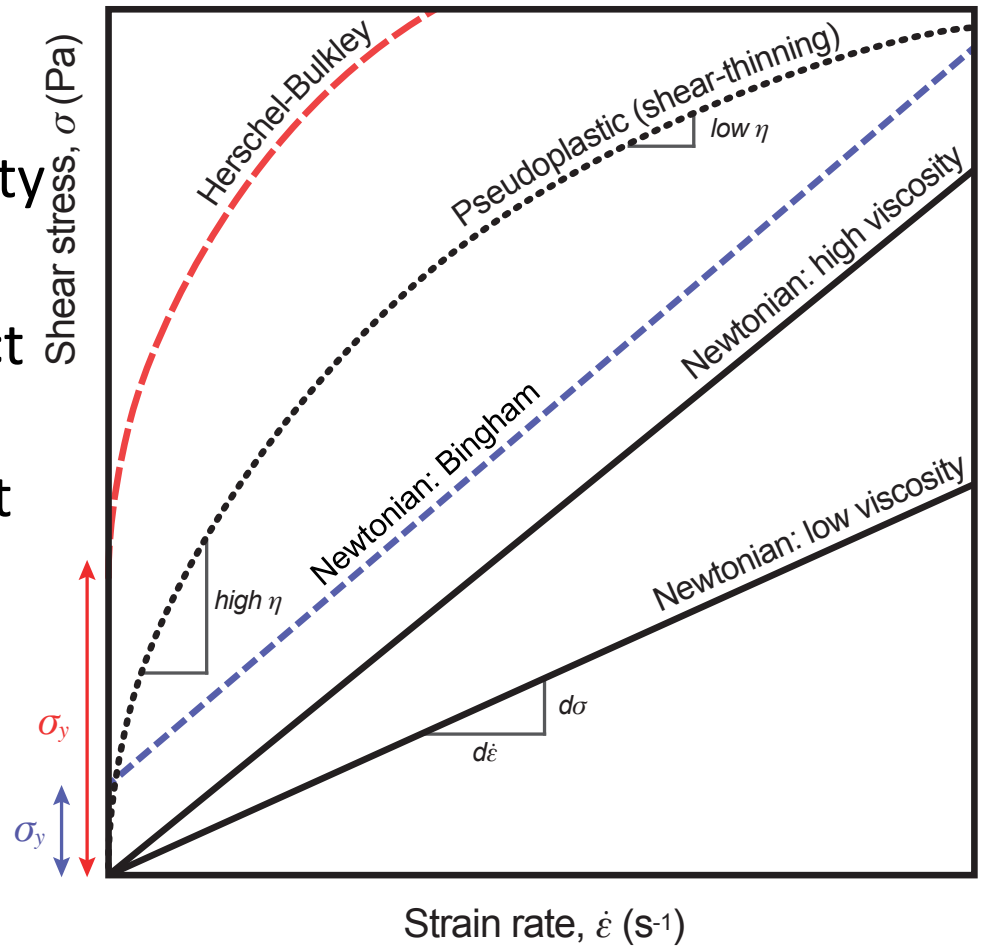


Viscosity – viscous flow

- **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

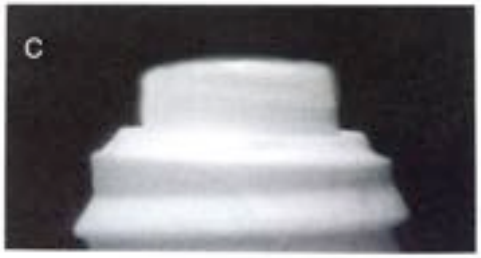
-> Yield strength (σ_y)



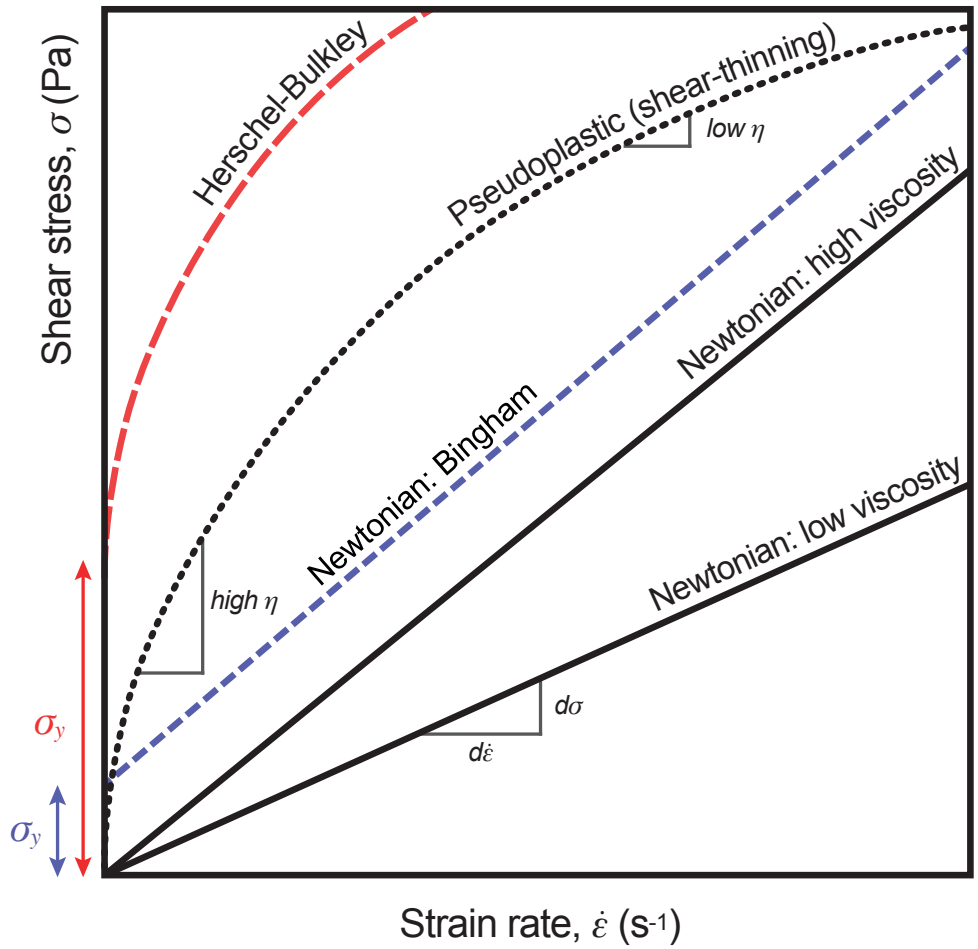
Viscosity – viscous flow

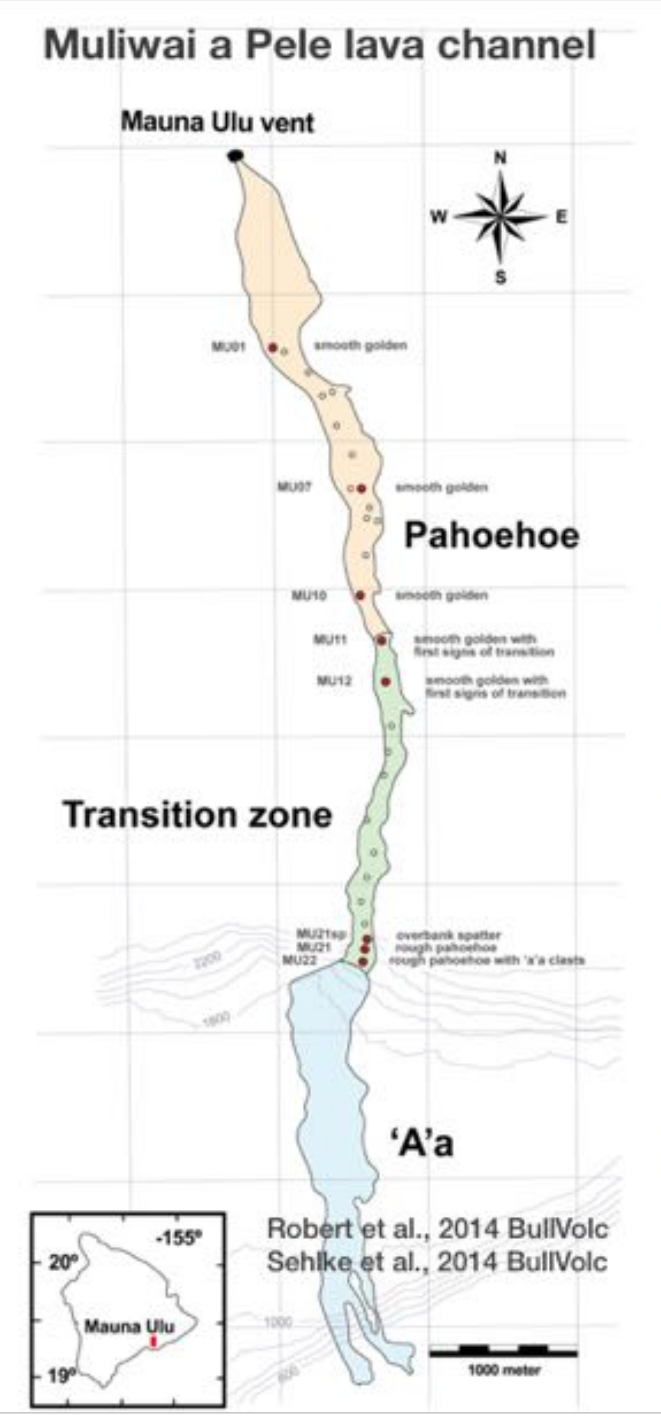
- **Newtonian fluid** **(Water, Oil)**

- **Bingham fluid** **(Toothpaste)**

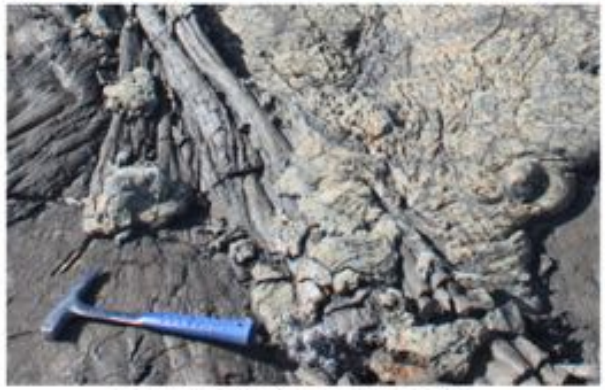


- **Pseudoplastic fluid**

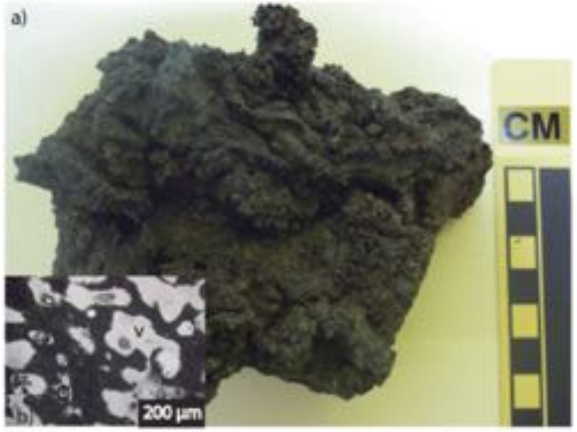


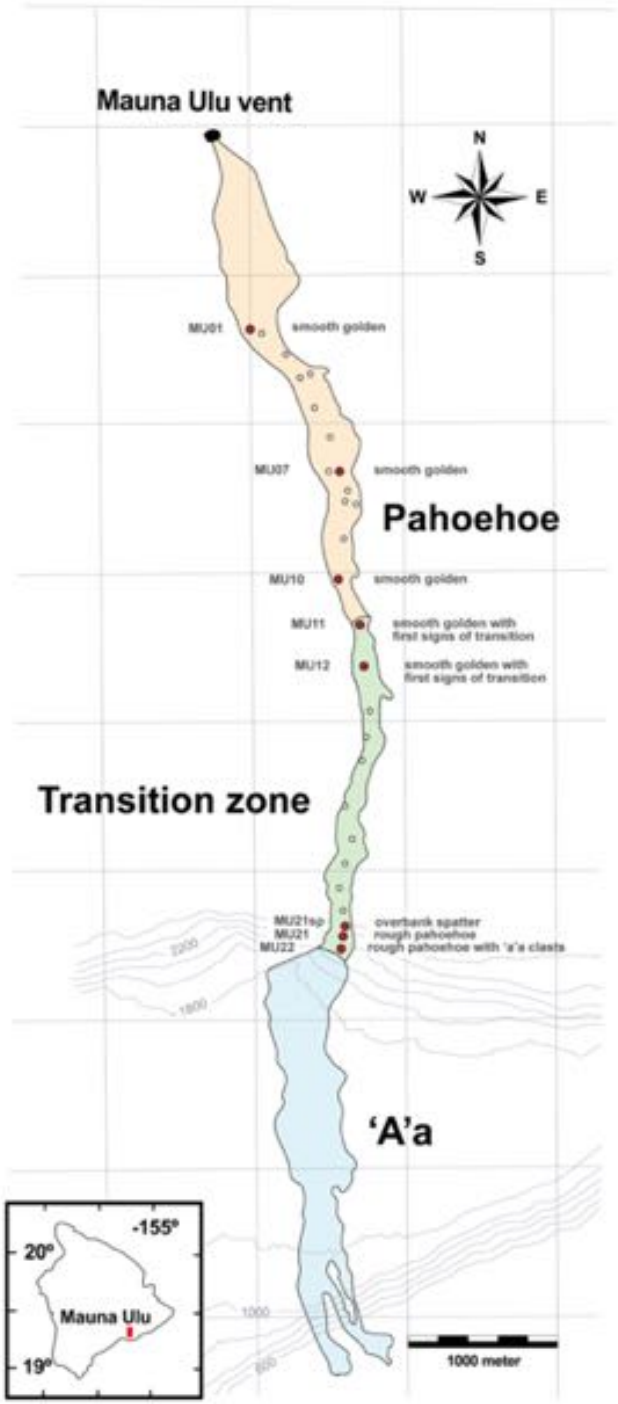


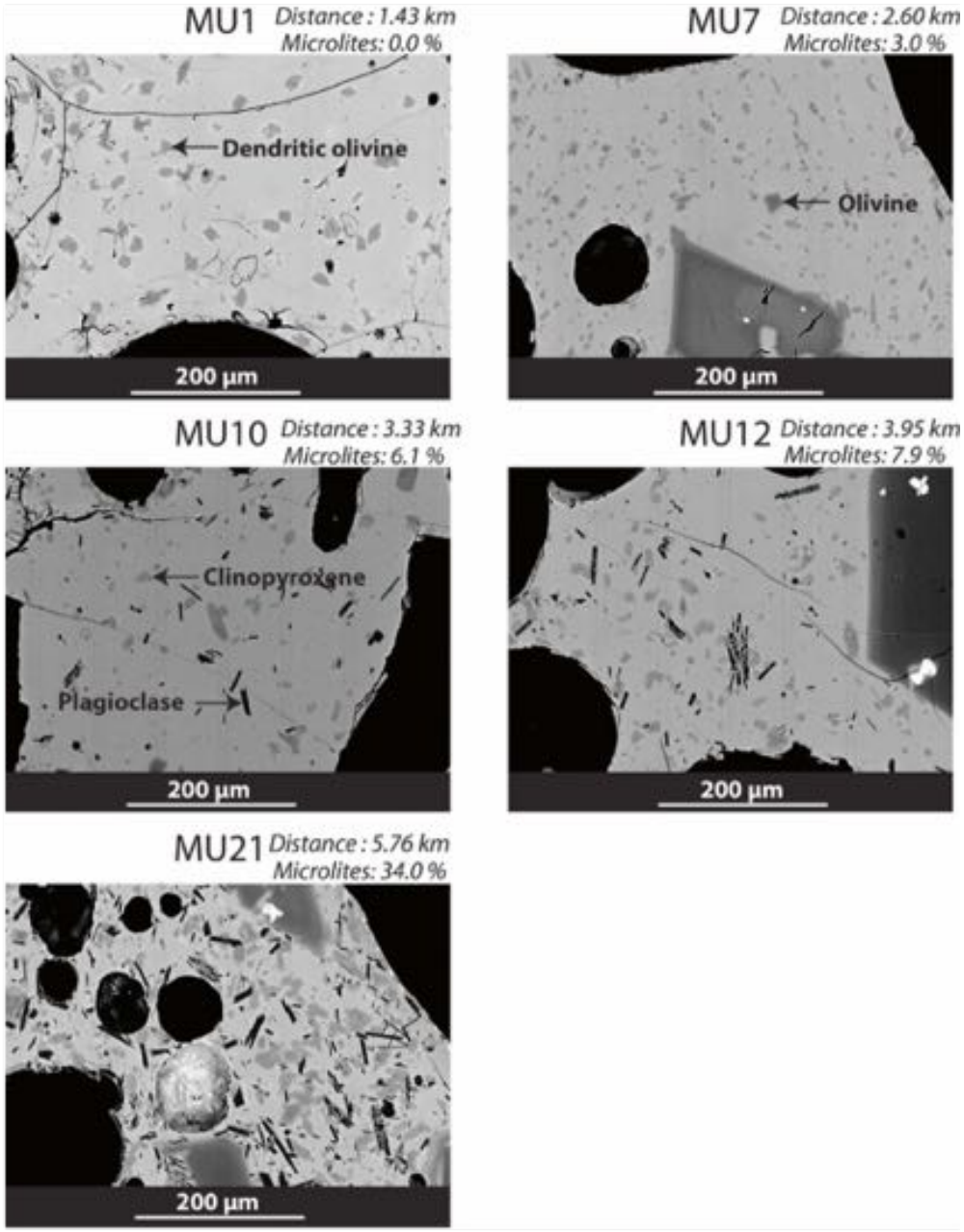
Pahoehoe sample - MU1 - Distance: 1.43 km



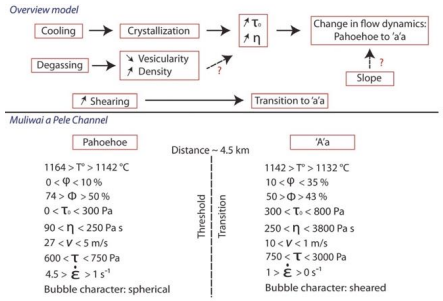
'A'a sample - MU22 - Distance: 5.95 km

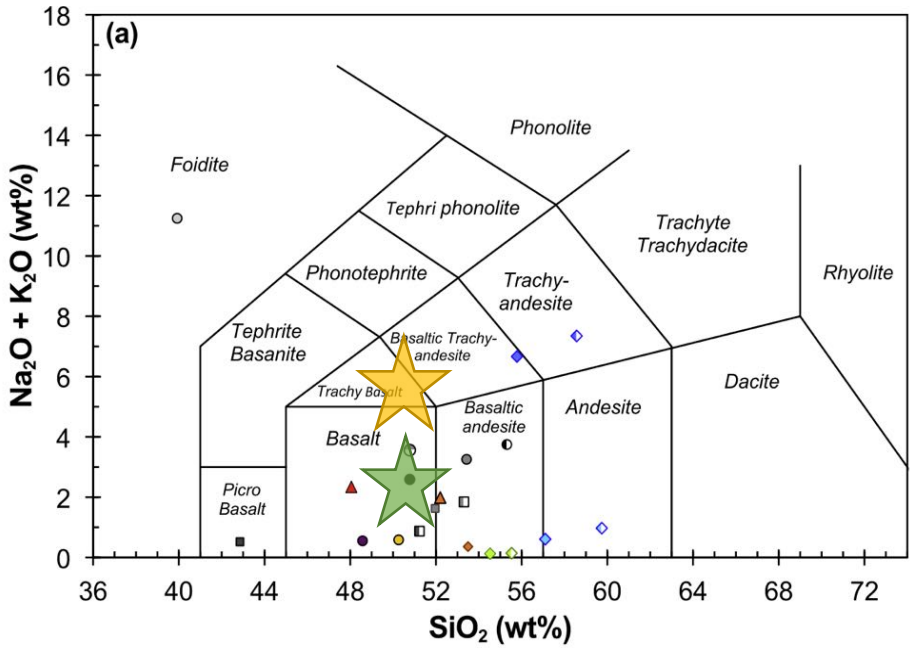


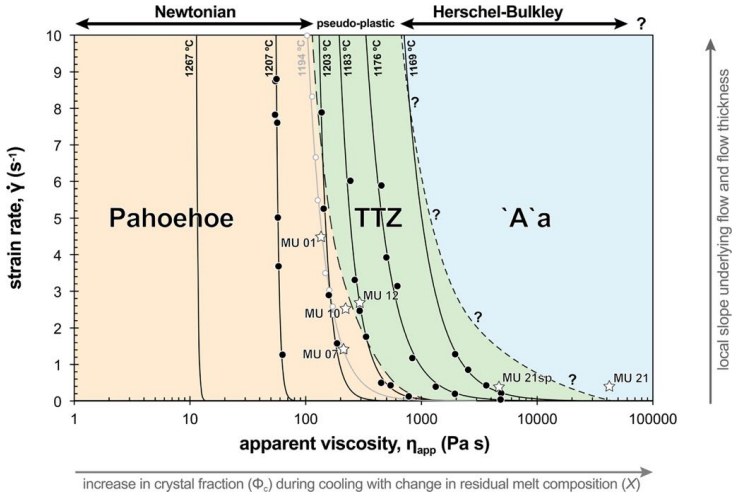

Mauna Ulu vent
N
W
E
S
MU01
smooth golden
MU07
smooth golden
Pahoehoe
MU10
smooth golden
MU11
smooth golden with first signs of transition
MU12
smooth golden with first signs of transition
Transition zone
MU21sp
MU21
MU22
overbank spatter
rough pahoehoe
rough pahoehoe with 'a'a clasts
'A'a
-155°
20°
19°
Mauna Ulu
1000 meter

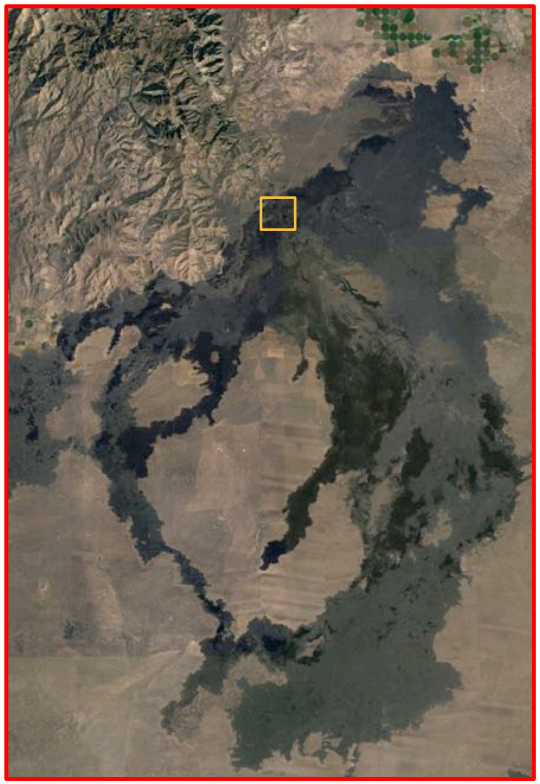

MU1 Distance : 1.43 km
Microlites: 0.0 %
Dendritic olivine
200 µm
MU7 Distance : 2.60 km
Microlites: 3.0 %
Olivine
200 µm
MU10 Distance : 3.33 km
Microlites: 6.1 %
Clinopyroxene
Plagioclase
200 µm
MU12 Distance : 3.95 km
Microlites: 7.9 %
200 µm
MU21 Distance : 5.76 km
Microlites: 34.0 %
200 µm

For Hawaiian lava: Morphology and physical properties quantified.
Coincidence? → Needs to be checked for other flow of different lava type







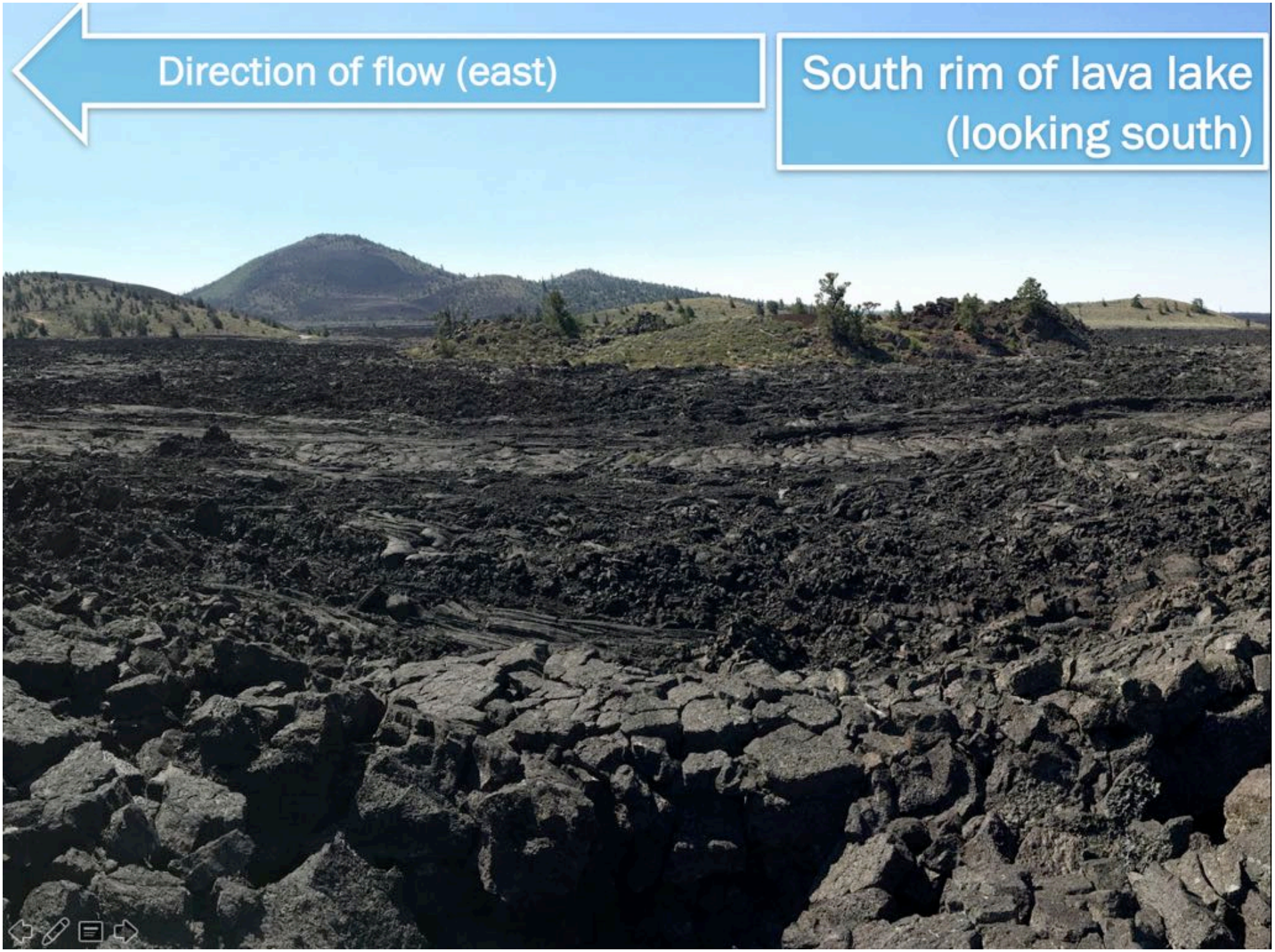


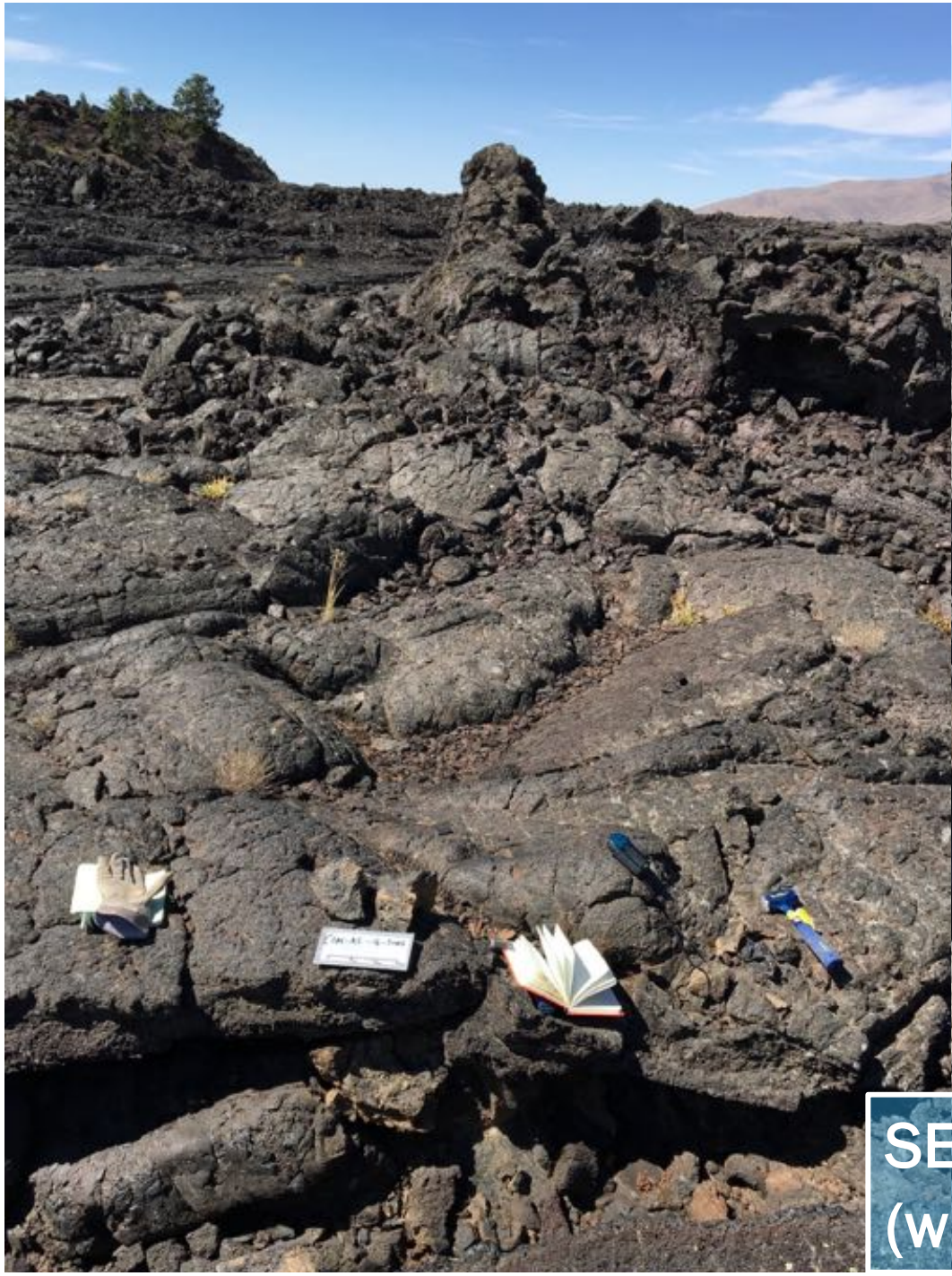
Craters of the Moon National Monument and Preserve, Idaho

Video 03: Blue Dragon Flow (COTM)

https://youtu.be/jyiKsEBk2b0

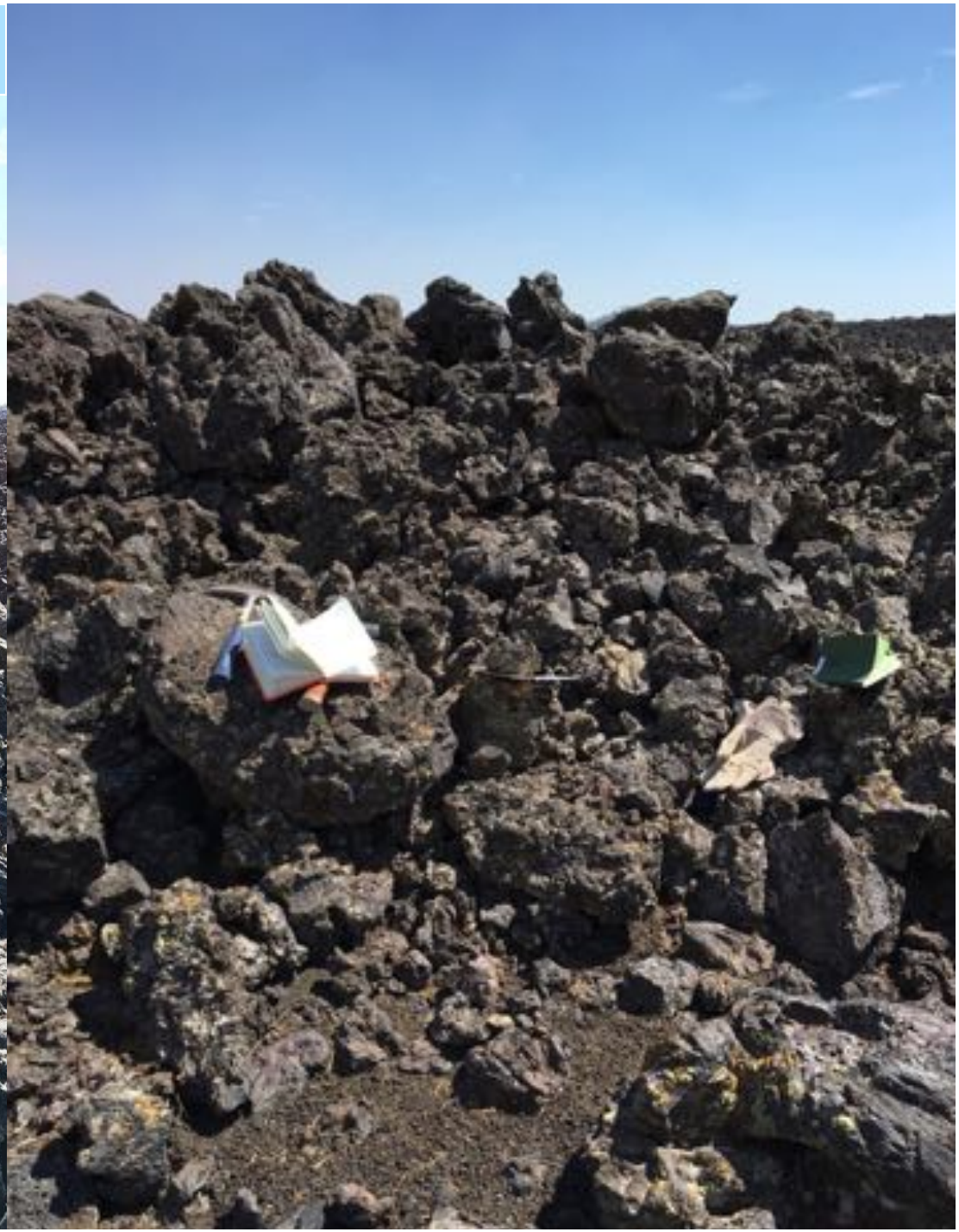
Near spatter cones (volcanic vents)


Direction of flow (east)
South rim of lava lake
(looking south)

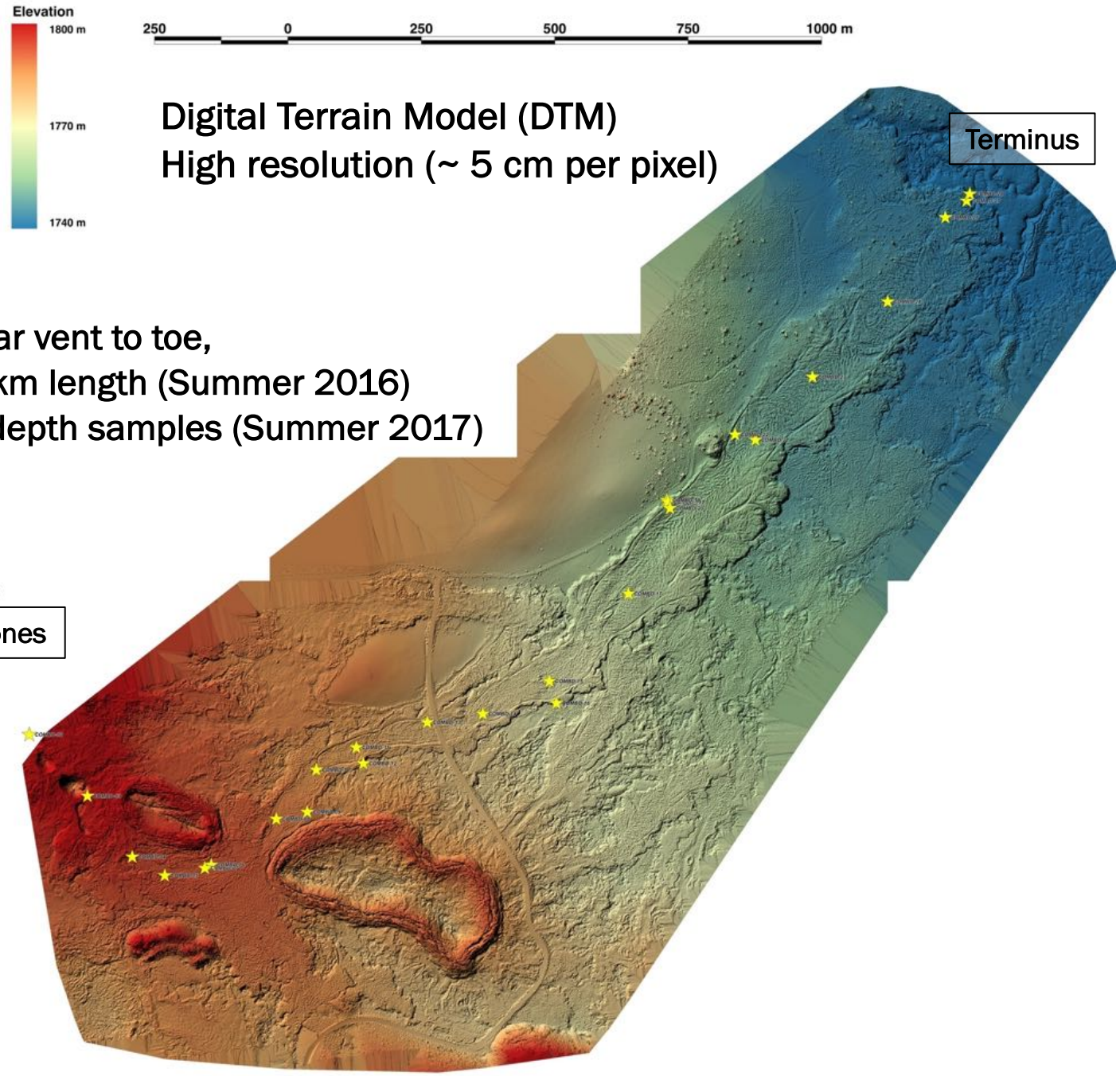


SE of lava lake
(white patches disappeared)

Near terminus



Digital Terrain Model (DTM)
High resolution (~ 5 cm per pixel)

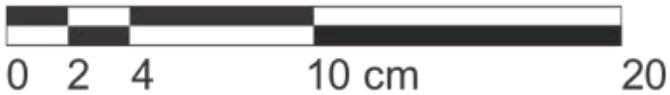


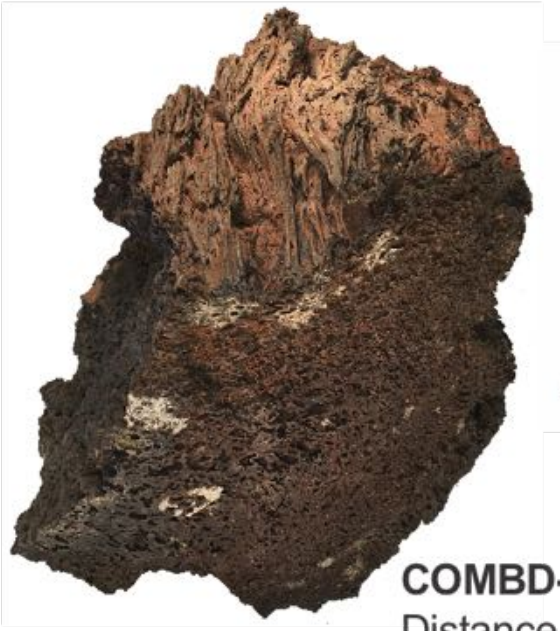
Mapped flow from near vent to toe,
Sampled over ~2.75 km length (Summer 2016)
Additional levee and depth samples (Summer 2017)
Total of 35 samples

COMBD-01
Distance: 0.0 km

COMBD-03
Distance: 0.45 km

COMBD-04
Distance: 0.75 km



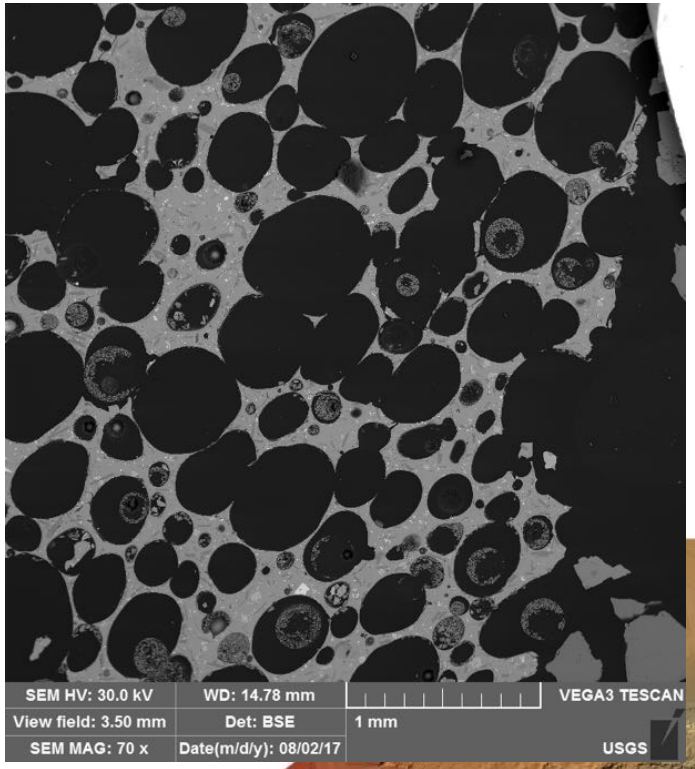


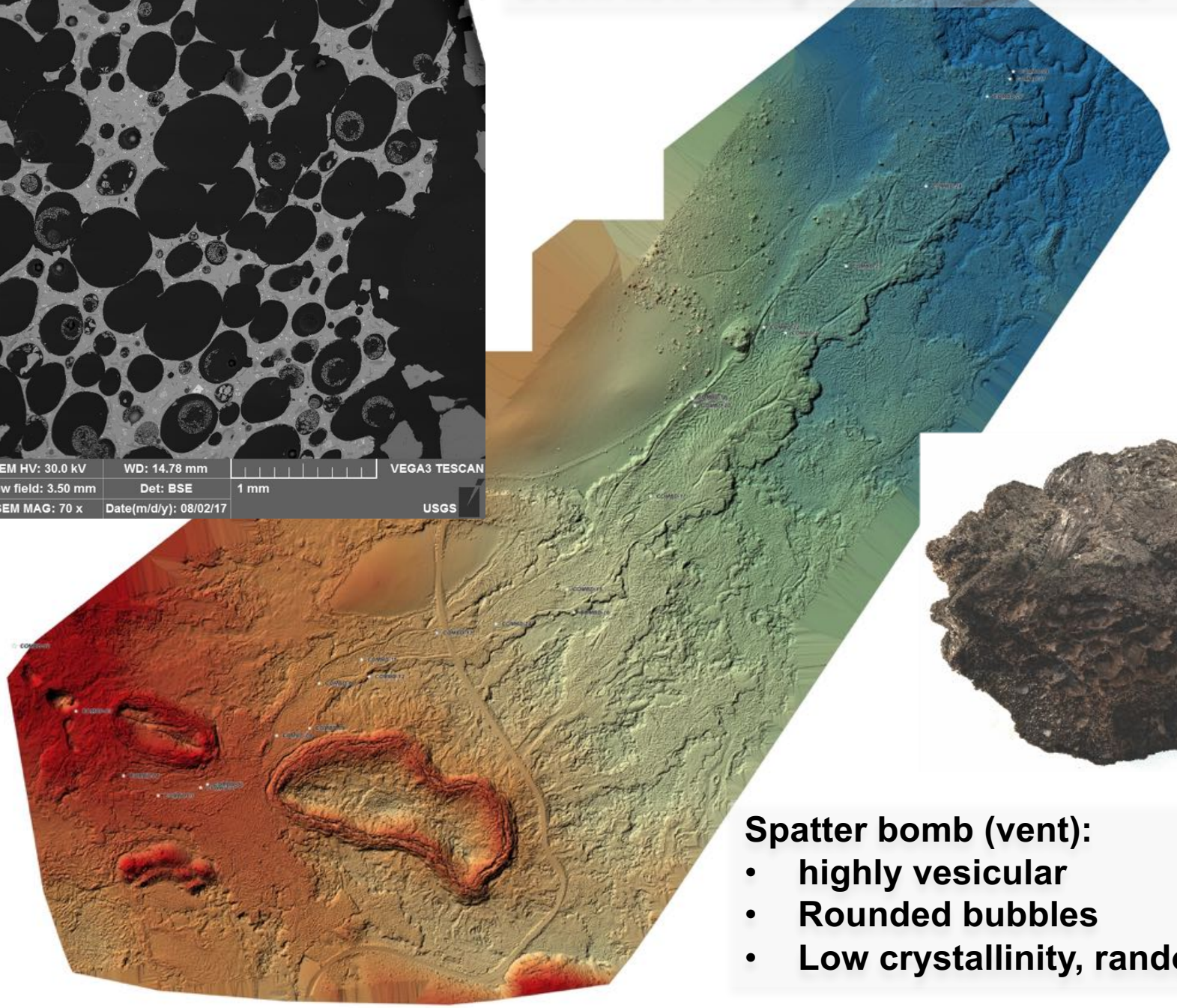
COMBD-10
Distance: 1.05 km

COMBD-14
Distance: 1.40 km

COMBD-27
Distance: 2.75 km

Down flow changes in sample texture

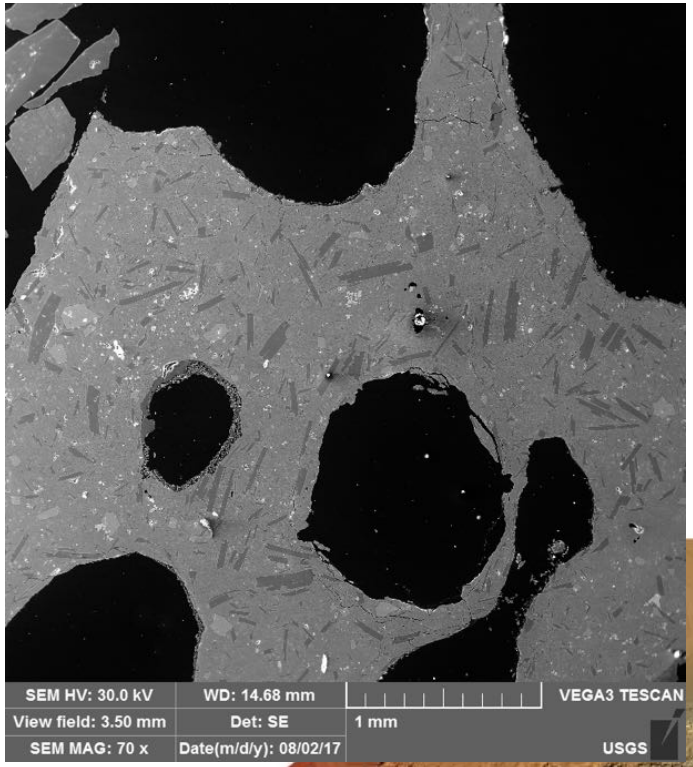


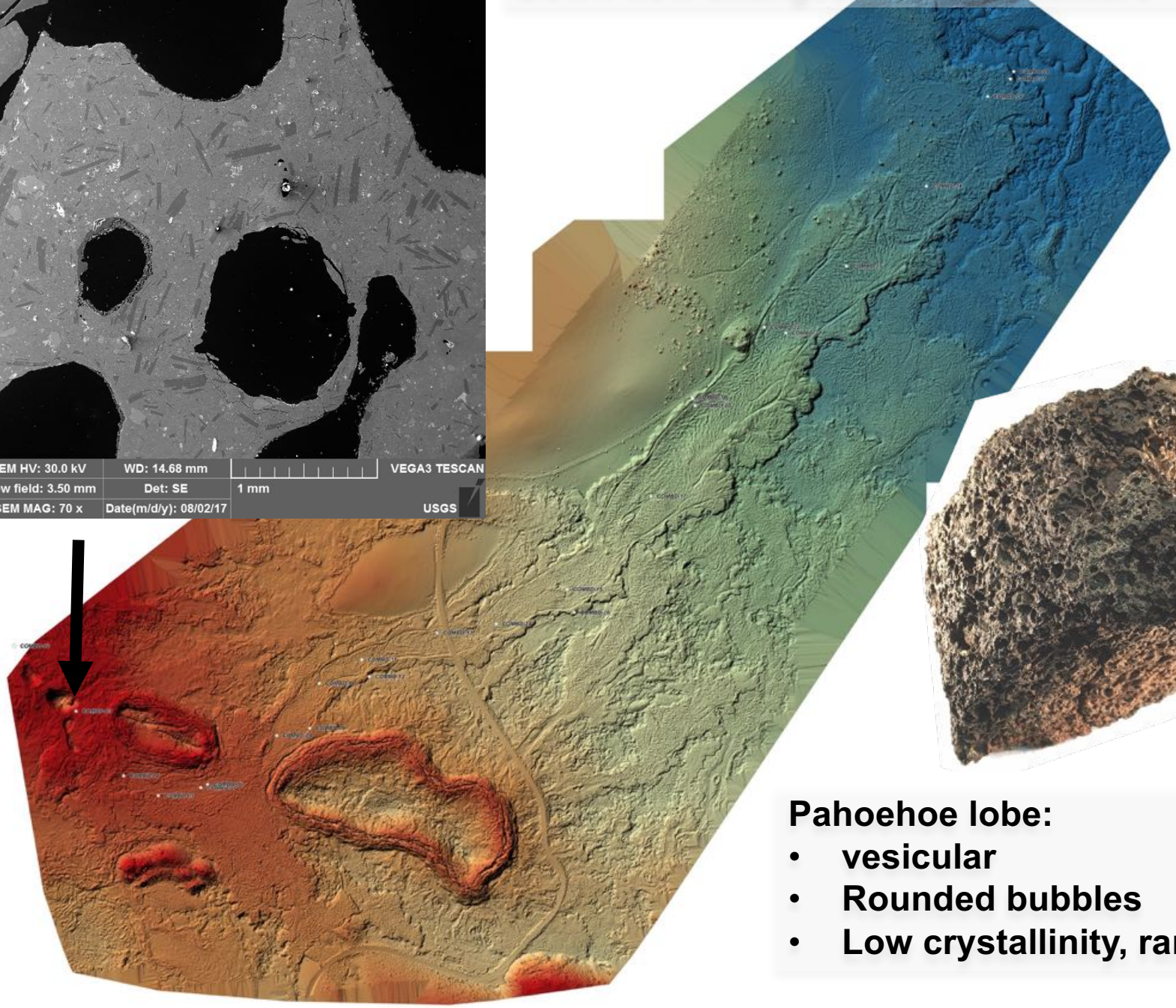


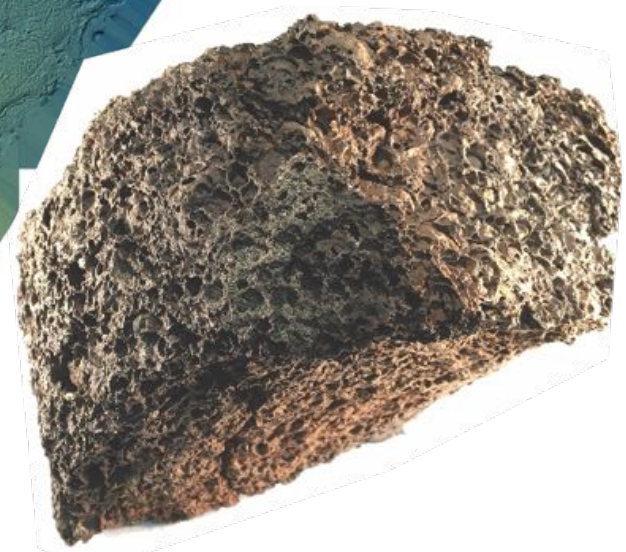
Spatter bomb (vent):

- **highly vesicular**
- **Rounded bubbles**
- **Low crystallinity, random order**

Down flow changes in sample texture



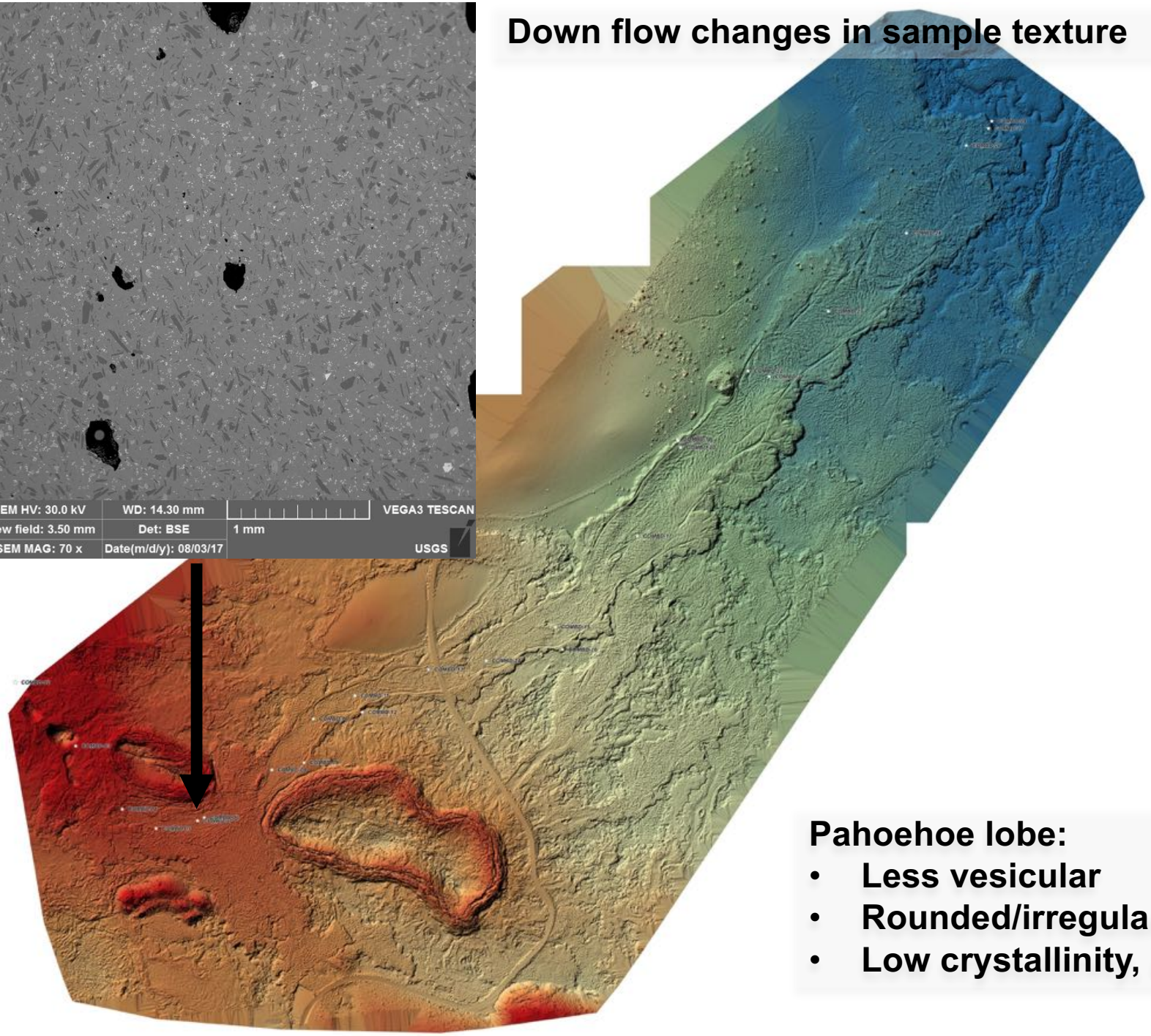




Pahoehoe lobe:

- **vesicular**
- **Rounded bubbles**
- **Low crystallinity, random order**

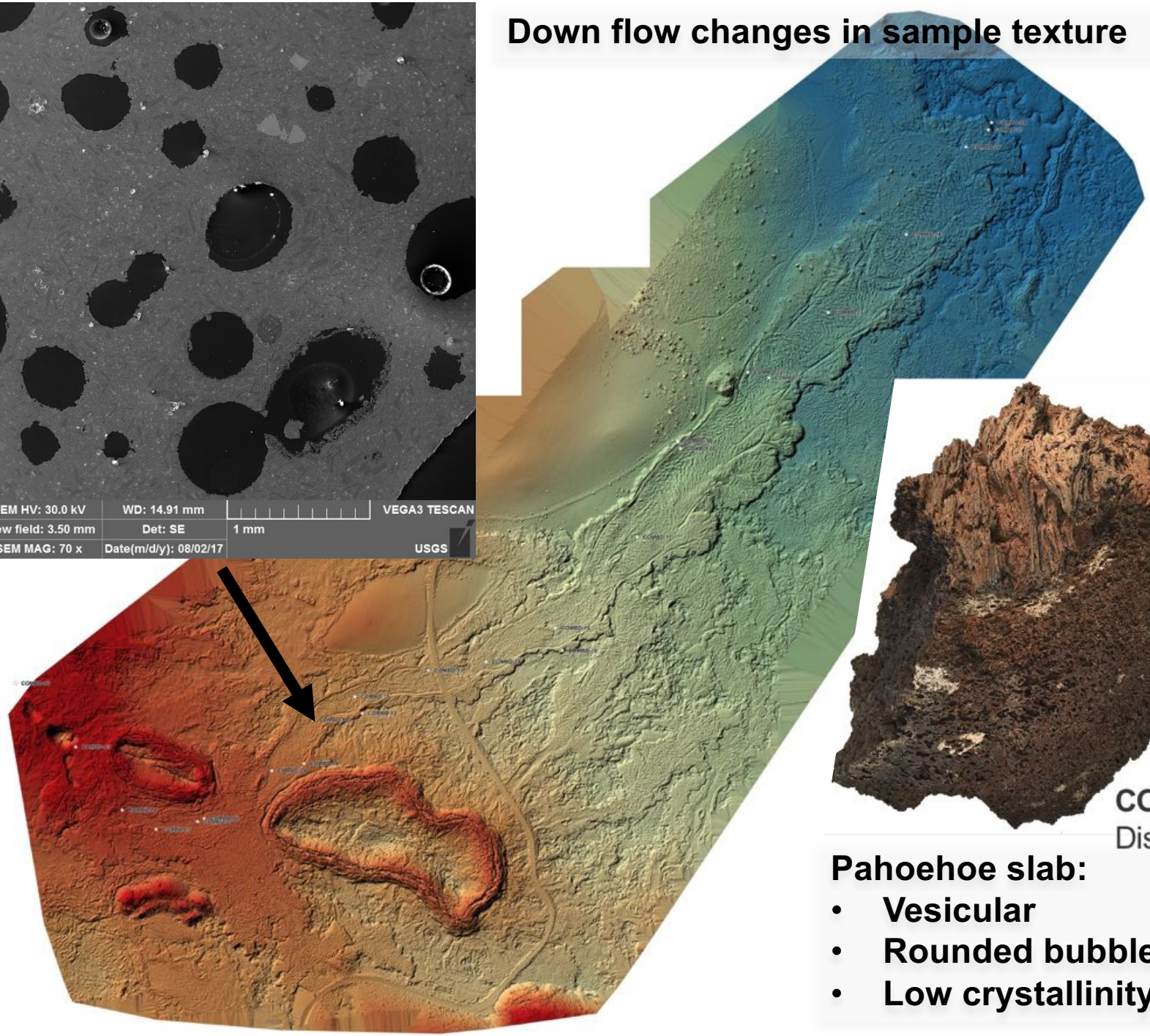
Down flow changes in sample texture

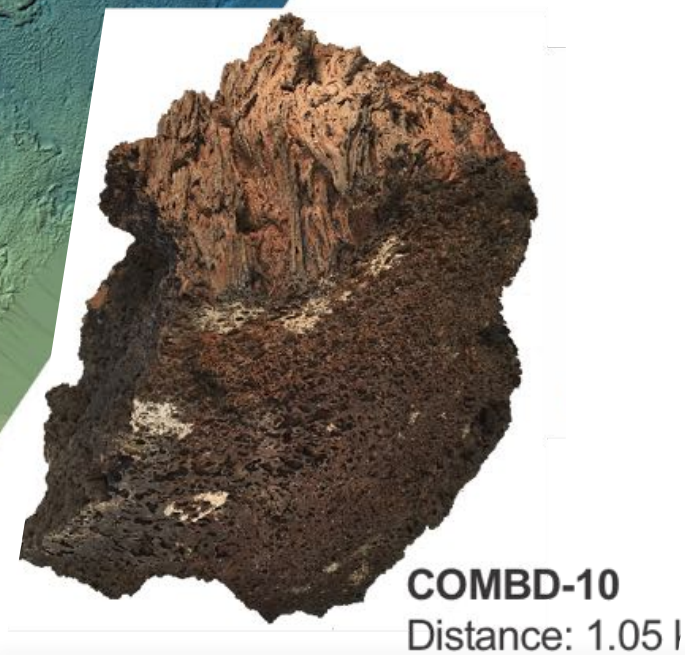


Pahoehoe lobe:

- **Less vesicular**
- **Rounded/irregular bubbles**
- **Low crystallinity, aligned**

Down flow changes in sample texture





Pahoehoe slab:

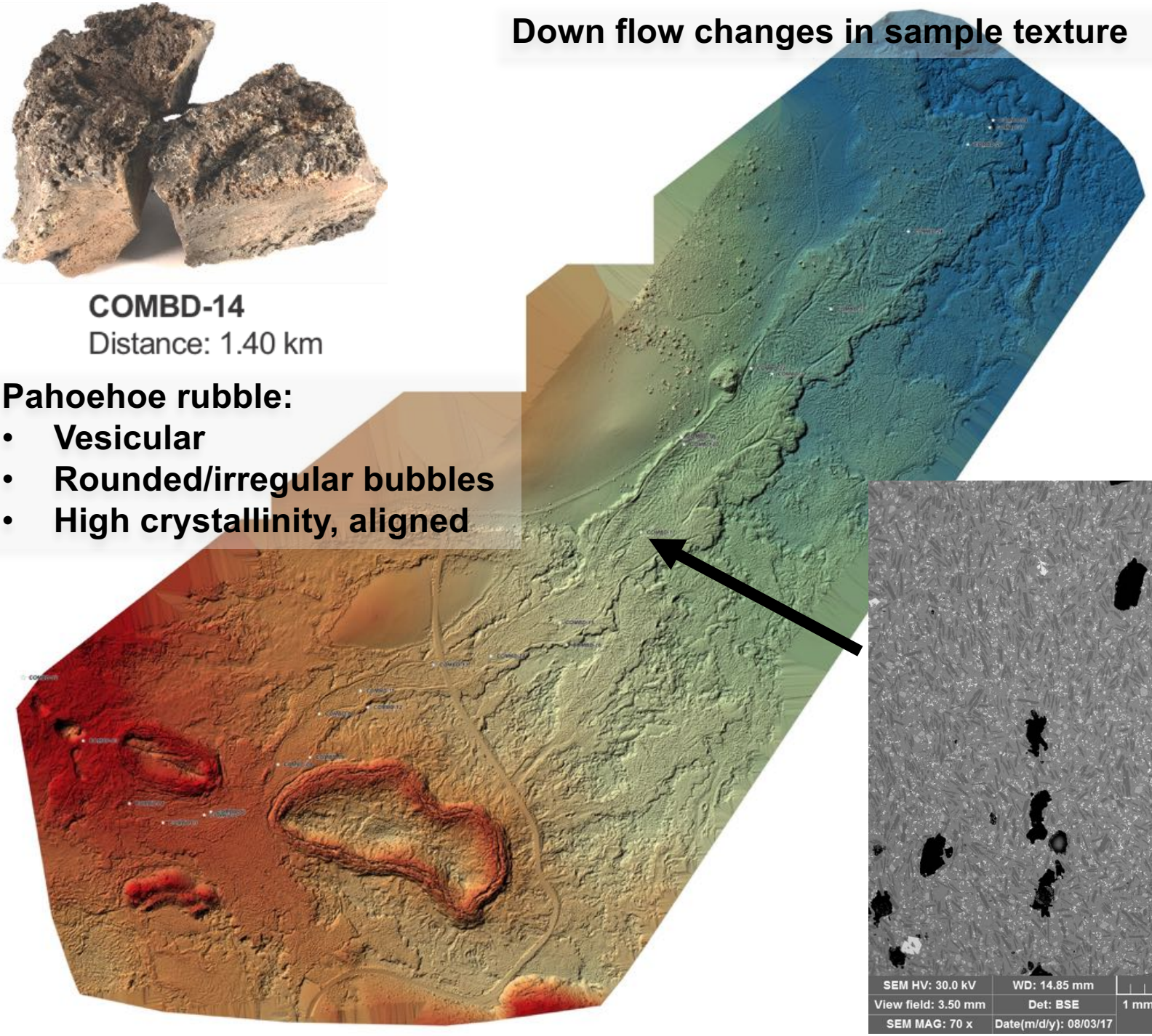
- **Vesicular**
- **Rounded bubbles**
- **Low crystallinity, aligned**

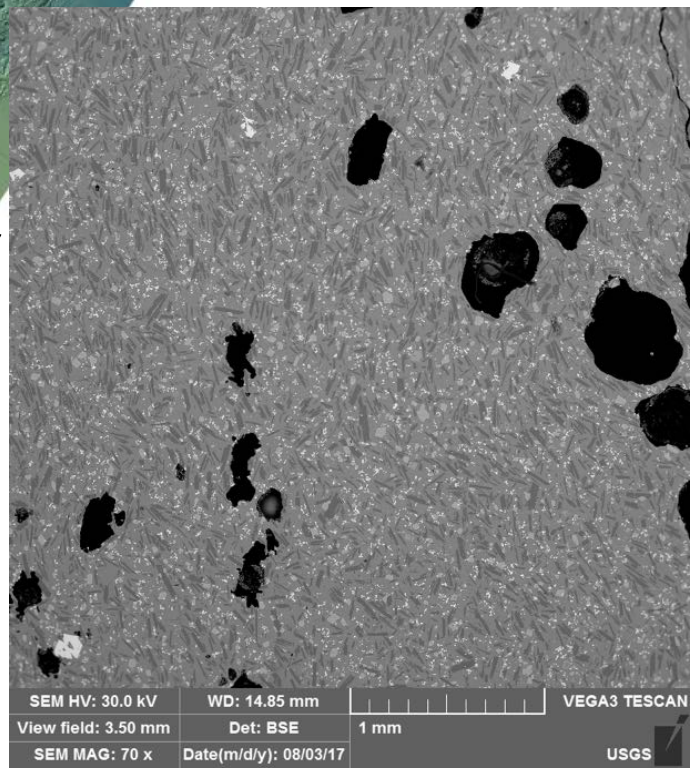
Down flow changes in sample texture

COMBD-14
Distance: 1.40 km

Pahoehoe rubble:

- **Vesicular**
- **Rounded/irregular bubbles**
- **High crystallinity, aligned**

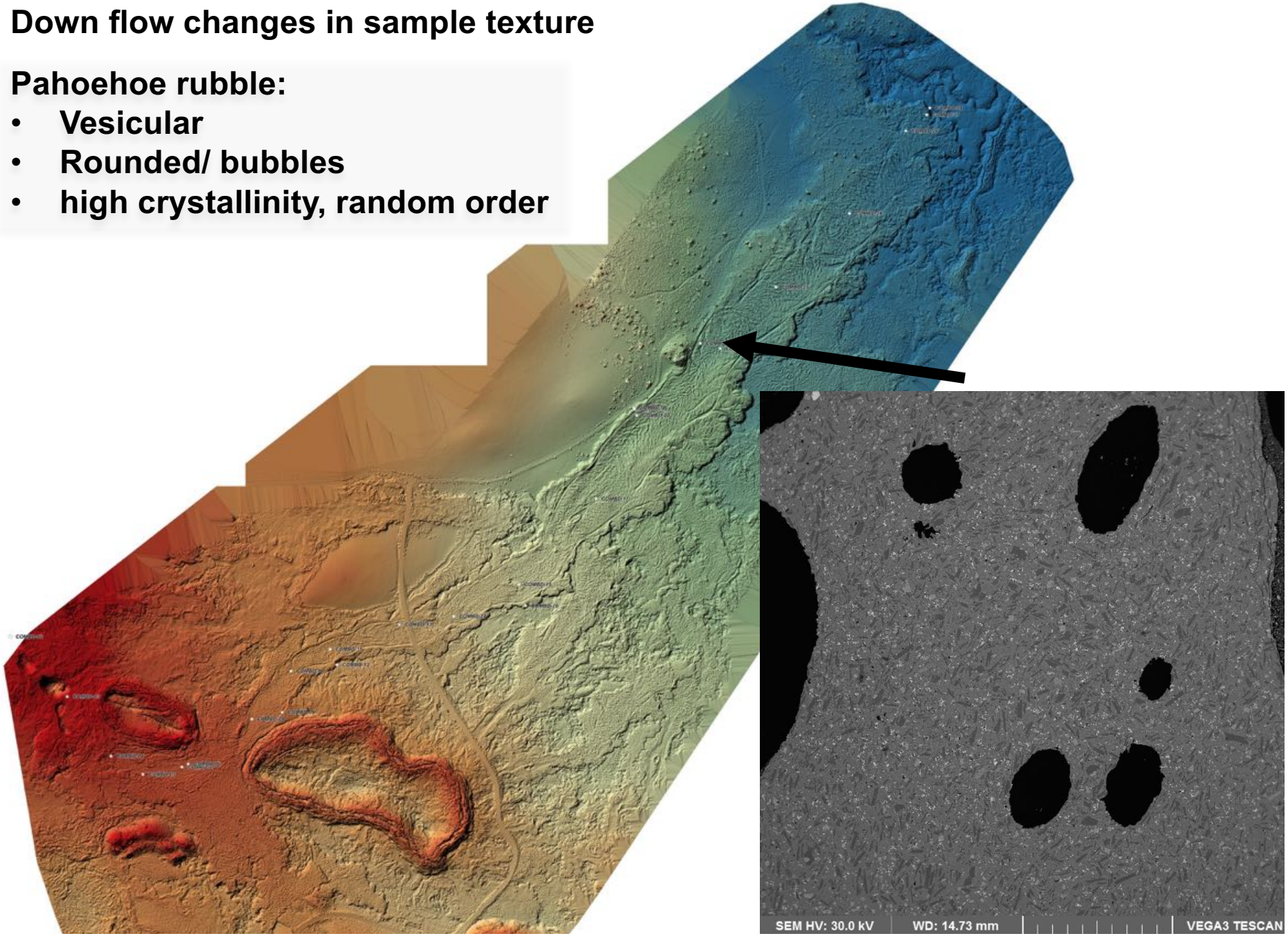




Down flow changes in sample texture

Pahoehoe rubble:

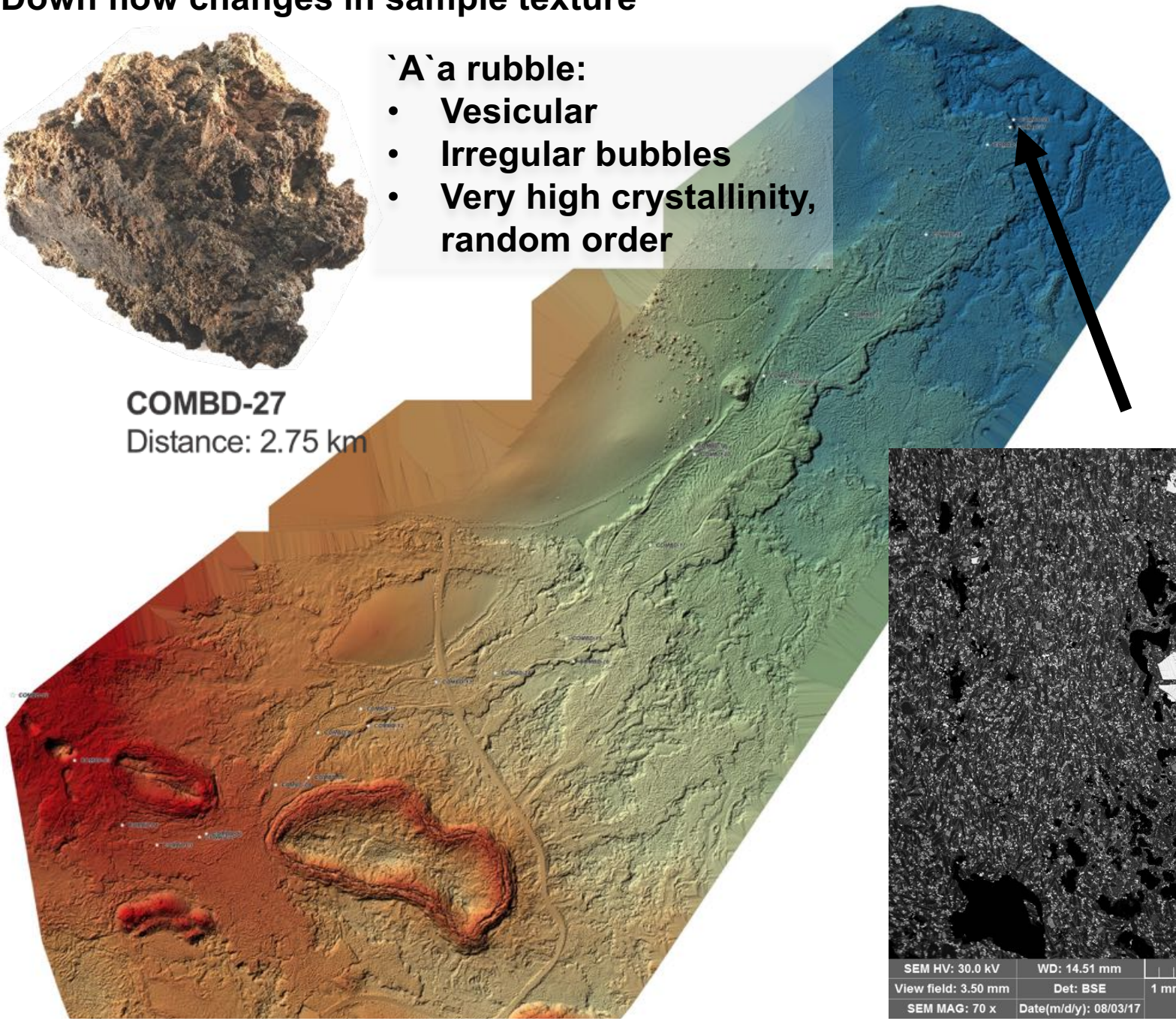
- **Vesicular**
- **Rounded/ bubbles**
- **high crystallinity, random order**

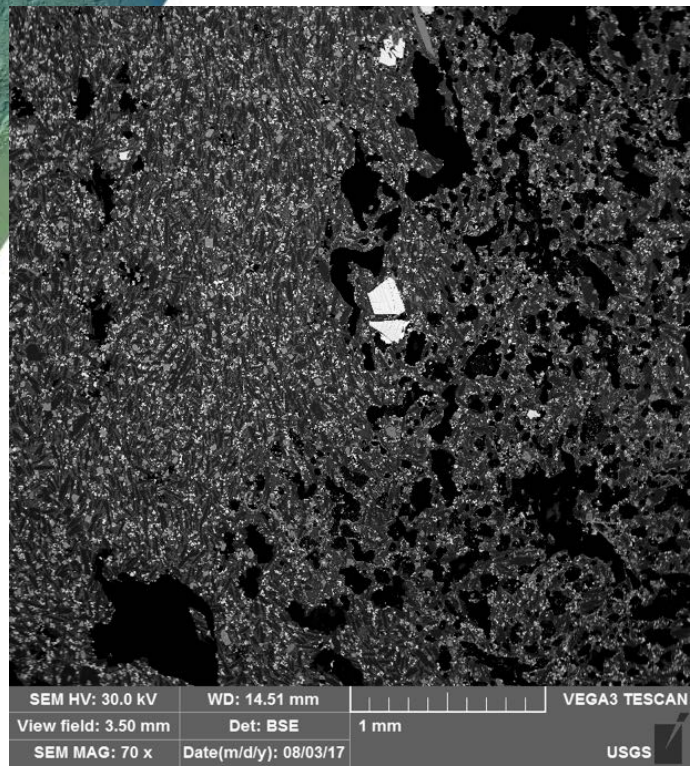


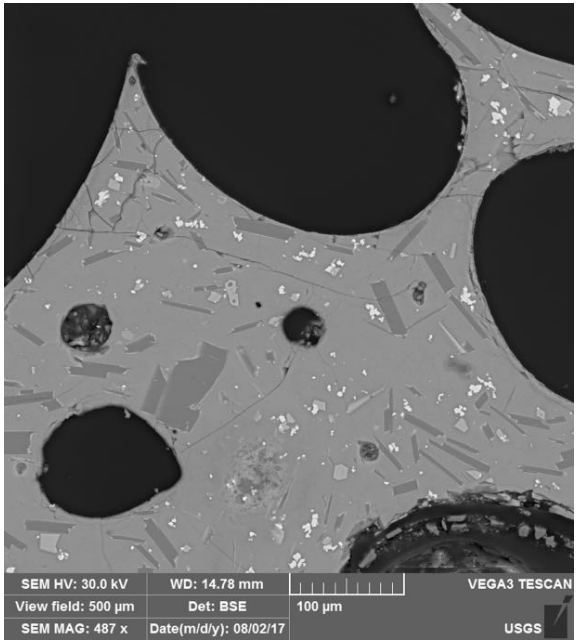
Down flow changes in sample texture

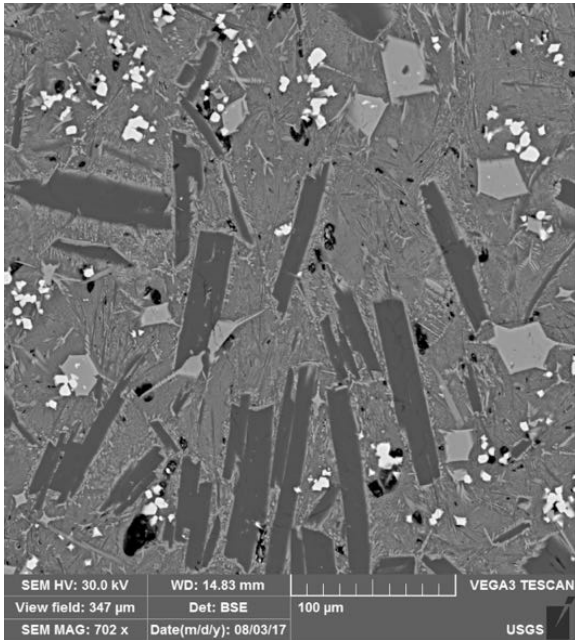
`A`a rubble:

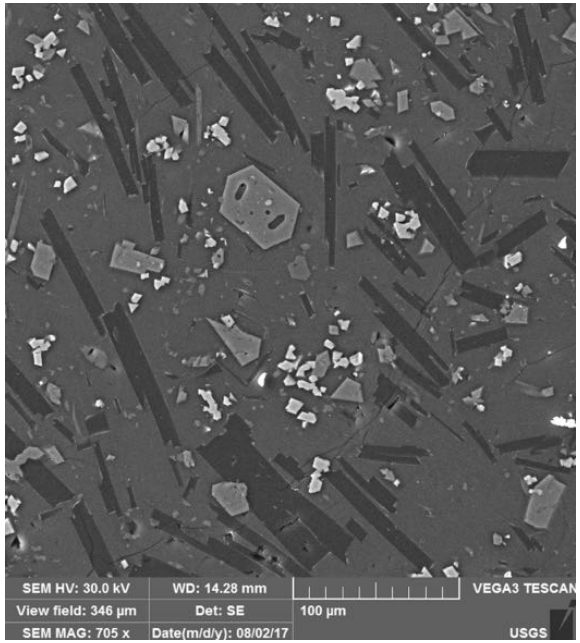
- **Vesicular**
- **Irregular bubbles**
- **Very high crystallinity, random order**



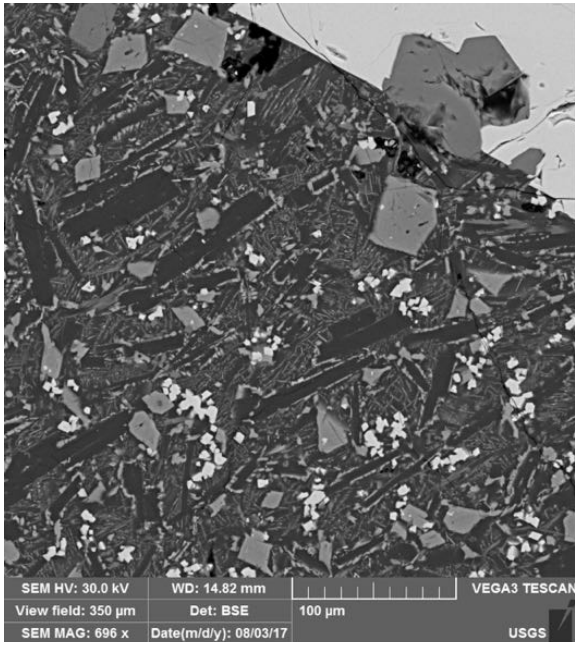


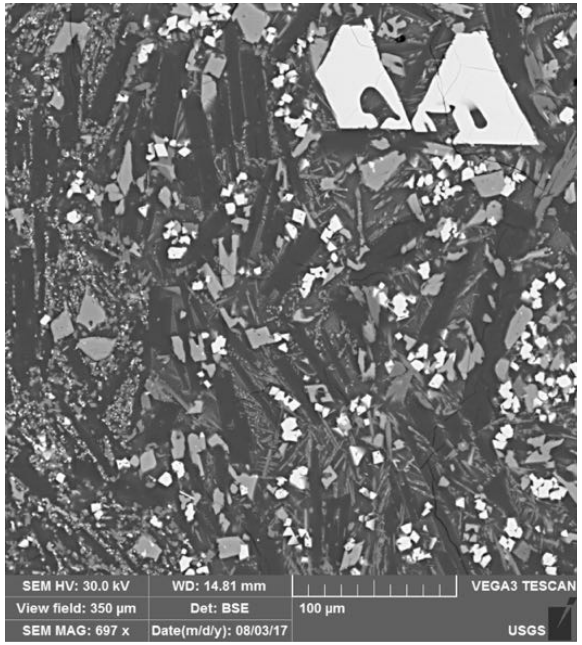

SEM HV: 30.0 kV
WD: 14.78 mm
VEGA3 TESCAN
View field: 500 µm
Det: BSE
100 µm
SEM MAG: 487 x
Date(m/d/y): 08/02/17
USGS

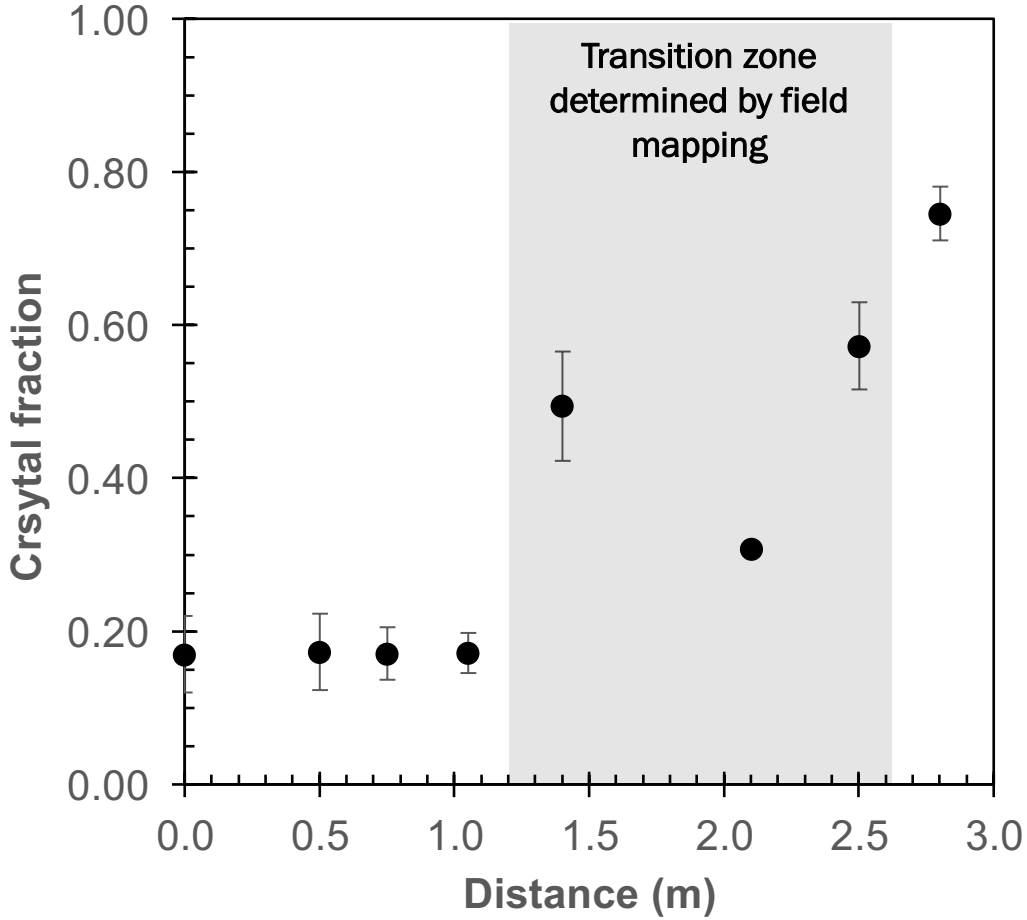

SEM HV: 30.0 kV
WD: 14.83 mm
VEGA3 TESCAN
View field: 347 µm
Det: BSE
100 µm
SEM MAG: 702 x
Date(m/d/y): 08/03/17
USGS

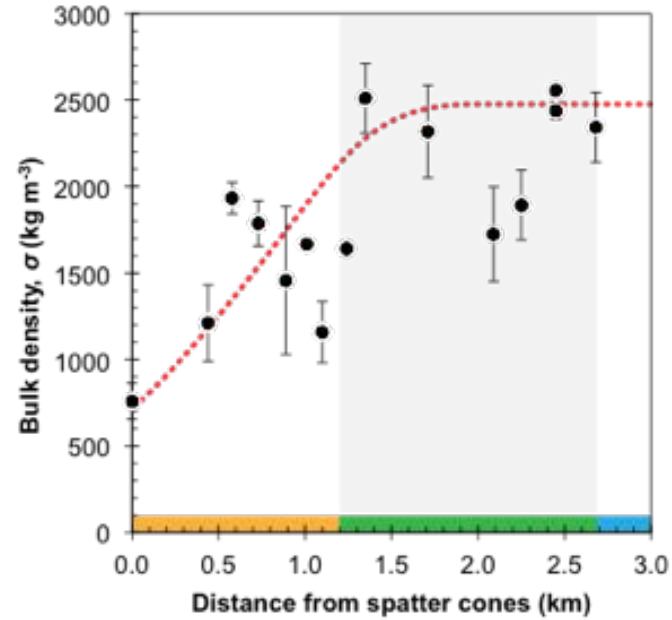

SEM HV: 30.0 kV
WD: 14.28 mm
VEGA3 TESCAN
View field: 346 µm
Det: SE
100 µm
SEM MAG: 705 x
Date(m/d/y): 08/02/17
USGS

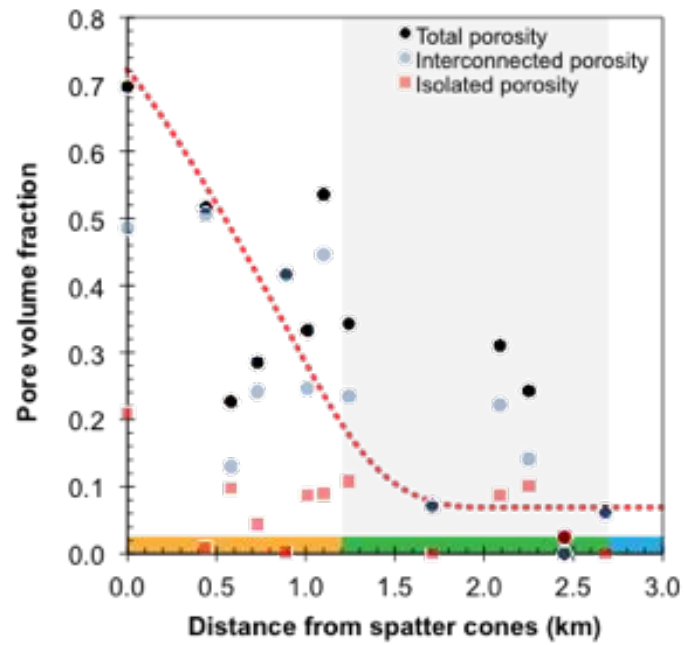
SEM HV: 30.0 kV
WD: 14.46 mm
VEGA3 TESCAN
View field: 350 µm
Det: BSE
100 µm
SEM MAG: 697 x
Date(m/d/y): 08/03/17
USGS


SEM HV: 30.0 kV
WD: 14.82 mm
VEGA3 TESCAN
View field: 350 µm
Det: BSE
100 µm
SEM MAG: 696 x
Date(m/d/y): 08/03/17
USGS


SEM HV: 30.0 kV
WD: 14.81 mm
VEGA3 TESCAN
View field: 350 µm
Det: BSE
100 µm
SEM MAG: 697 x
Date(m/d/y): 08/03/17
USGS



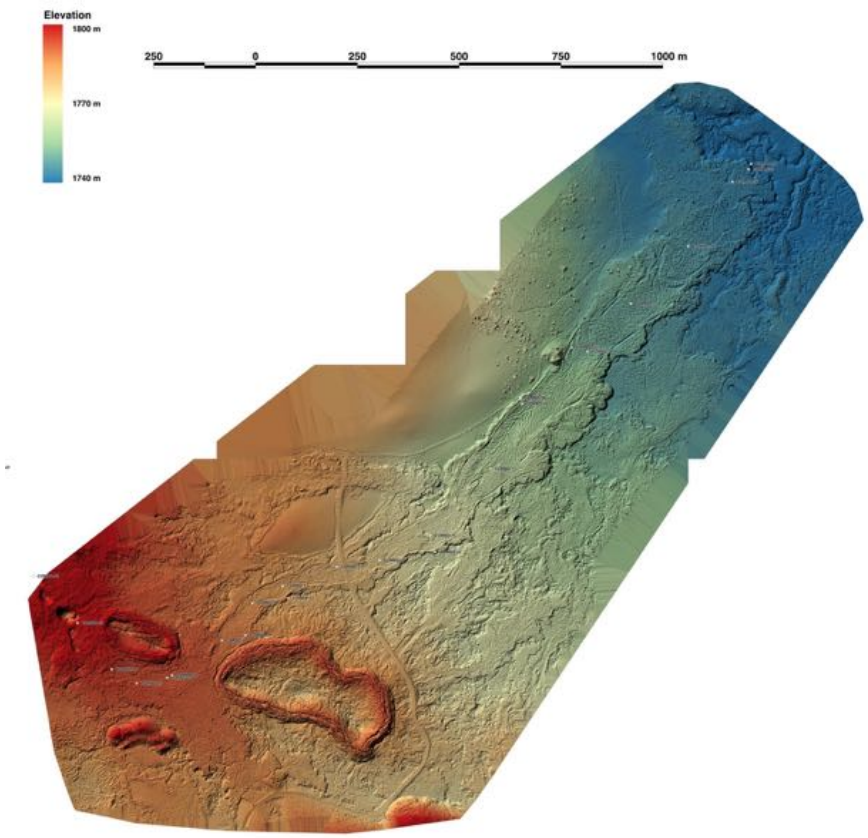


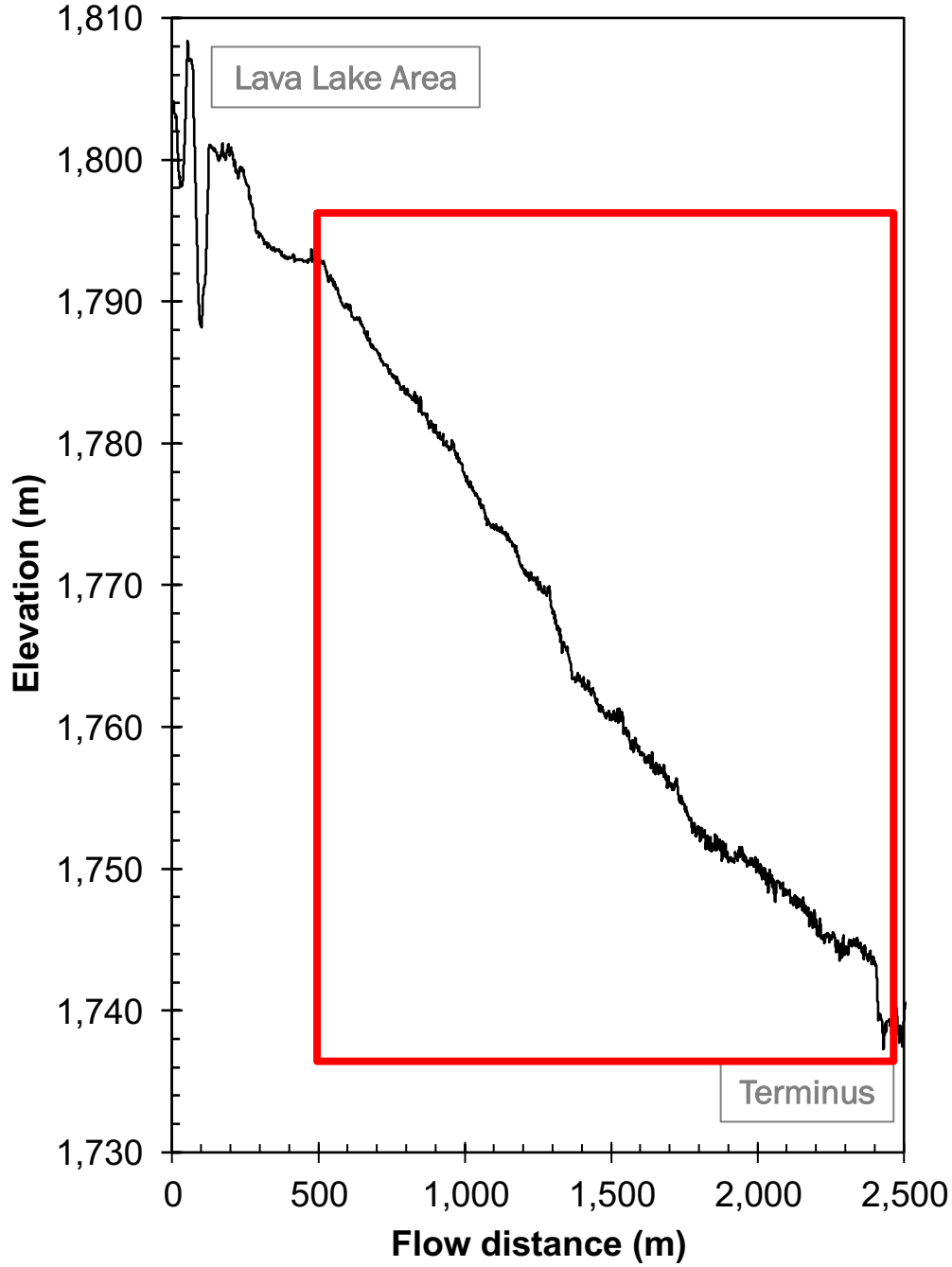


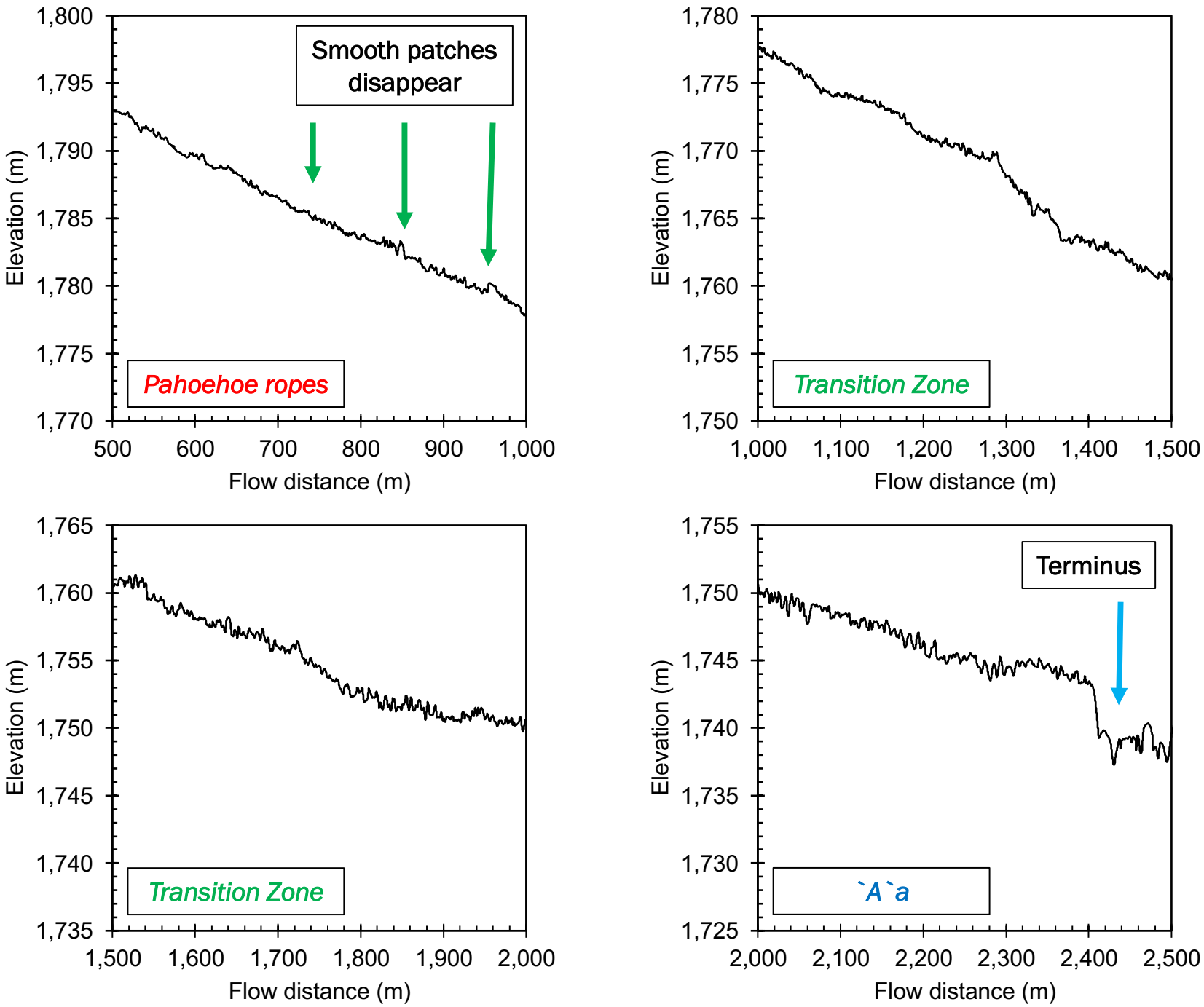
Seeing trends with flow distance in

- Crystallinity
- Bulk density
- Pore space

Height profile through center of lava flow extracted from DTM






Smooth patches disappear
Pahoehoe ropes
Transition Zone
Transition Zone
Terminus
`A`a
Elevation (m)
Flow distance (m)
1,800
1,795
1,790
1,785
1,780
1,775
1,770
500
600
700
800
900
1,000
1,780
1,775
1,770
1,765
1,760
1,755
1,750
1,000
1,100
1,200
1,300
1,400
1,500
1,765
1,760
1,755
1,750
1,745
1,740
1,735
1,500
1,600
1,700
1,800
1,900
2,000
1,755
1,750
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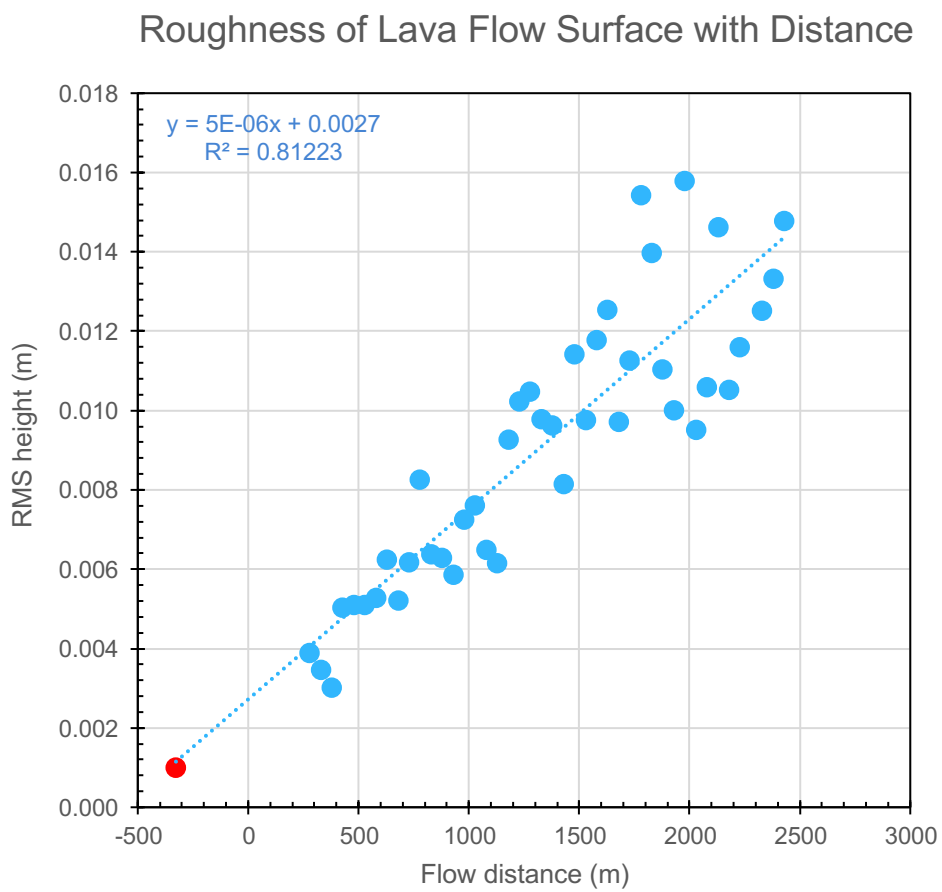
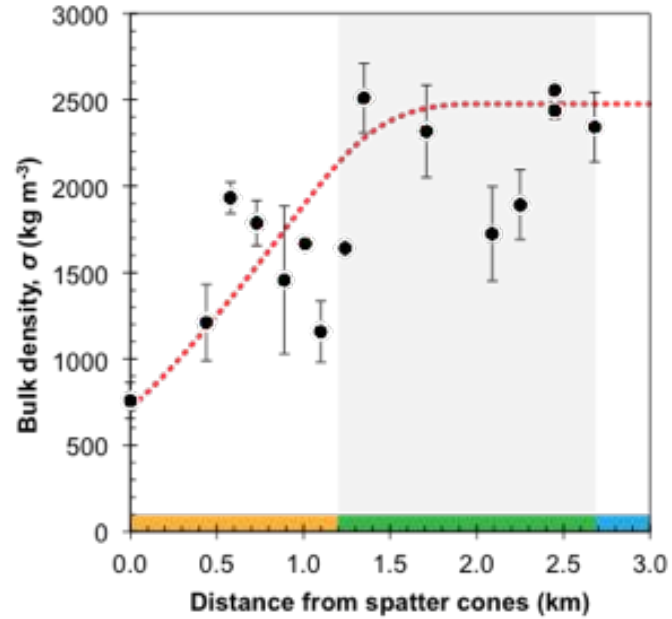
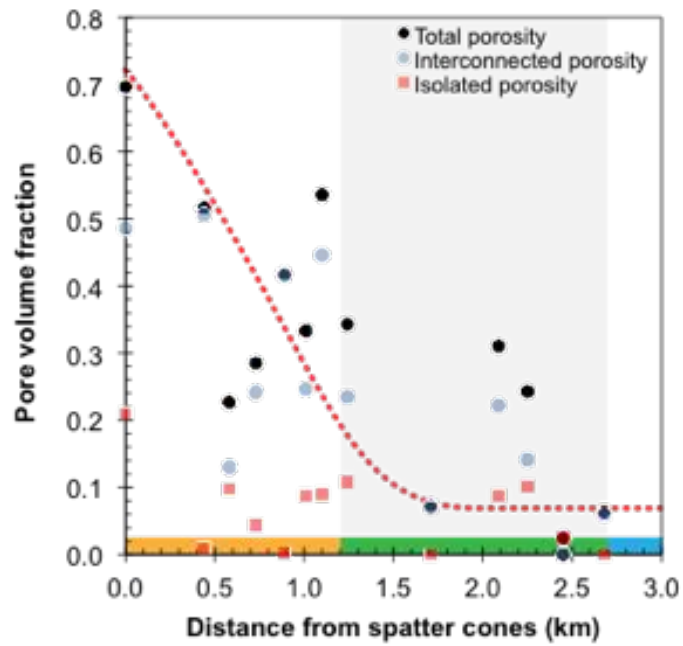
1,735
1,730
1,725
2,000
2,100
2,200
2,300
2,400
2,500



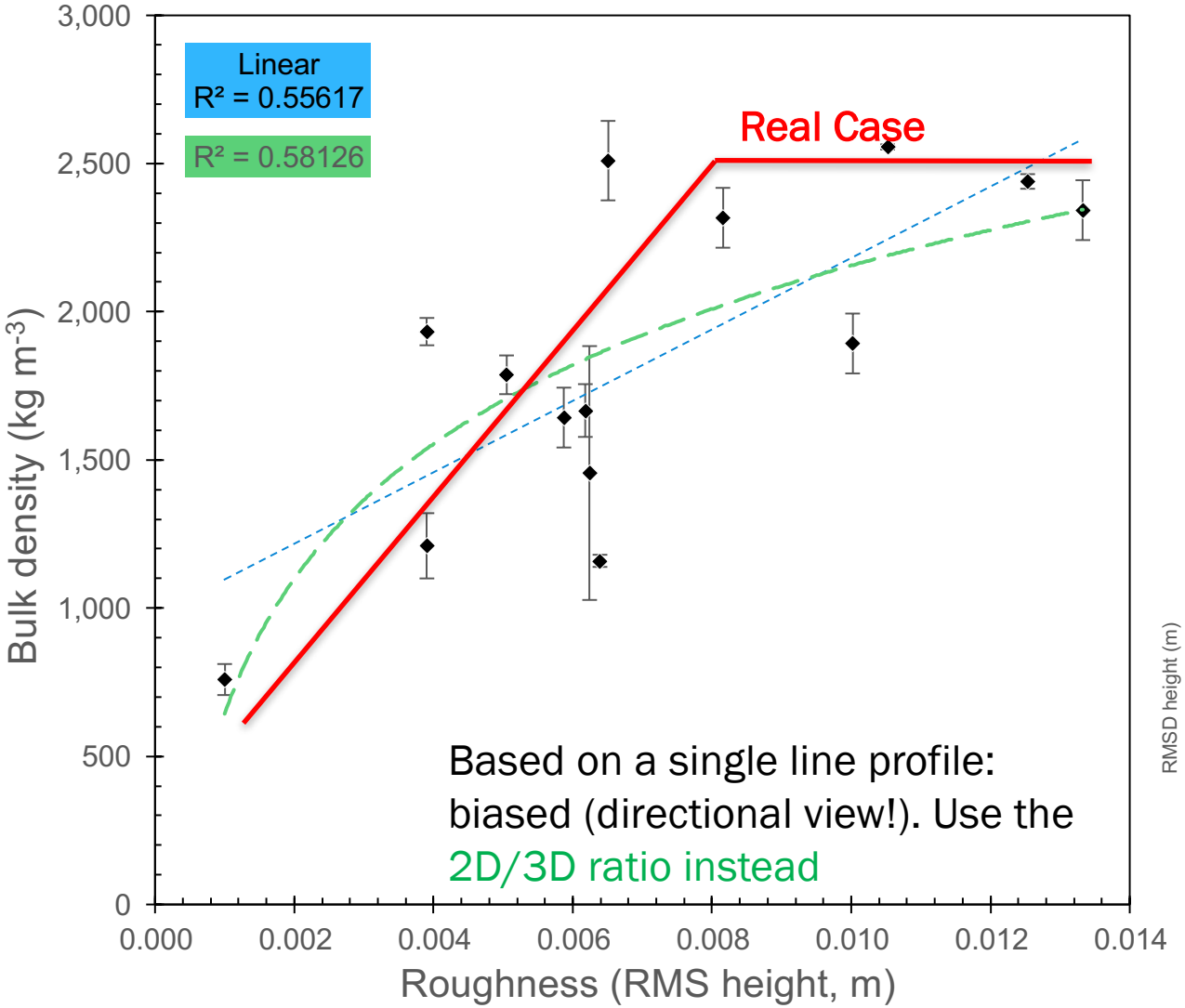


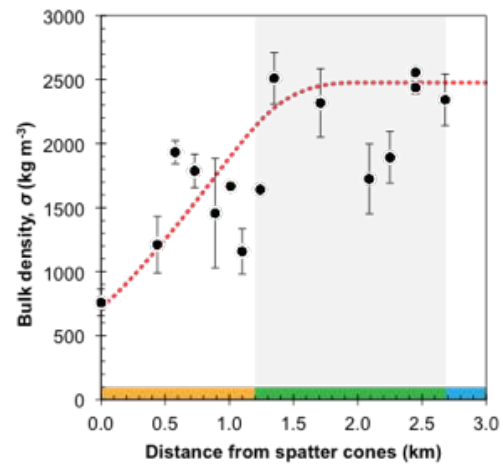


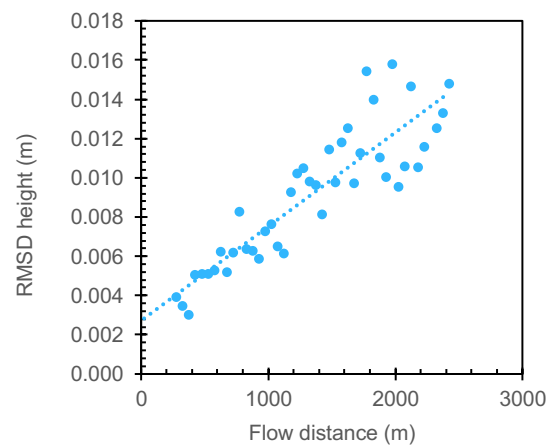
Height/elevation between each adjacent pixel averaged over length 50 meter. Based on center line profile.

- Correlation between flow distance and roughness exists.
- Correlation between flow distance and density and vesicularity exists

Roughness vs Density

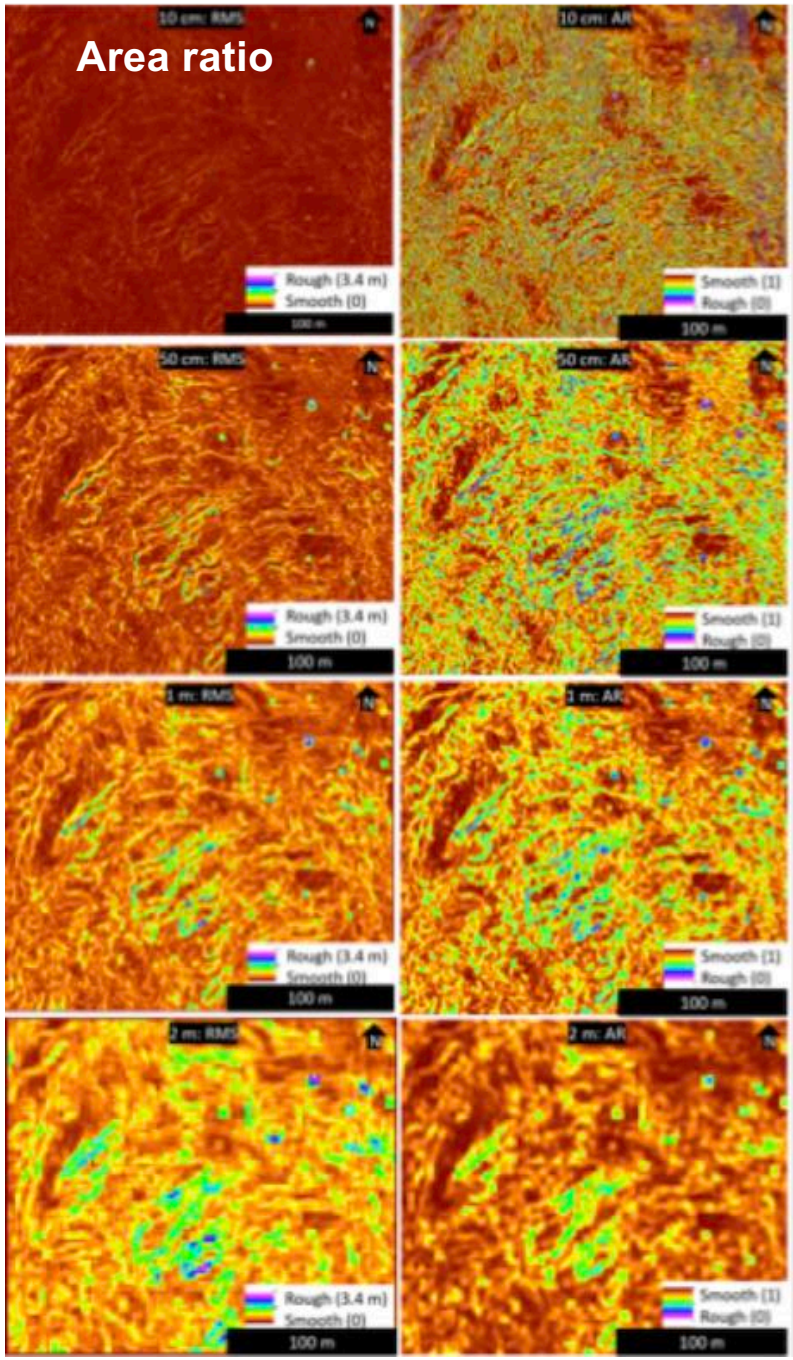




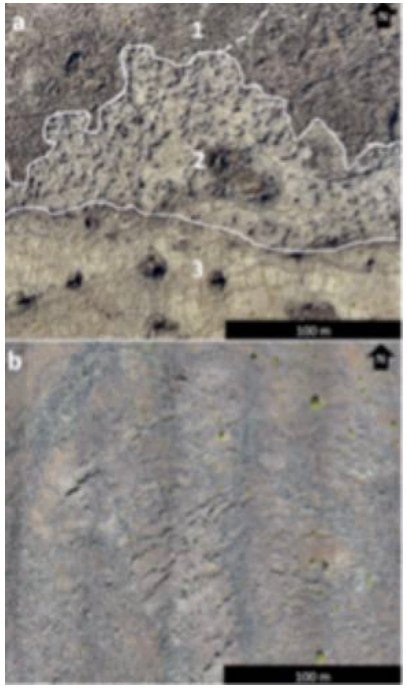


Surface roughness classification
Currently developed by Mallonee and Kobs Nawotniak at Idaho State University

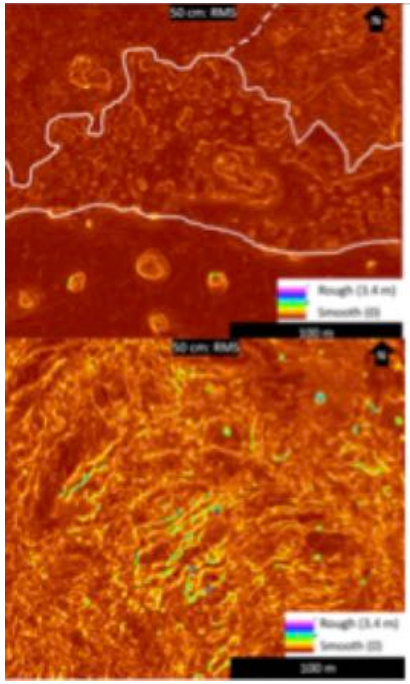
- RMS (root-mean-square) height, below
- Area ratio (2D/3D), left



Satellite imagery



RMS height



Thermo-Physical Properties of Lava Flows

Looking at the morphology and estimate a temperature?
Not impossible!

MISSION: IMPOSSIBLE ?

Viscosity measurements

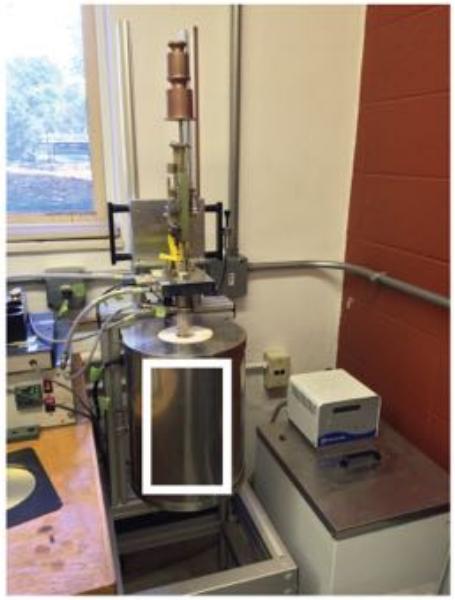
High temp.

1600ºC – 1150ºC

low viscosity

0.1 – 10^5 Pa s

Concentric Cylinder



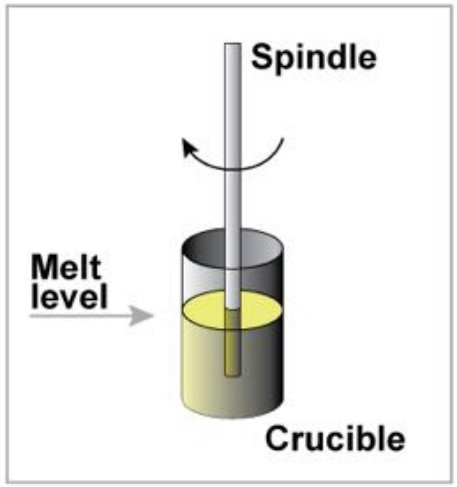
Parallel plate

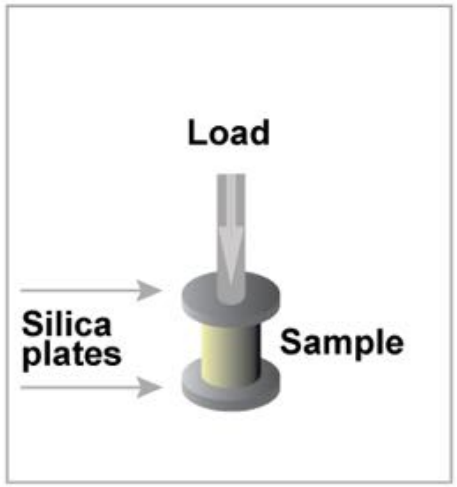
Low temp.

1000ºC – 500ºC

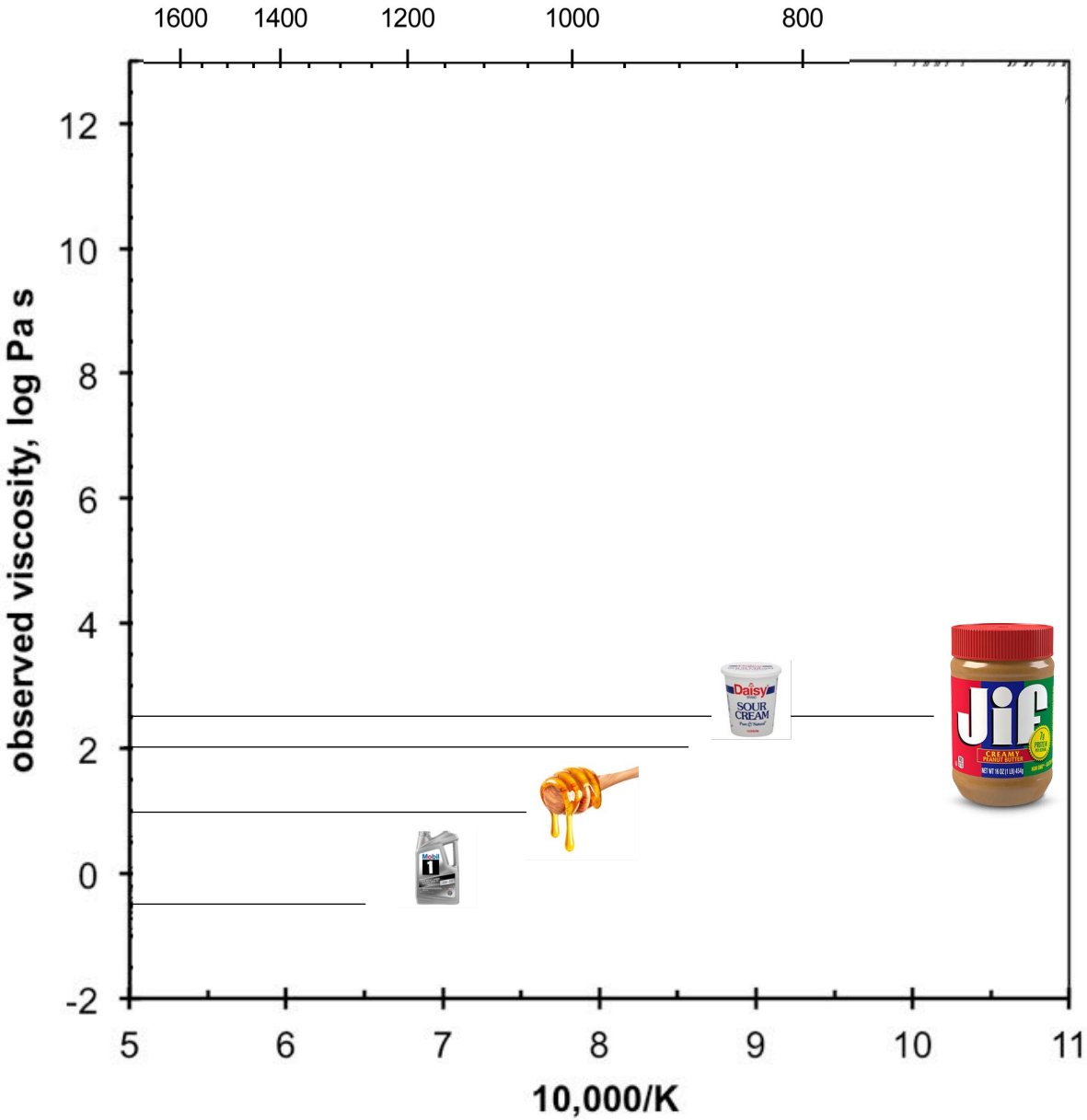
high viscosity

10^8 – 10^{13} Pa s



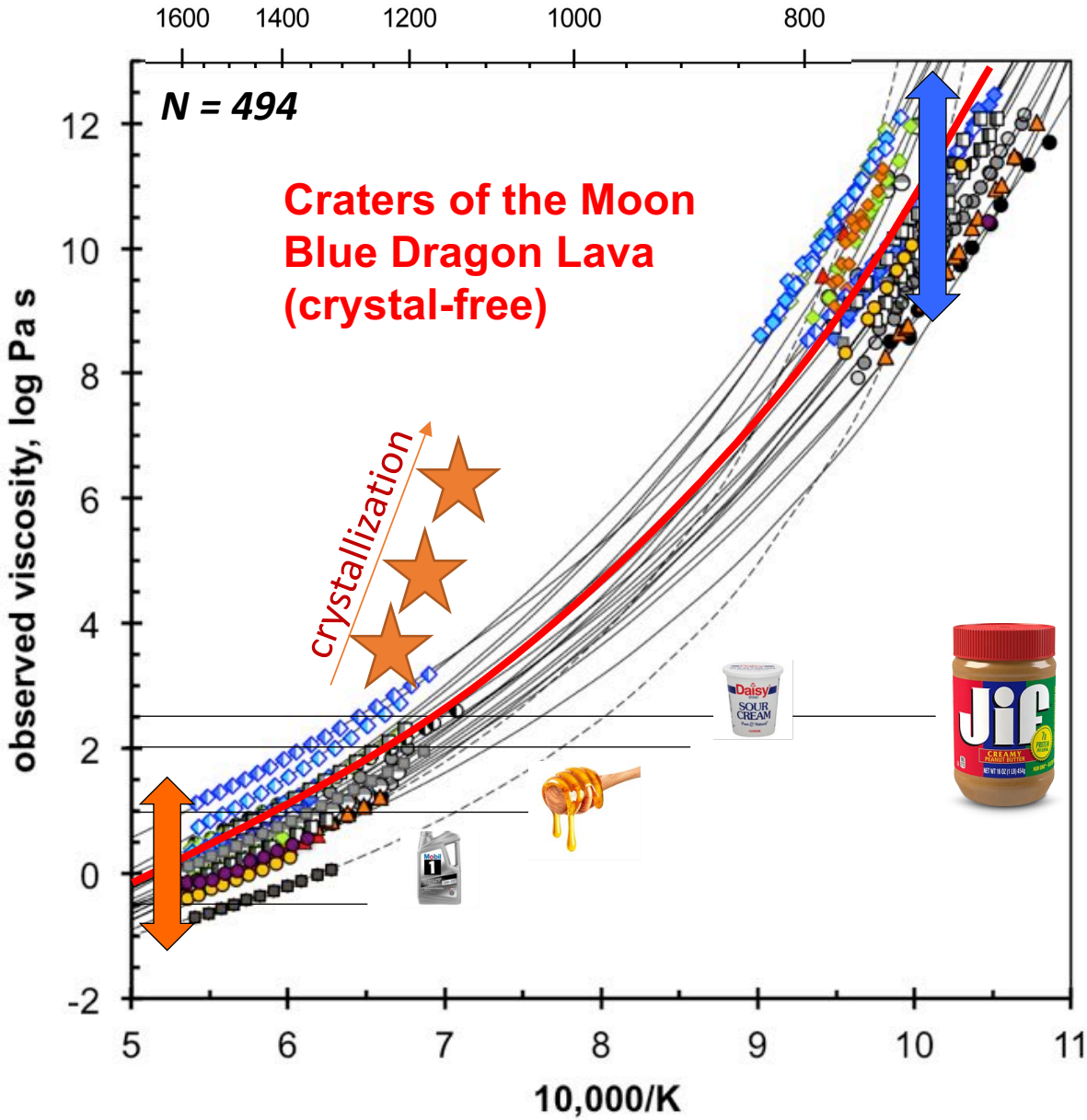


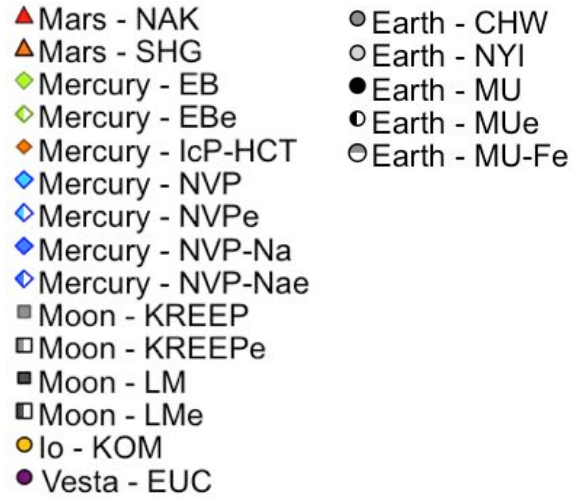
Viscosity of crystal-free lavas across the Solar System



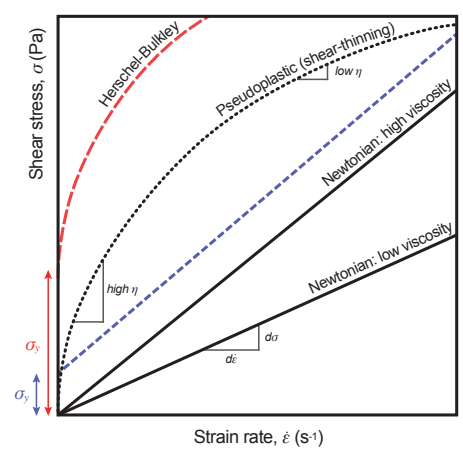
Sehlke and Whittington (2016). Geochim. Cosmochim. Acta

Viscosity of crystal-free lavas across the Solar System

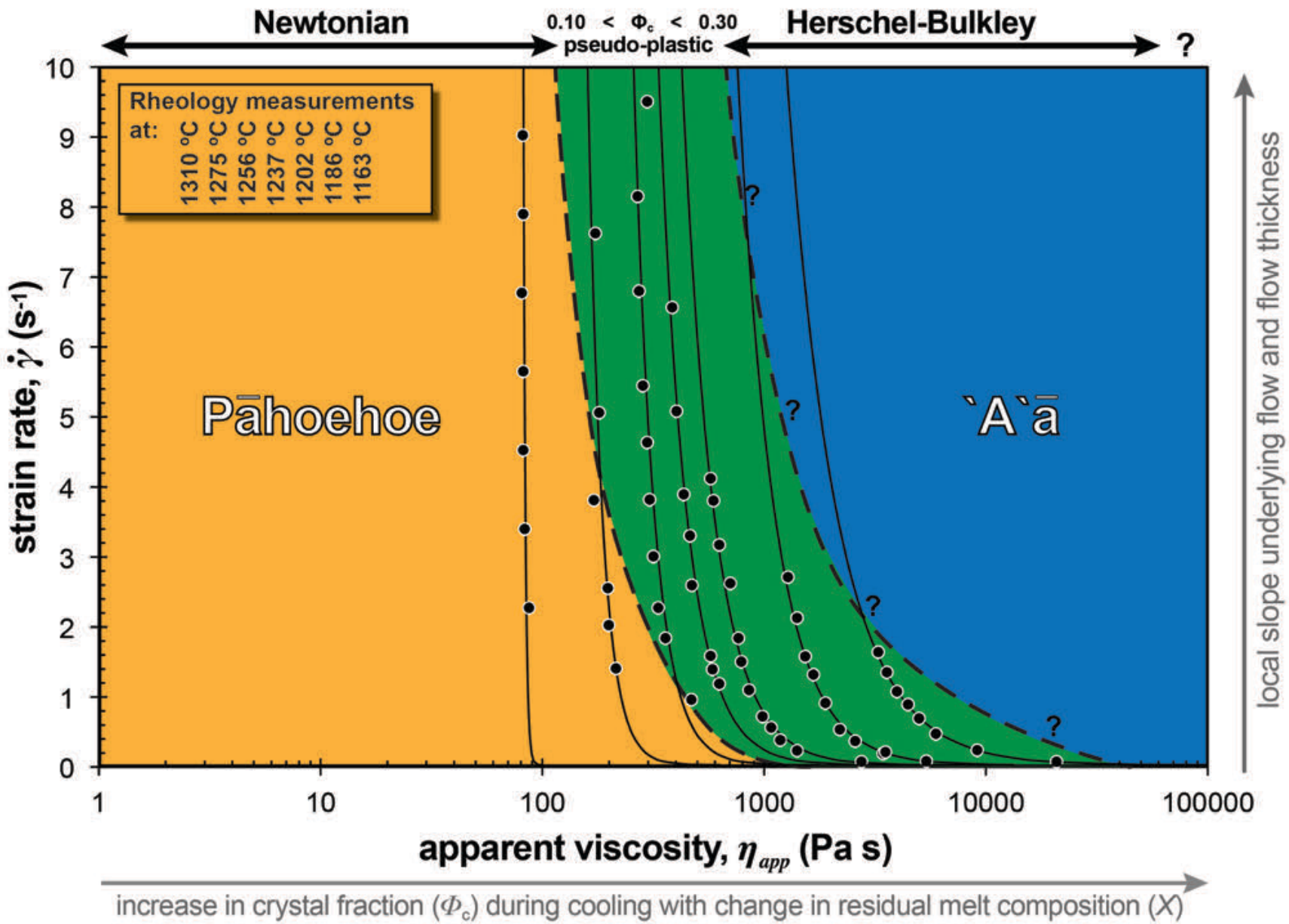


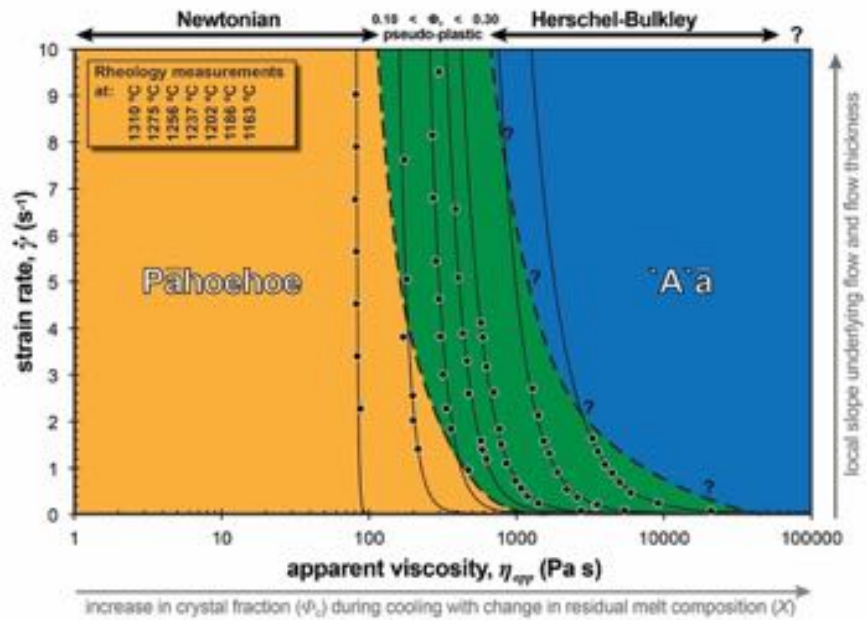


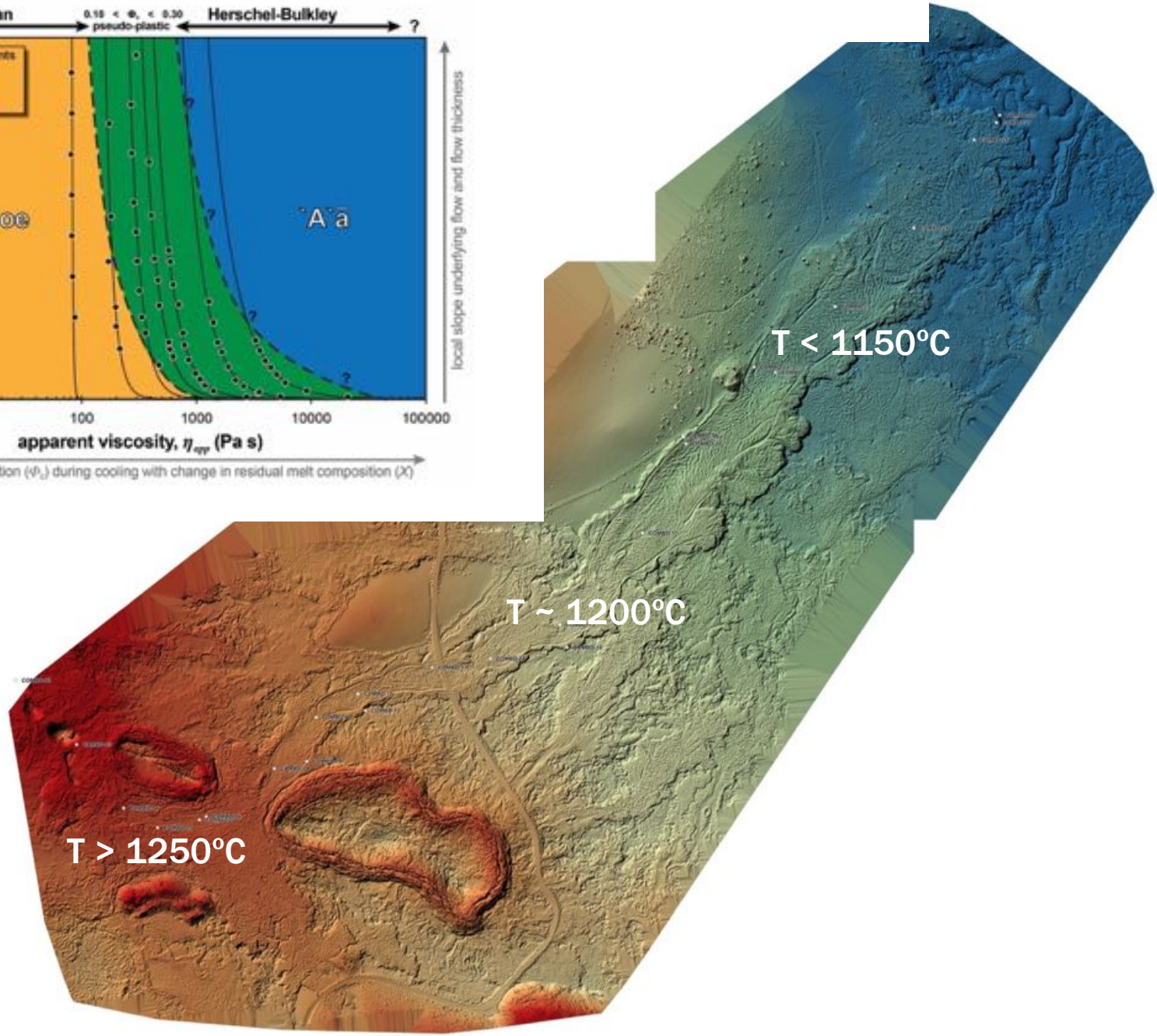
- **Crystal-free lavas = Melts**
- **Newtonian fluids**

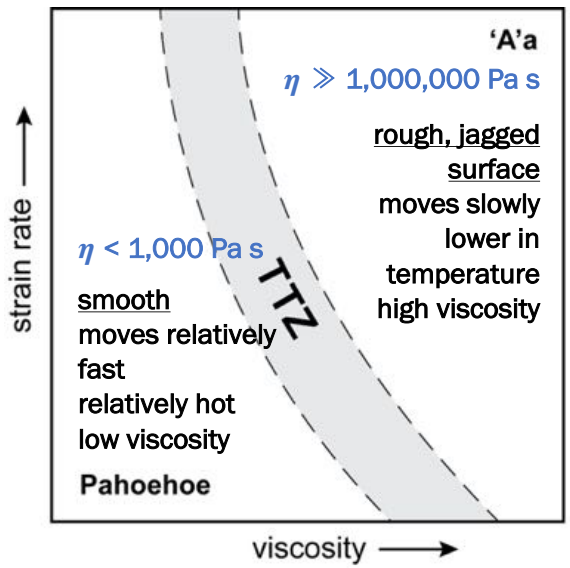


Sehlke and Whittington (2016). Geochim. Cosmochim. Acta


Newtonian
0.10 < Φc < 0.30
pseudo-plastic
Herschel-Bulkley
?
Rheology measurements
at:
1310 °C
1275 °C
1256 °C
1237 °C
1202 °C
1186 °C
1163 °C
Pāhoehoe
`A`ā
strain rate, γ̇ (s-1)
apparent viscosity, ηapp (Pa s)
local slope underlying flow and flow thickness
increase in crystal fraction (Φc) during cooling with change in residual melt composition (X)


Newtonian
0.10 < Φc < 0.30
pseudo-plastic
Herschel-Bulkley
?
Rheology measurements
at: 1310 °C 1275 °C 1256 °C 1237 °C 1202 °C 1186 °C 1163 °C
Pāhoehoe
ʻAʻa
strain rate, γ̇ (s⁻¹)
apparent viscosity, η_app (Pa s)
local slope underlying flow and flow thickness
increase in crystal fraction (Φc) during cooling with change in residual melt composition (X)


T < 1150°C
T ~ 1200°C
T > 1250°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