# *Lava Flows*

Einat Lev
Columbia University

CIDER 2019

# This talk will cover:

- Why study lava flows?
- How lava flows are currently observed?
- How lava flows are currently modeled?
- What do we still need to learn about lava flows?

# Why study lava flows?

- Hazard
- Long-term record of eruption history
- Environmental impacts (not covered here)

# Lava flows as a natural hazard

Kīlauea 2018


Before
Copyright 2014 DigitalGlobe
NextView License


After
0
0.4 Miles
Image ©2018 Planet Labs, Inc., cc-by-sa 4.0


Before
Copyright 2014 DigitalGlobe
NextView License


After
0
0.3 Miles
Image ©2018 Planet Labs, Inc., cc-by-sa 4.0

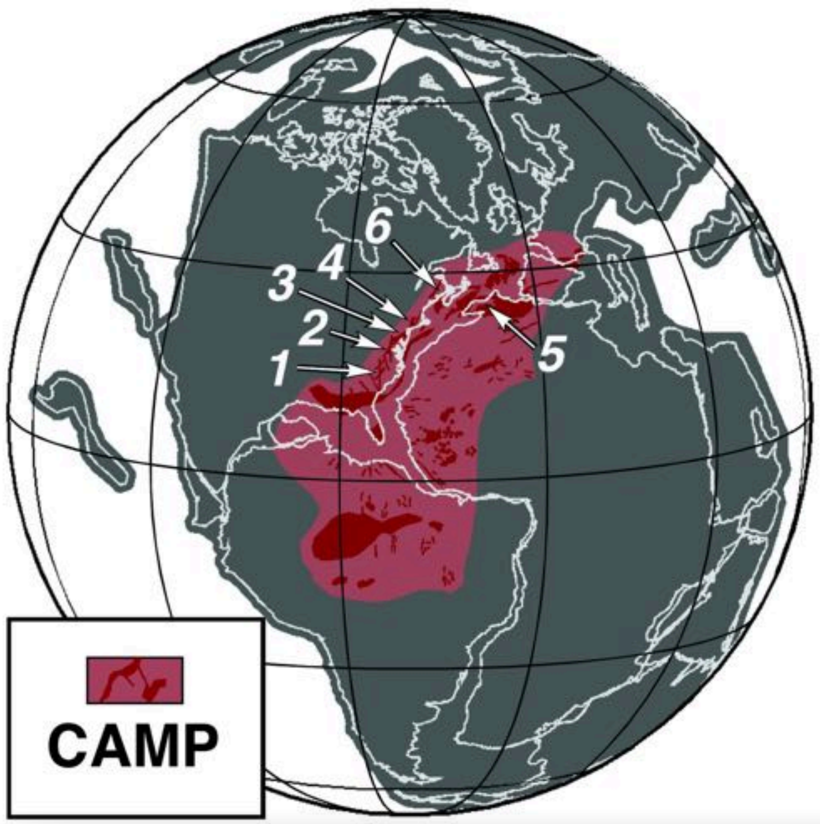
# Damage to utilities

Puna Geothermal Venture power plant during the 2018 Kilauea eruption

Protecting power poles in Pahoa, 2014

# Pico do Fogo, 2014-2015

# Lava flows as a record of eruption conditions





**OMB2:**
**Pillows.**
**Subaqueous**

**OMB1:**
**Pahoehoe tows,**
**cooling joints.**
**Subaerial**

Blackburn et al., 2013; Puffer et al., 2018

# Lava flows as a record of eruption conditions

Pillow lavas, Columbia River flood basalt
Lake Roosevelt National Recreation Area

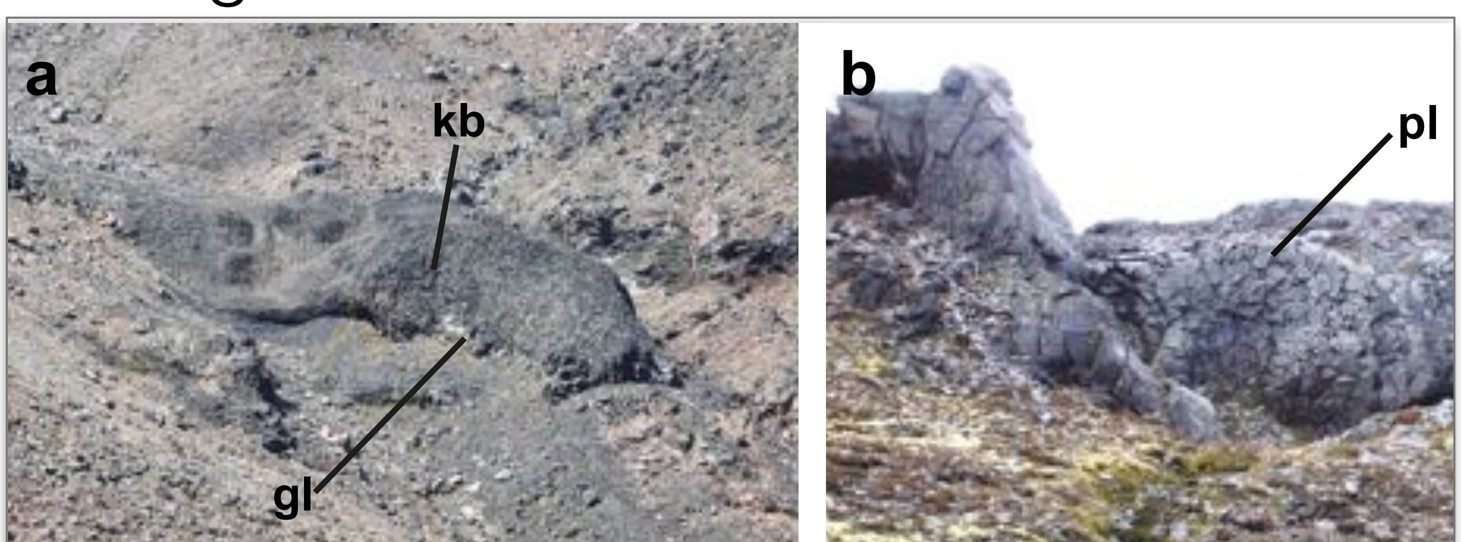
**Photo: Callan Bentley**

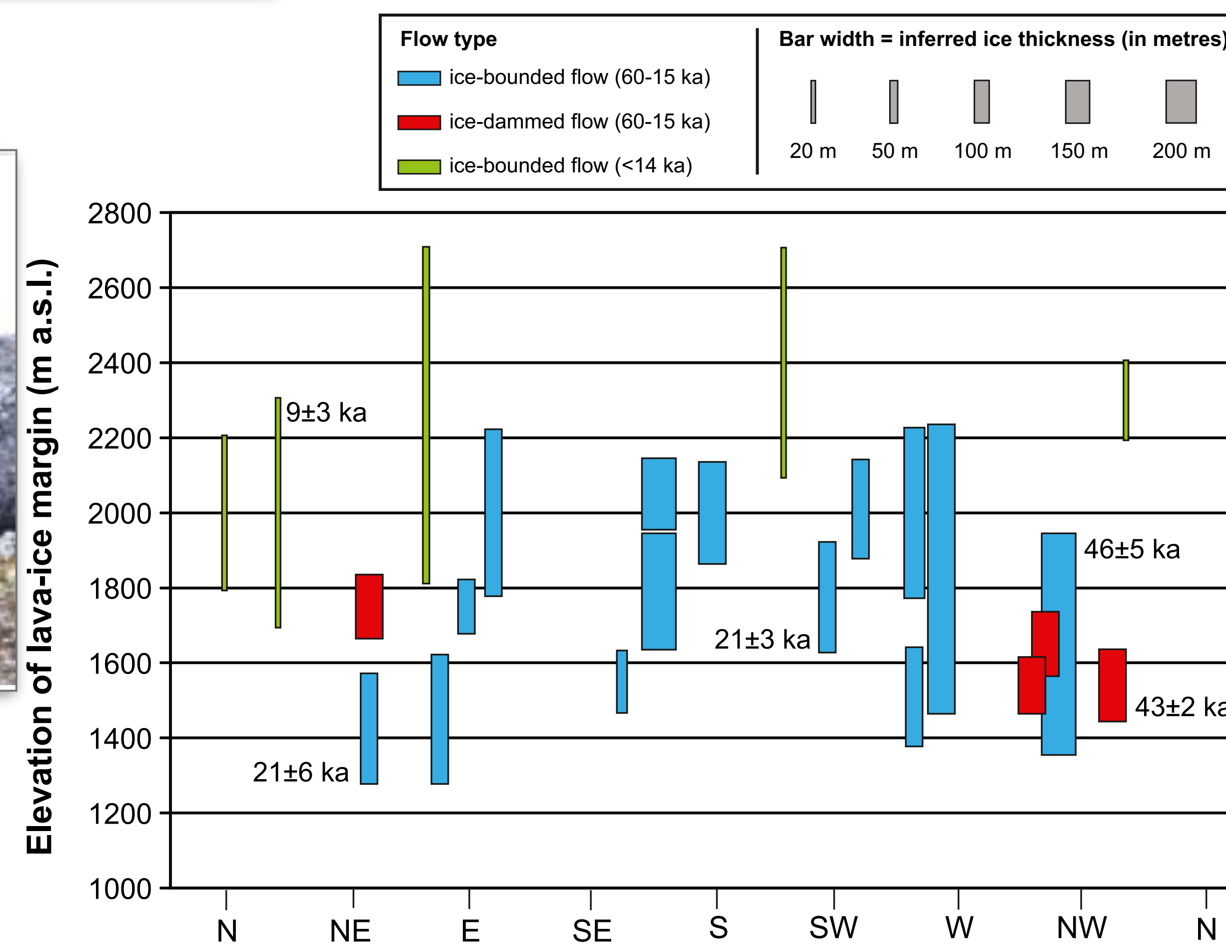
# Lava flows as a record of eruption conditions

## Ice-bounded flow



## Sub-glacial flows



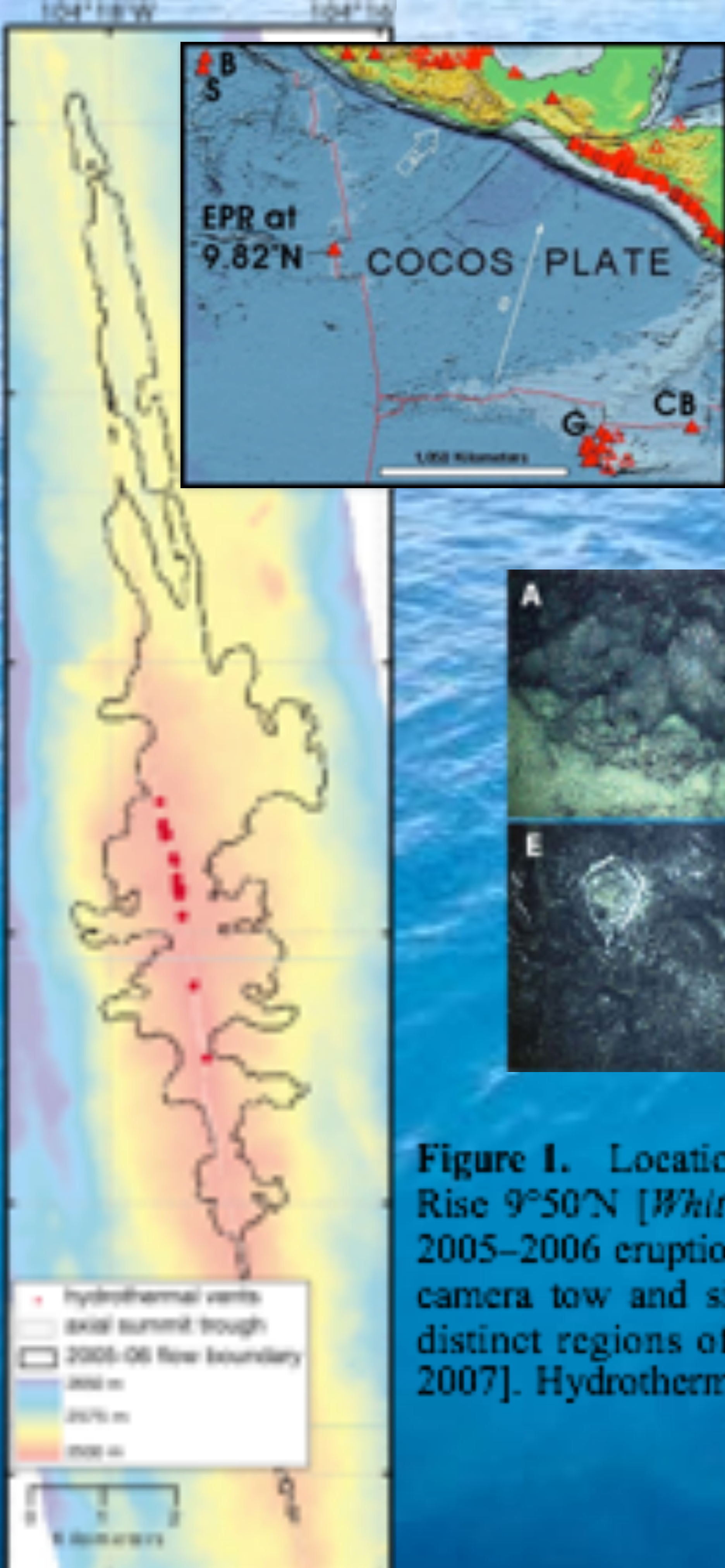




**Conway et al., 2015**

*"Lava flows are the single most common feature on the surfaces of the terrestrial planets. They cover 90% of Venus, 50% of Mars, at least 20% of the Moon, and some 70% of the Earth"*

*Encyclopedia of Volcanoes*

# Building the ocean floor



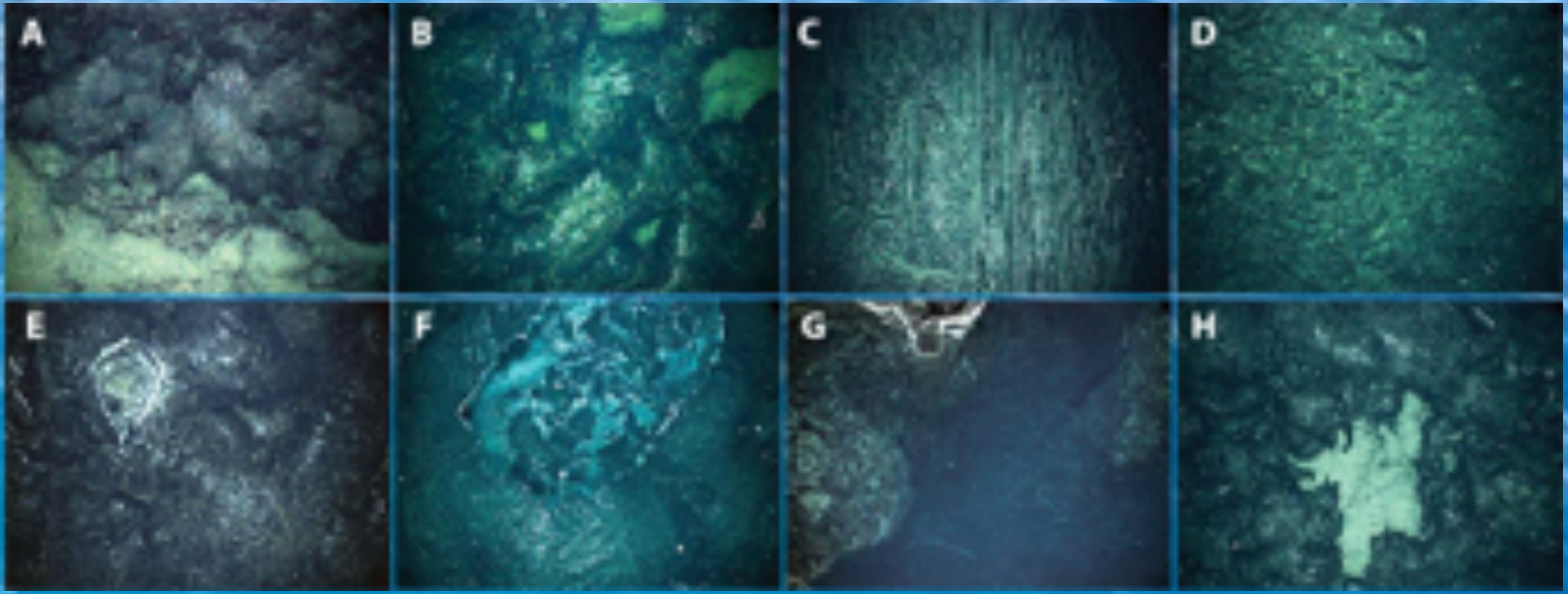
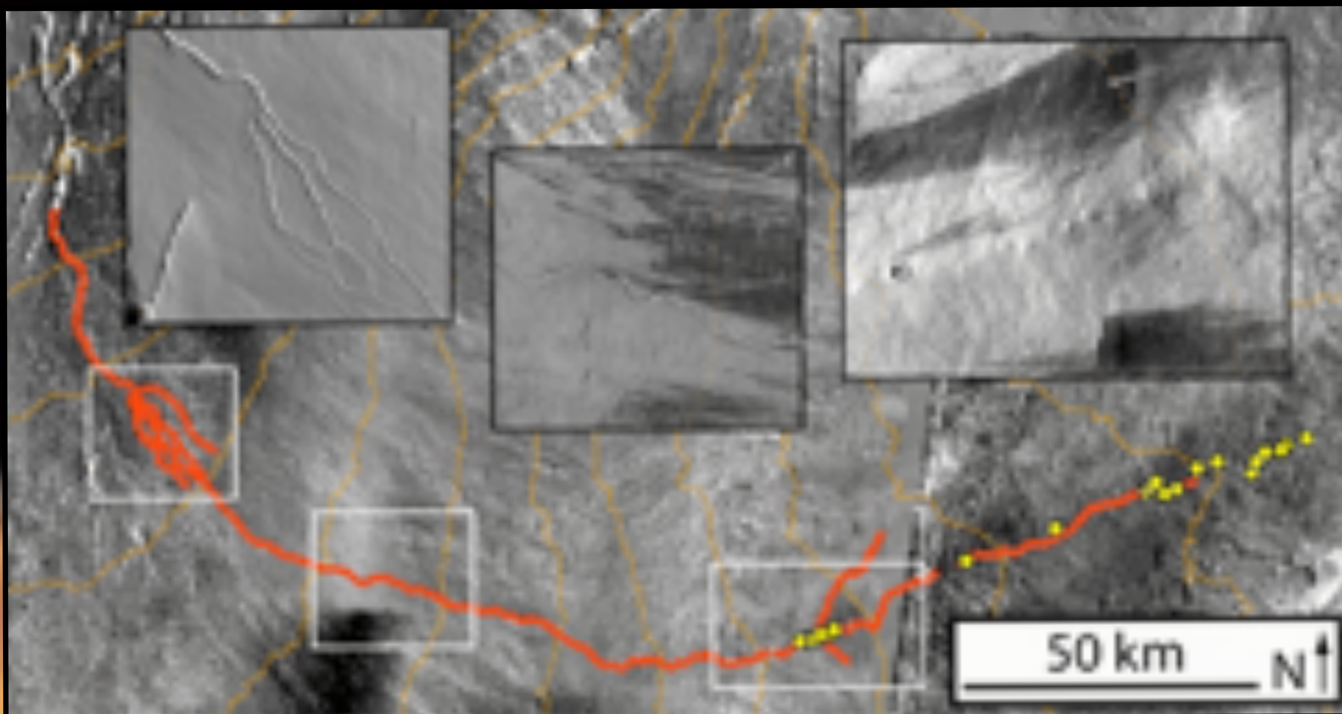



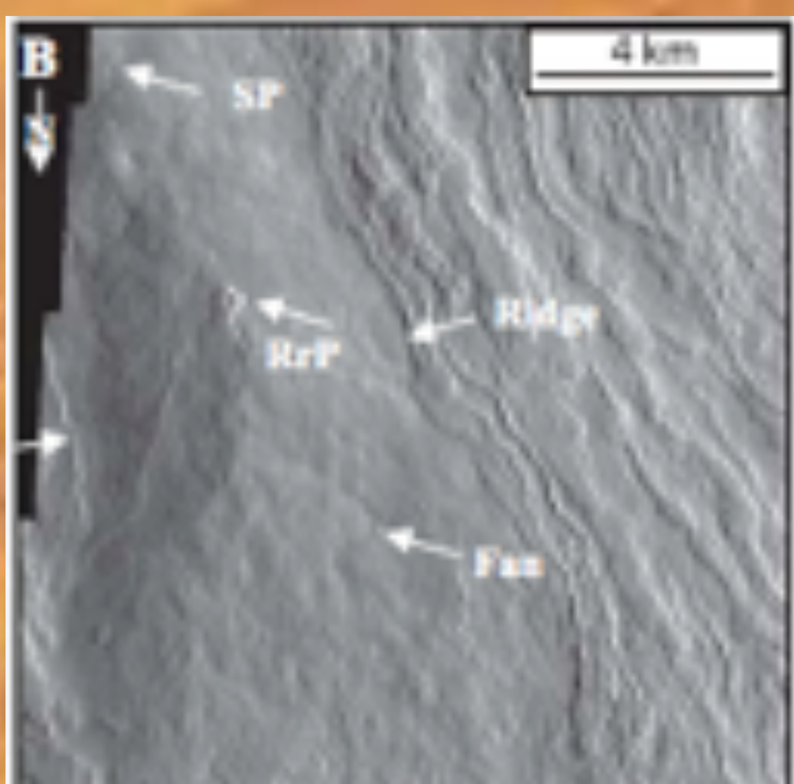

**Figure 1.** Location and bathymetry of the East Pacific Rise 9°50′N [*White et al.*, 2006]. Area covered by the 2005–2006 eruptions is outlined in black (derived from camera tow and side scan imagery data) and the four distinct regions of the flow are defined [*Soule et al.*, 2007]. Hydrothermal vents are marked by red dots.

Fundis et al G3 2010

# on Mars ...




Debated channel at Ascraeus Mons (HiRISE, NASA)




Themis VIS image showing an Olympus Mons lava tube with several rimless depressions that are sinuously aligned (SP) along the axis of a raised ridge (Ridge). A raised rim pit (RrP) also is located at the apex of a lava fan (Fan). (Bleacher et al., LPSC 2011)

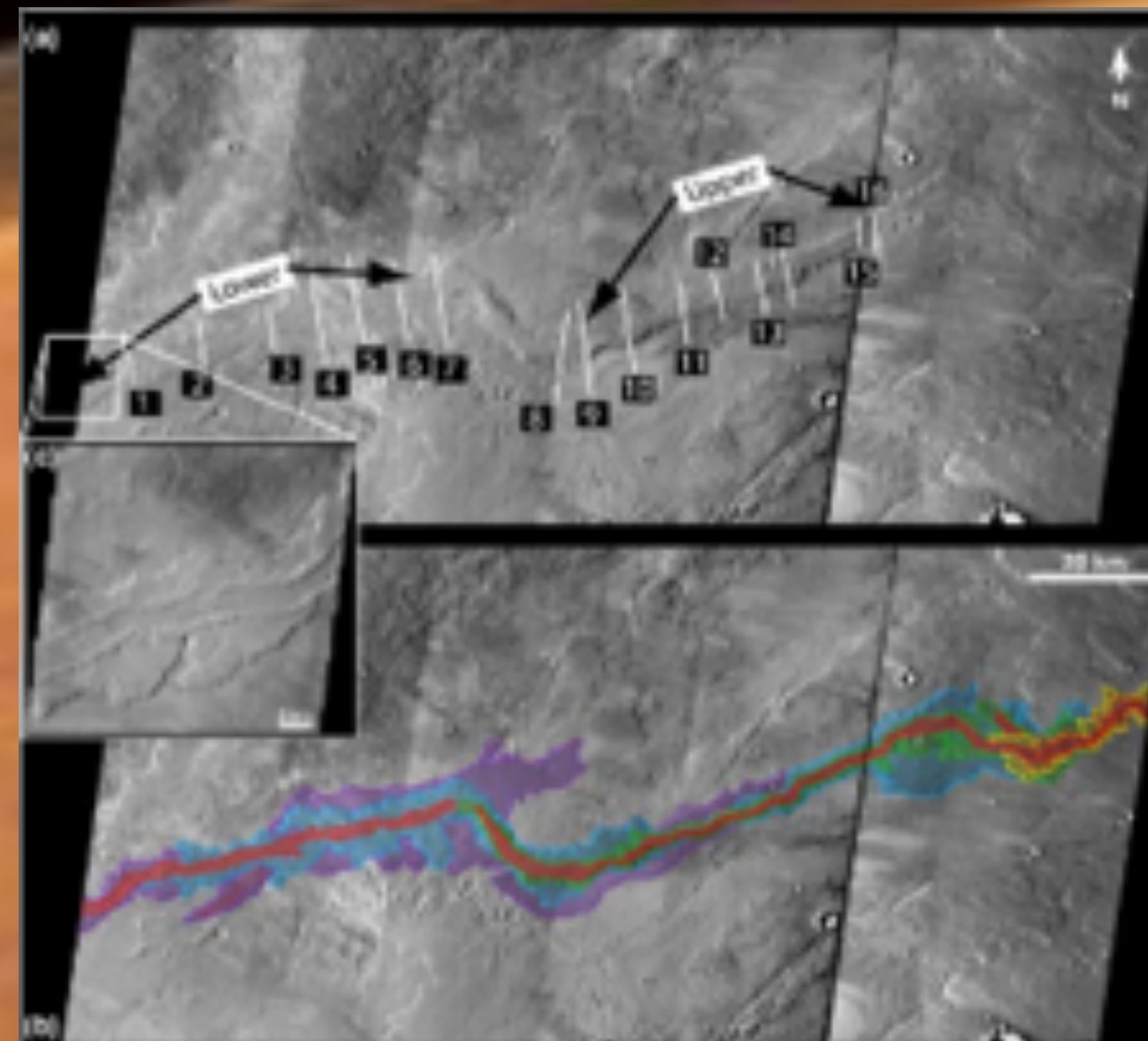
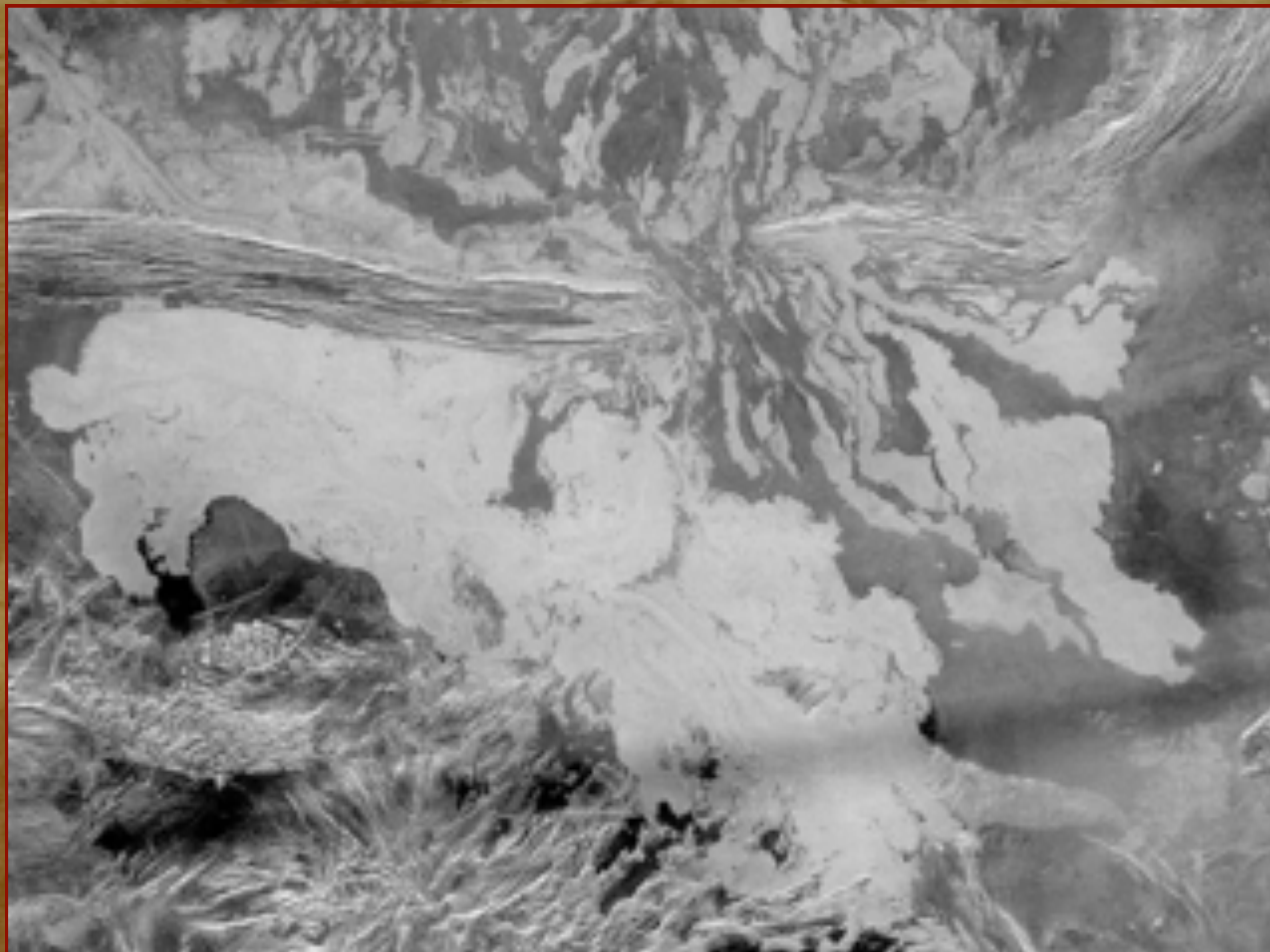



**Figure 1.** (a) Mosaic of Thermal Emission Imaging System (THEMIS) daytime infrared images (100 m pixel$^{-1}$) showing a 189 km long segment of a lava flow (flow 3 in Table 1 and Figure 7) in the Tharsis plains southwest of Alba Patera. Flow direction is from east to west (right to left). Cross-flow profile locations (white lines) and corresponding numbers refer to detailed measurement locations in Tables 4 and 5. (b) Coloration depicts central channel (red) and several generations of levees ranging in approximate order of youngest to oldest from orange, yellow, green, blue, and purple. (c) Inset is THEMIS Visible image V12686014 (37 m pixel$^{-1}$) showing detail of channel and levees.

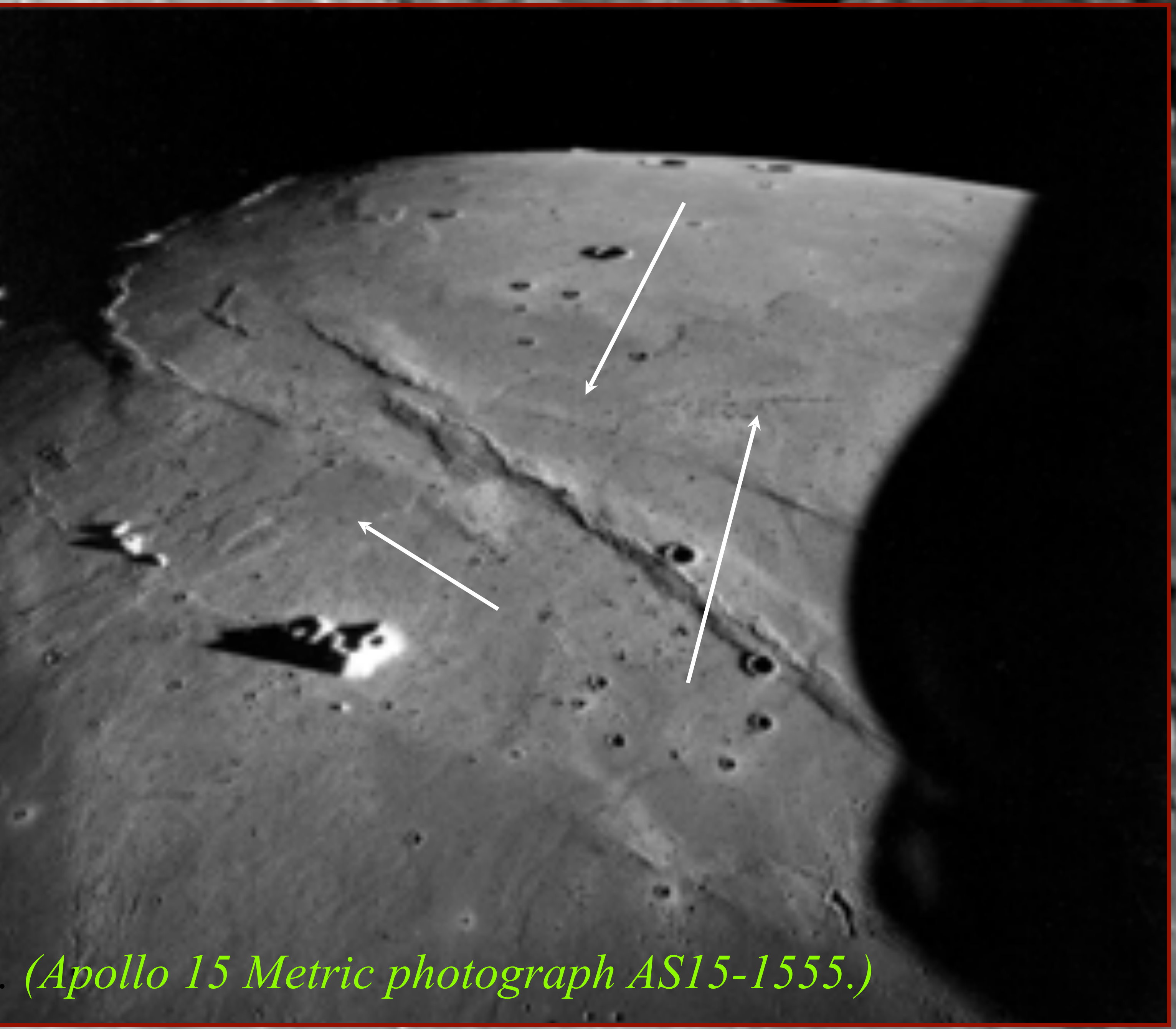
Glaze et al., 2009

# and Venus...



NASA's Magellan project

# On our moon

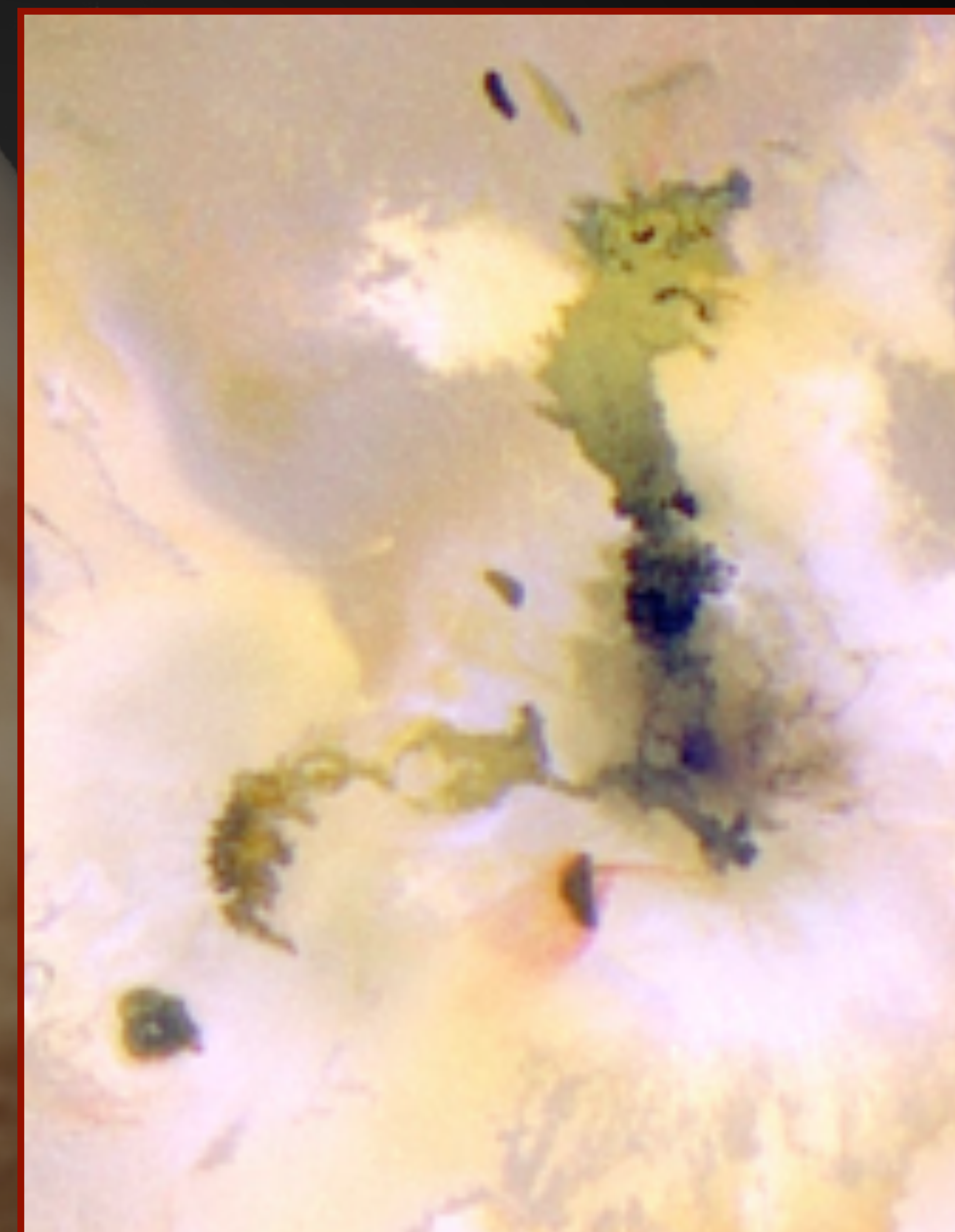


(Apollo 15 Metric photograph AS15-1555.)

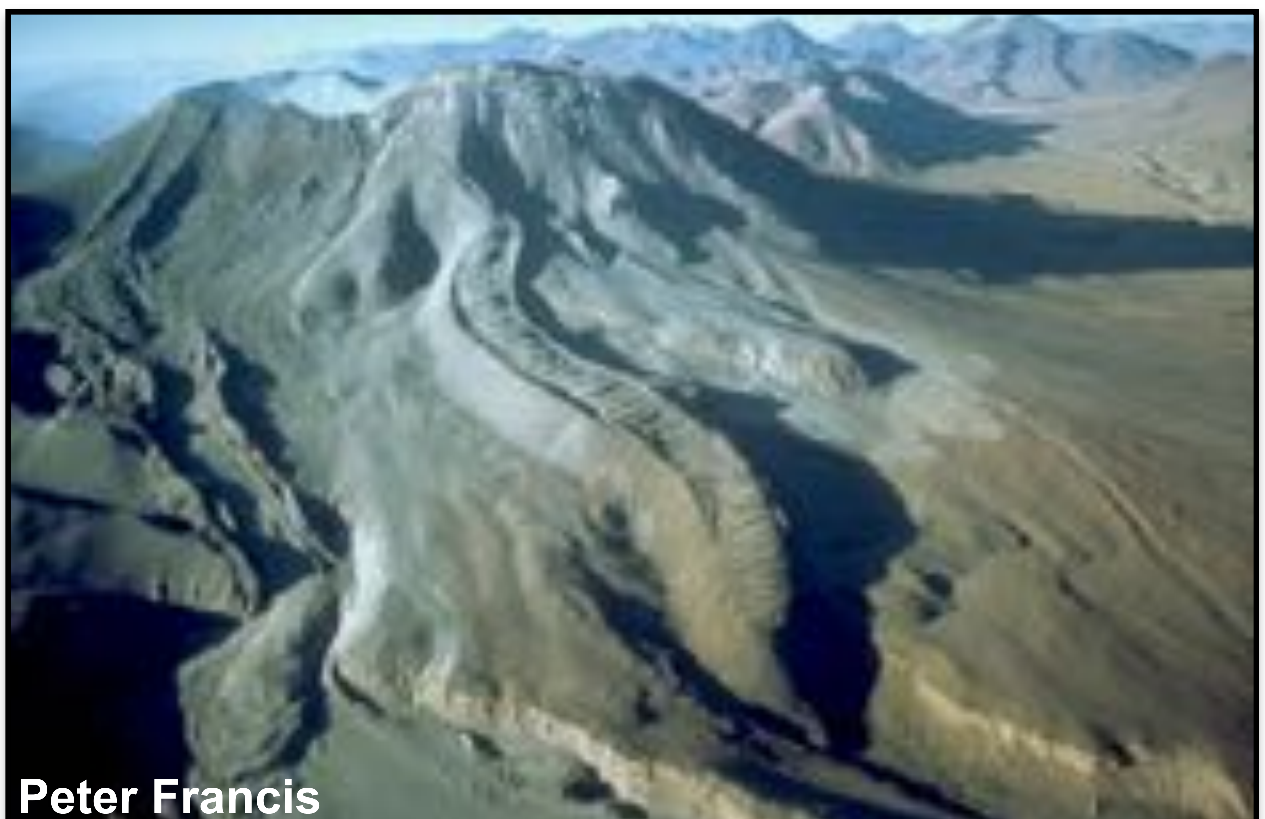

Zimbelman 2008

# on Jupiter's moon Io

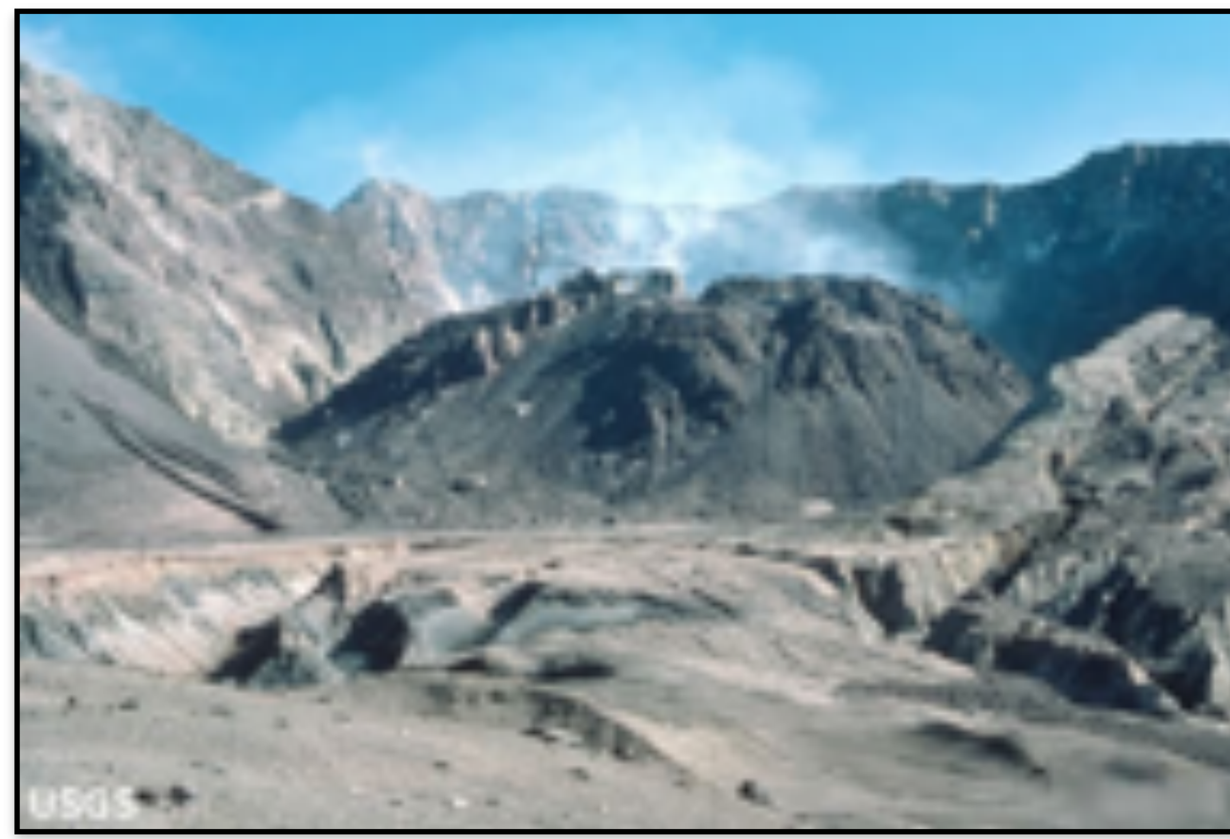
**Amirani-Maui: longest currently-active lava flow in the solar system, at 250 km**
**Picture taken by NASA's Galileo mission**



Basaltic flow, Kīlauea, Hawai`i



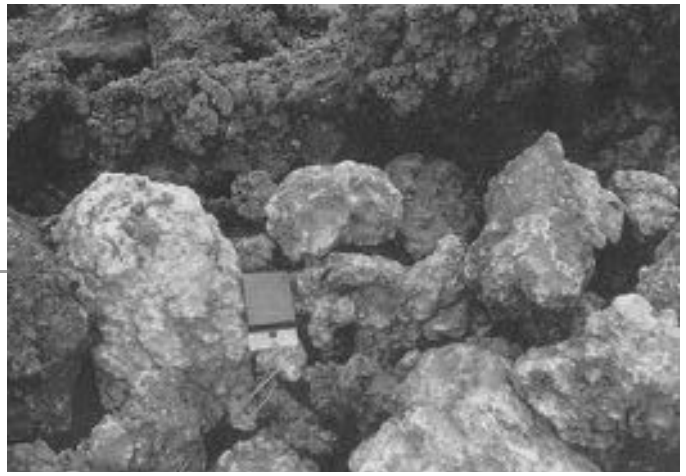

Andesite flow, Lascar, Chile




Dacite lava dome
Mt. St. Helens, USA

# Types of lava surfaces

| Feature | Description |
|---|---|
| 1. Aa Lava | Surface is covered by a jumble of irregular crustal fragments. |
| Cauliflower | Crust twists upwards as cauliflower-like protrusions. These break to give fragments up to decimetres across. Surfaces are grey-black, often glassy, and rough and spinose at the millimetre scale. |
| Rubbly | Crust fractures downwards to yield rounded rubble up to metres across, often with an ochre-black granular surface, millimetres deep |
| 2. Blocky Lava | Surface is covered by broken lava, containing fragments up to metres across with smooth, planar, and angular surfaces. |
| 3. Pahoehoe Lava | Surface is smooth and continuous, often with a millimetre-scale texture of interweaved lava threads or filaments. |
| Entrail | Dribbles of lava yield convoluted surfaces reminiscent of entrails. |
| Ropy (or corded) | Flexible crusts ruck into tight folds before chilling. Surface resembles segment of coiled rope. Each "rope" can be centimetres thick. |
| Shelly | Highly vesicular, fragile crusts. Often associated with skins, centimetres thick, over hollow lava blisters. The skins break underfoot, giving the impression of walking on egg shells. |
| Slabby (sometimes slab aa) | Slabs of broken crust, up to metres across and centimetres thick. |
| 4. Toothpaste Lava | Protrusions of viscous lava squeezed through gaps in flow crust. They may be tens of metres long and their cross-sections often mimic the shape of the source gap, like toothpaste emerging from its container. |



Kilburn, 2000

# Some questions people ask about lava flows

1. Short-term forecasting:

   *Where will this lava go?*

   *How quickly will it get there?*

2. Hazard assessment and planning:

   *Where will some future lava go?*

3. Deposit interpretation:

   *How fast was this lava erupting?*

   *What was this lava like?*


4. Insight into processes:

   *How can deposit characteristics be inverted to constrain eruption processes?*

# What controls lava flow emplacement?

$$w = 2\left[\frac{(g\Delta\rho)^2 Q^7 \eta^4 \cos^9\theta}{\sigma_c^6 \kappa^3 \sin^7\theta}\right]^{1/13}$$

flux

flow width

gravity

density

viscosity

slope

yield strength

thermal diffusivity

One form out of many…

Kerr et al., 2006

# What controls lava flow emplacement?

$$w = 2\left[\frac{(g\Delta\rho)^2 Q^7 \eta^4 \cos^9\theta}{\sigma_c^6 \kappa^3 \sin^7\theta}\right]^{1/13}$$

- flow width ($w$)
- gravity ($g$)
- density ($\Delta\rho$)
- flux (speed x cross-section area) ($Q$)
- viscosity ($\eta$)
- slope ($\theta$)
- yield strength ($\sigma_c$)
- thermal diffusivity ($\kappa$)

One form out of many…

Kerr et al., 2006

# How are lava flows currently observed?

What kind of observations do we want to make?

- Topography
- Morphology
- Volume

- Speed / flux

- Temperature

- Rheology

… and how all of these change over time and space

# How lava flows are currently observed?

What kind of observations do we want to make?

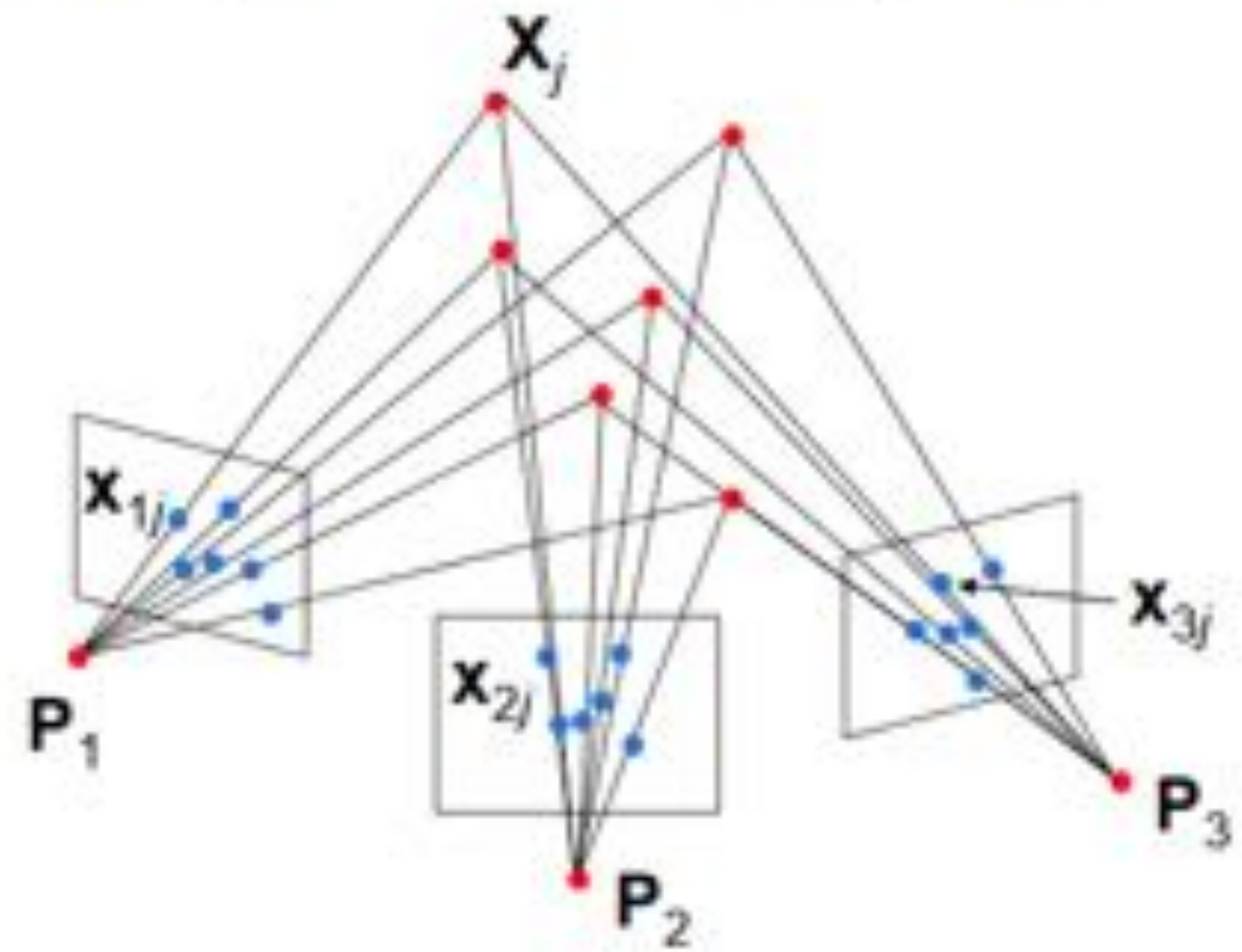
| | |
| --- | --- |
| Topography<br>Morphology<br>Volume | Ground and airborne photogrammetry<br>LiDAR<br>Radar (SAR, InSAR)<br>Satellite-derived DEMs |
| Speed / flux | Areal mapping, Front tracking<br>Velocimetry |
| Temperature | Thermal cameras and probes |
| Rheology | In-situ viscometry<br>Kinematics |

# Topography from Photogrammetry

- Given: *m* images of *n* fixed 3D points

$$\mathbf{x}_{ij} = \mathbf{P}_i \mathbf{X}_j, \quad i = 1, \ldots, m, \quad j = 1, \ldots, n$$

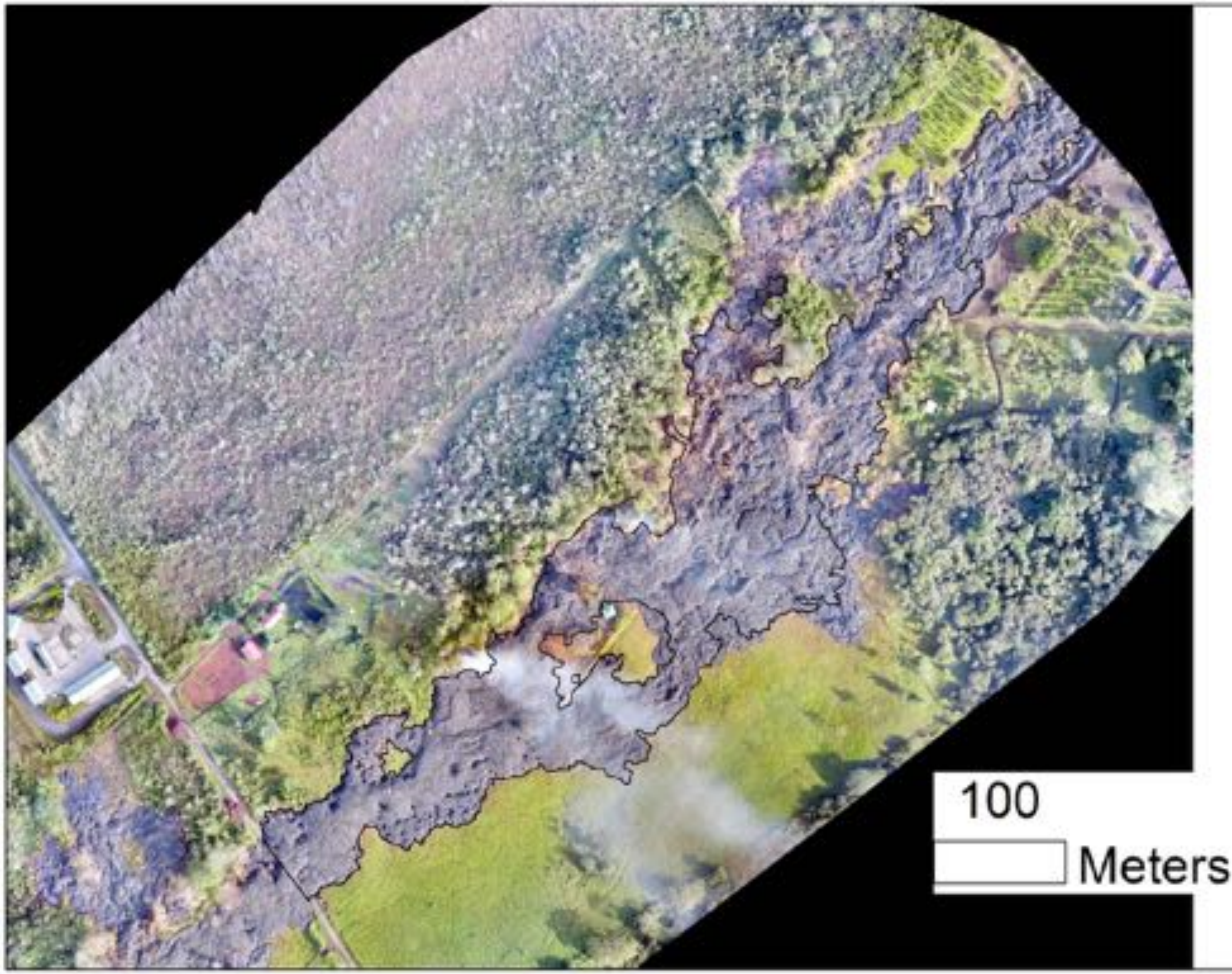
- Problem: estimate *m* projection matrices $\mathbf{P}_i$ and *n* 3D points $\mathbf{X}_j$ from the *mn* correspondences $\mathbf{x}_{ij}$




Slide: S. Lazebnik

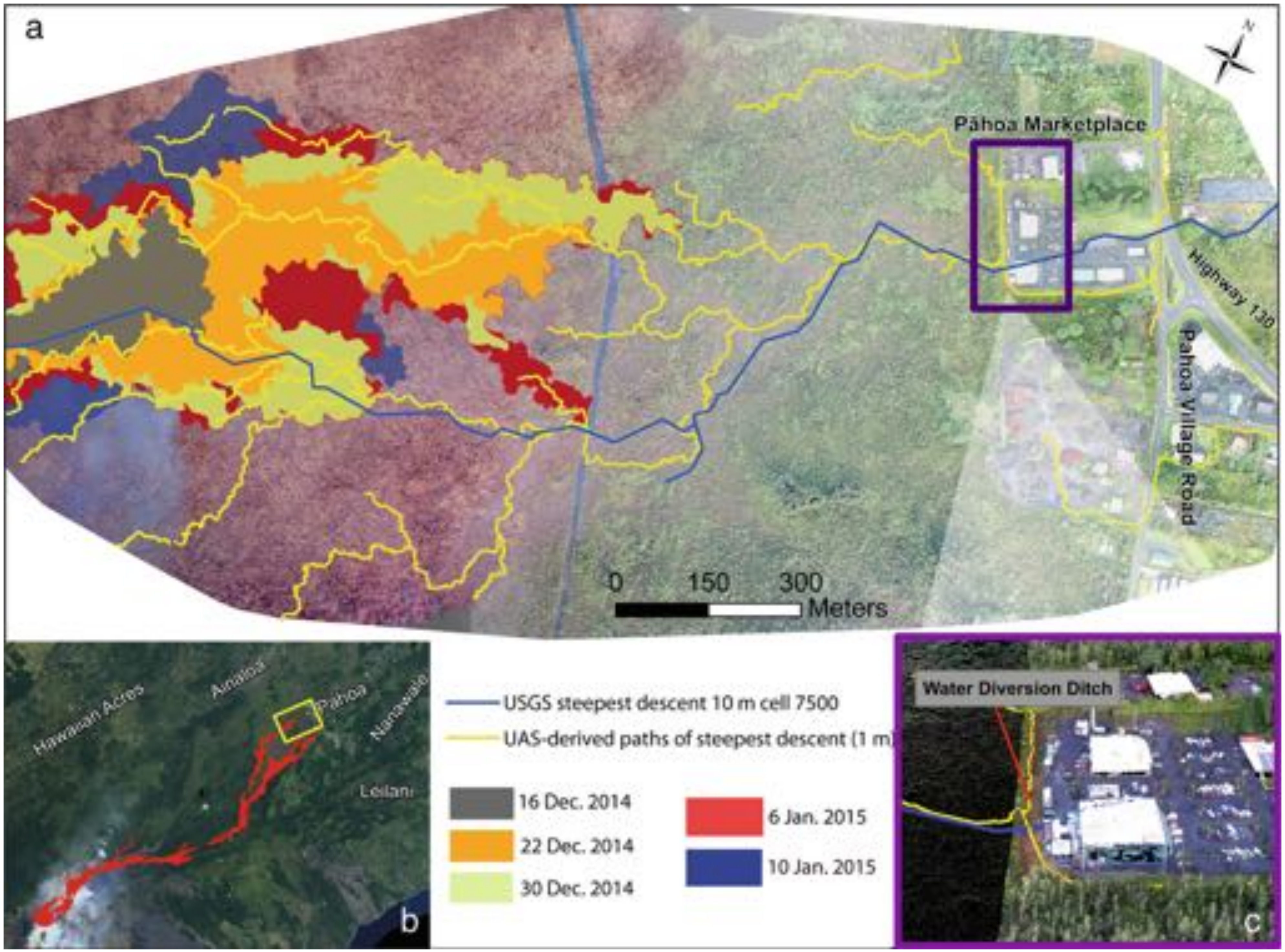
Ryan Perroy, UH-Hilo, mapping the 2014 Pahoa flows

# High resolution mosaic and DEM



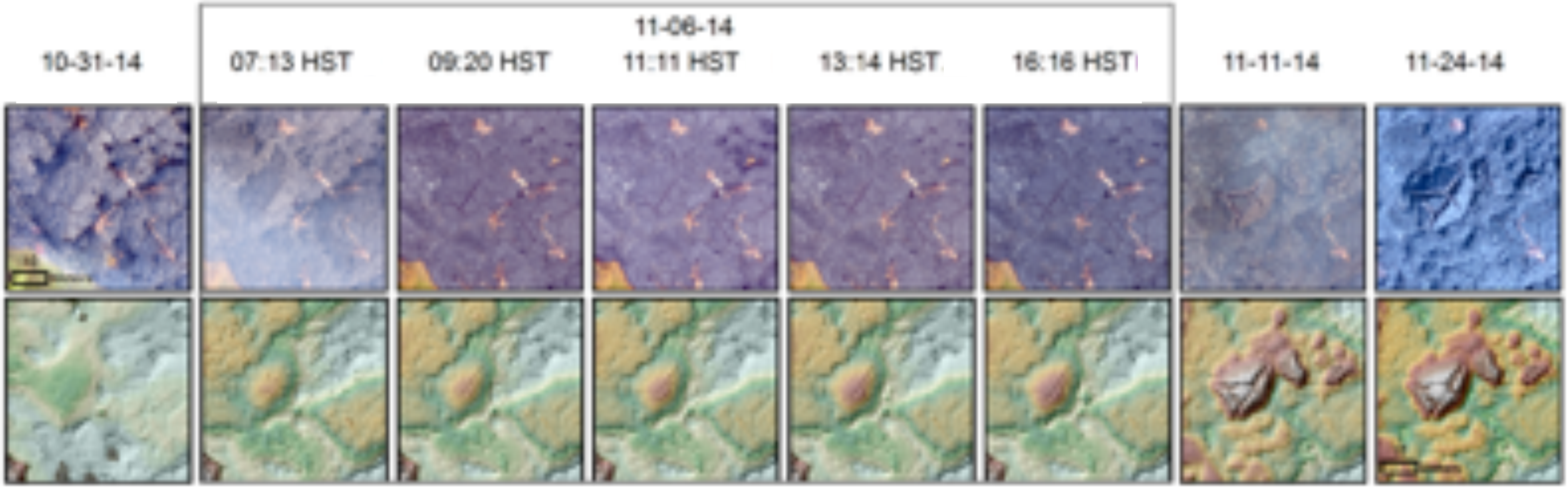

Ryan Perrot (UH-Hilo), Nick Turner (UH-Manoa), USGS

# Flow routing forecasting



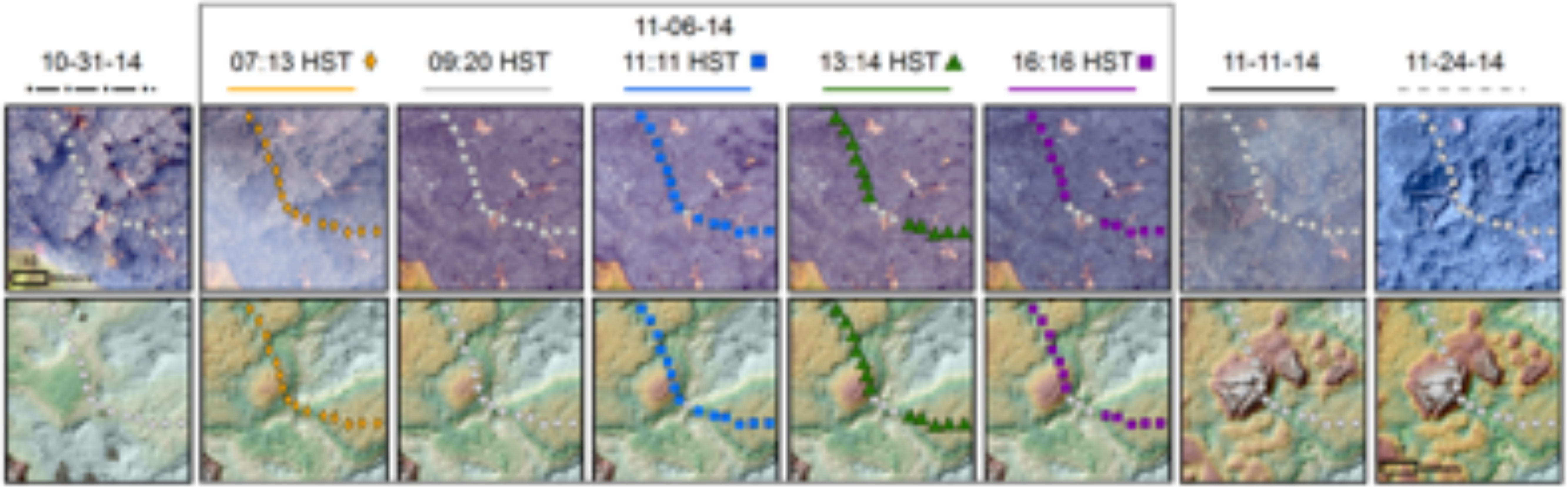

Turner et al., 2017

# Topographic change and flow inflation

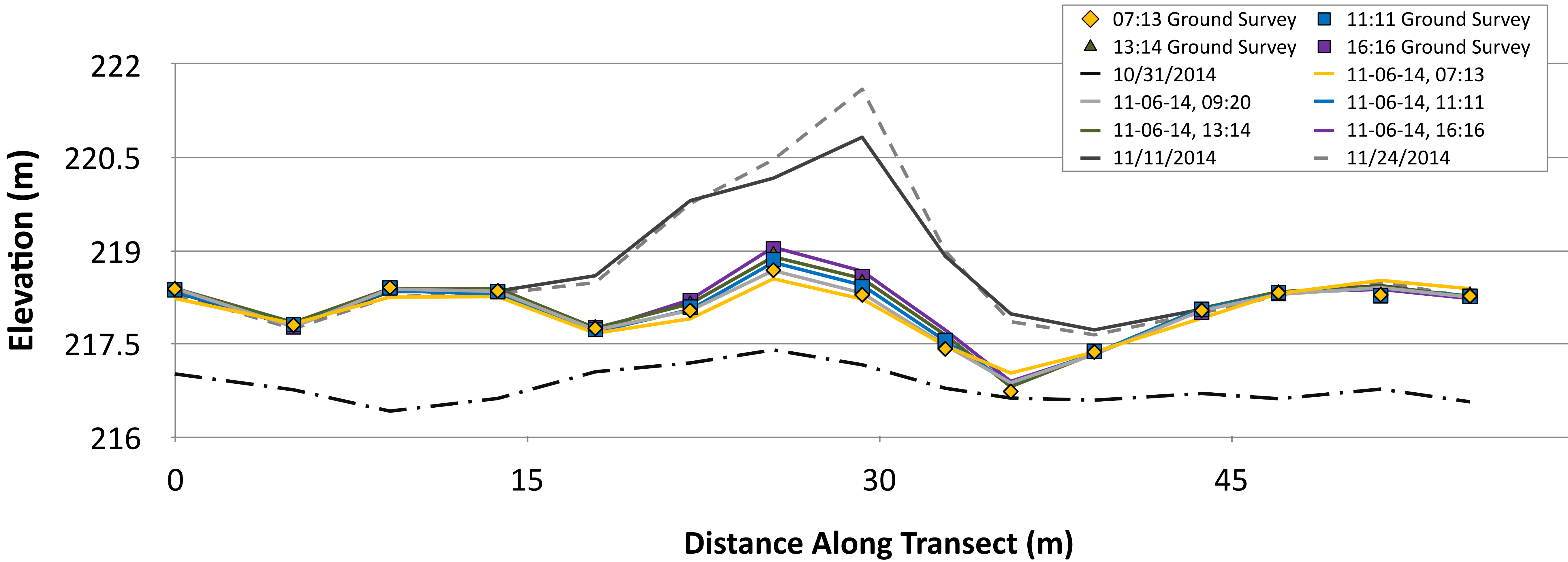


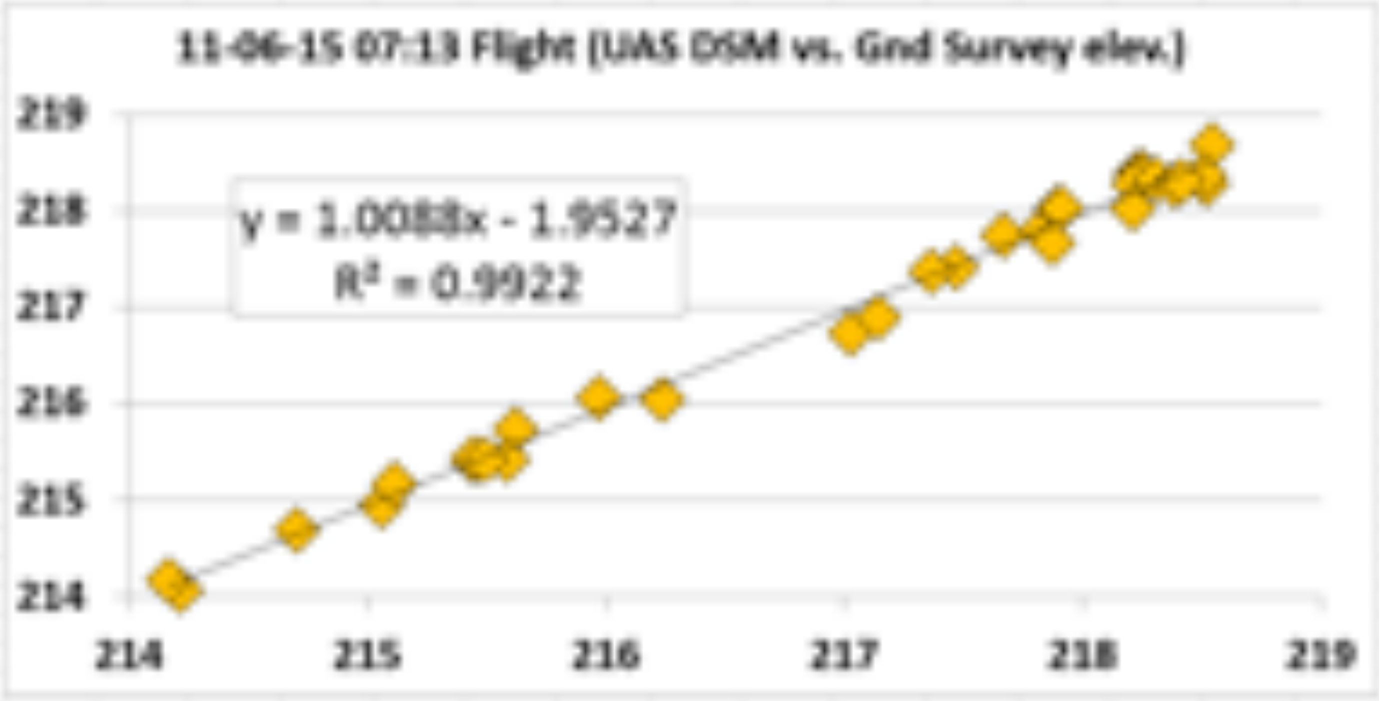

Ryan Perrot (UH-Hilo), Nick Turner (UH-Manoa), USGS

# Topographic change and flow inflation




Ryan Perrot (UH-Hilo), Nick Turner (UH-Manoa), USGS



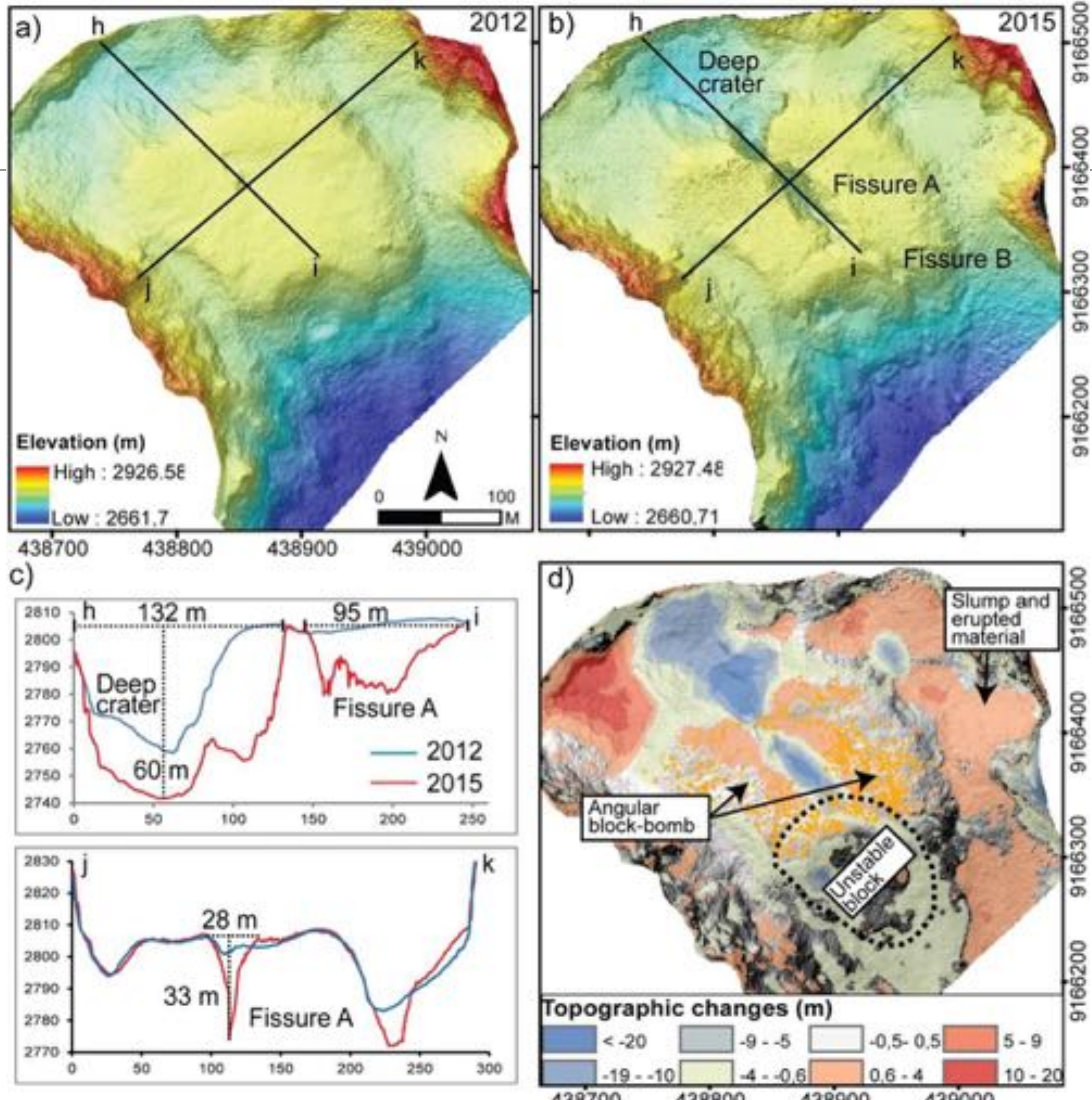




Ryan Perrot (UH-Hilo), Nick Turner (UH-Manoa), USGS

2012 2015

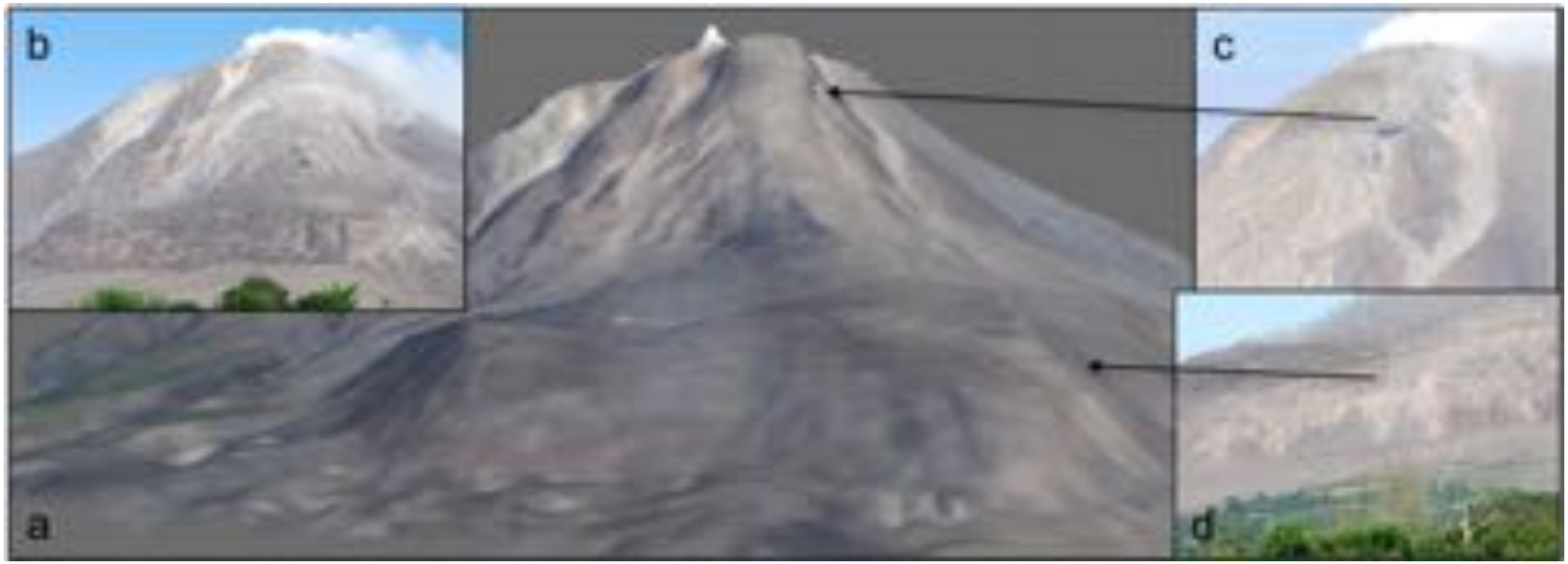
Merapi (Indonesia)

Surveyed using sUAS




**Darmawan et al., 2018**

# Topographic change

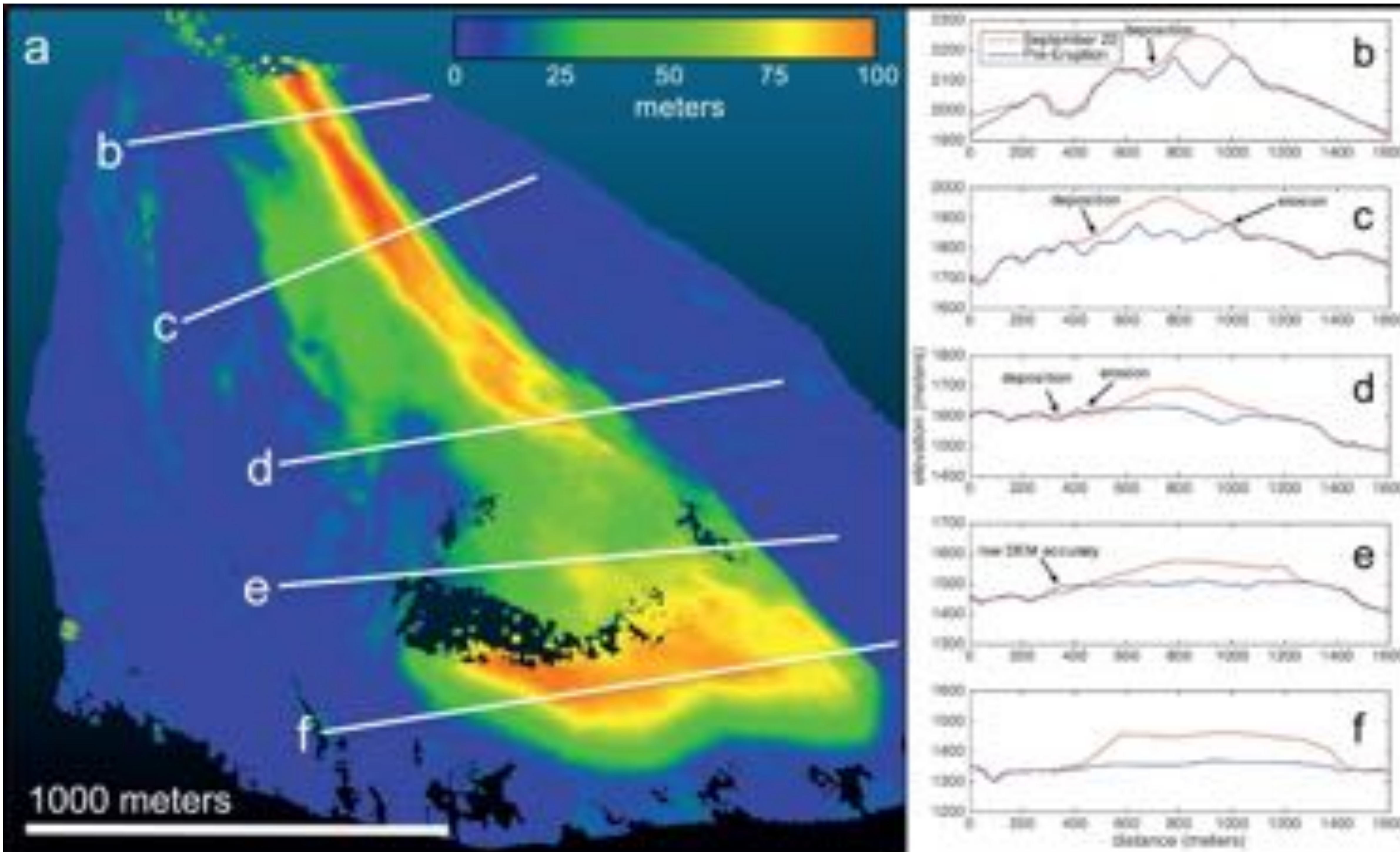



Sinabung (Indonesia)

Ground-based camera, detecting change from 2010 to 2014

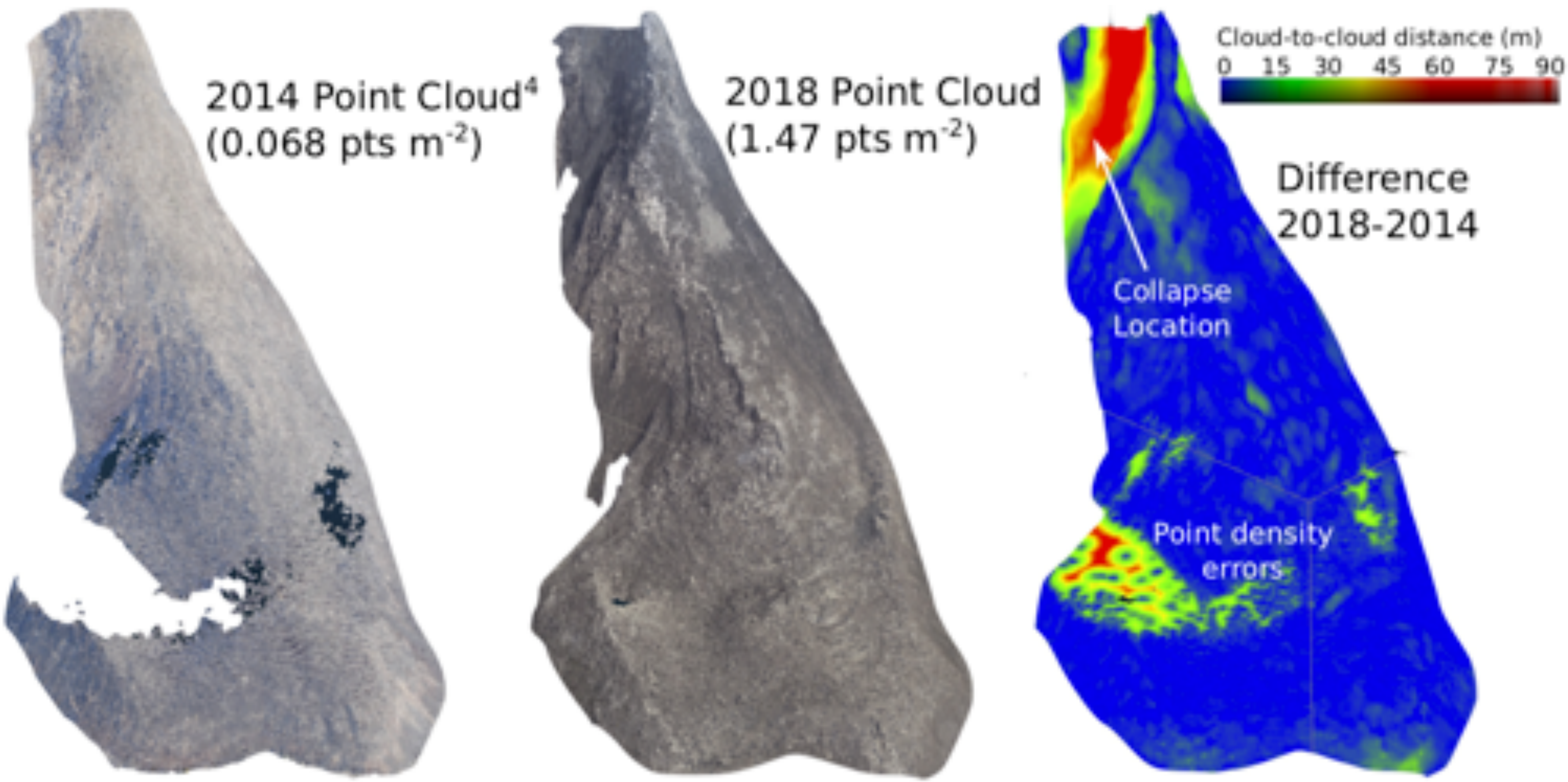
**Carr et al., 2018**

# Topographic change — flow emplacement




Carr et al., 2018

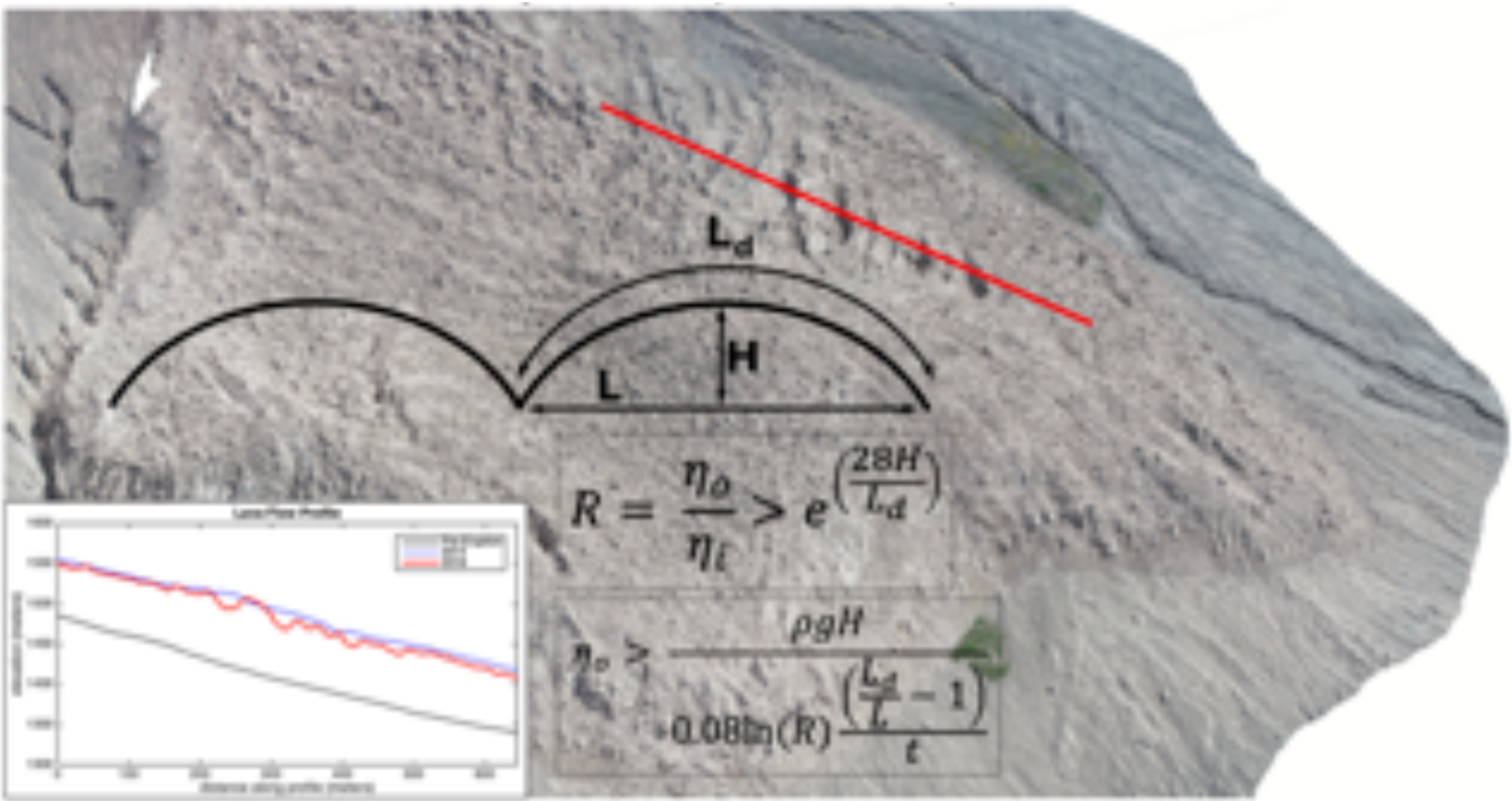
# Topographic change — flow/dome collapse




Collapse Volume: $0.15 \times 10^8$ $m^3$

Carr and Lev, in prep

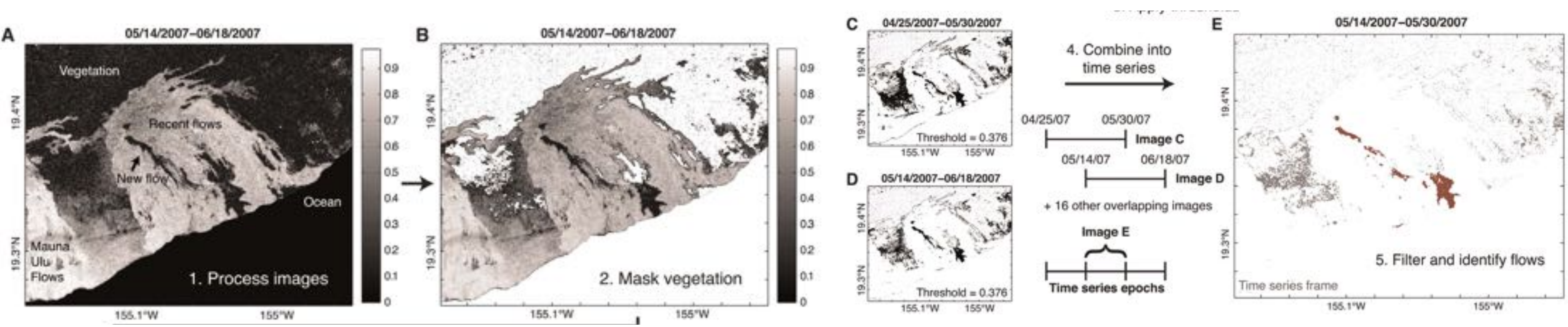
# Emplacement conditions from flow topography

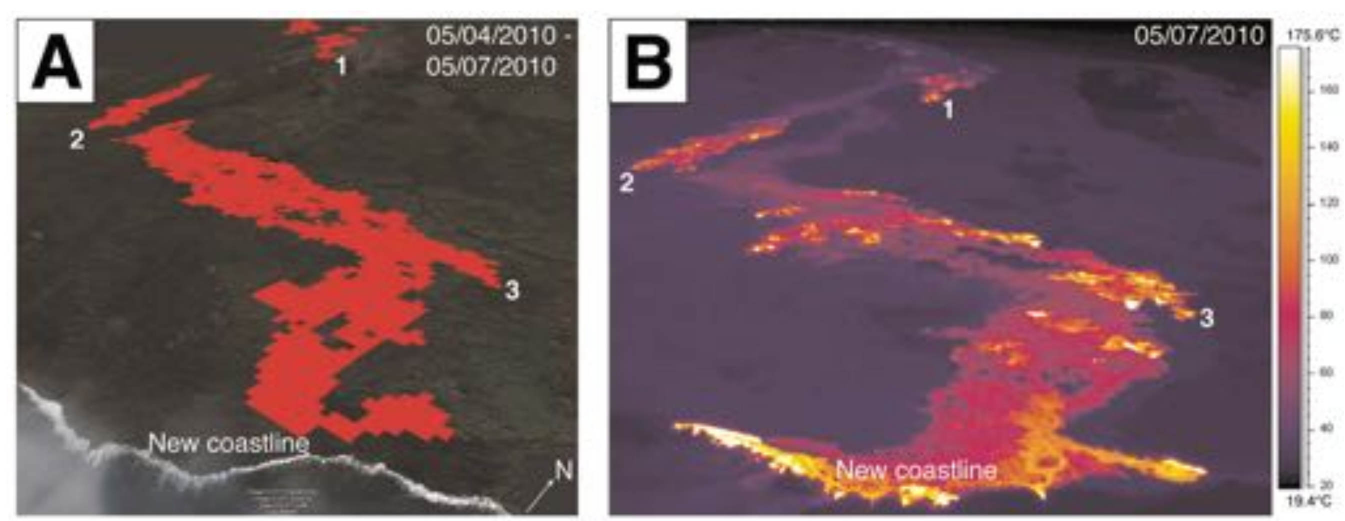


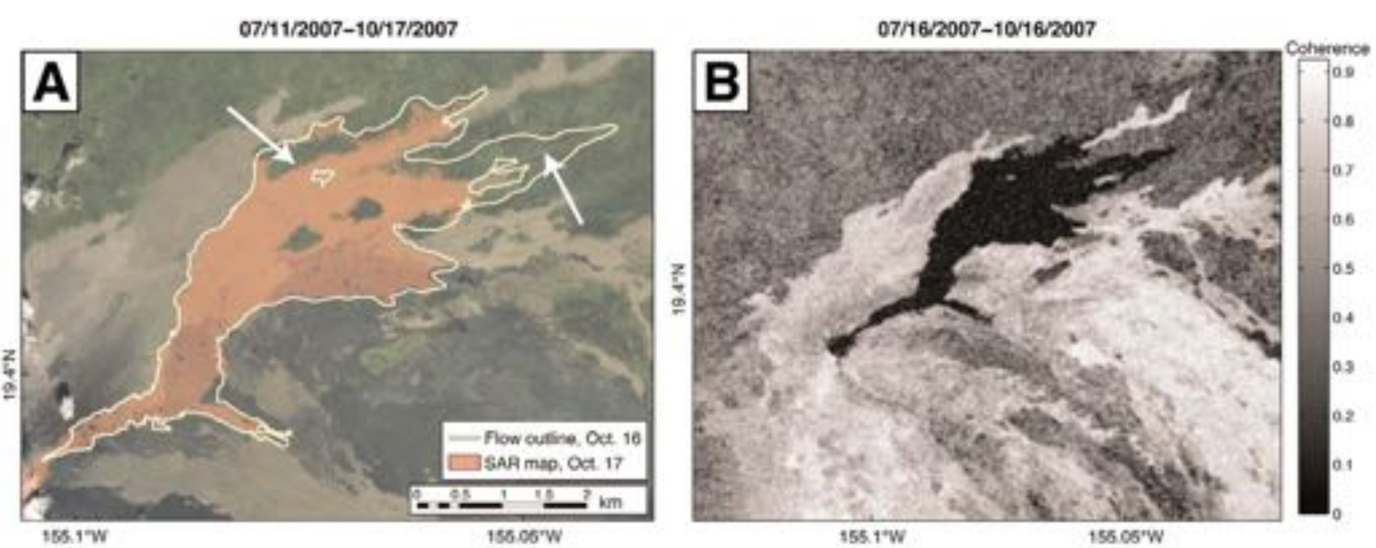

**Fink 1980; Carr and Lev, in prep**

| Variable | From Topography | Observed |
|---|---|---|
| Density ($\rho$) (kg/m$^3$) | | 2500 (Nakada et al.) |
| Flow Thickness (m) | 80 | |
| Flow Width (m) | 1000 | |
| **Ridge Spacing ($L$) (m)** | **44 ± 18** | |
| **Arc Length ($L_{arc}$) (m)** | **53 ± 22** | |
| **Ridge Height ($H$) (m)** | **11 ± 5** | |
| Ridge formation time ($t$) (s) | 1 week[8] | |
| Surface ($\eta_{surf}$):Internal ($\eta_i$) Viscosity Ratio ($R$) | 362 | |
| **Internal Viscosity ($\eta_i$) (Pas)** | **$0.5 - 0.7 \times 10^{10}$** | **$1.5 - 1.6 \times 10^{10}$** (Carr et al.; Nakada et al.) |
| **Strain Rate ($s^{-1}$)** | **$2.5 - 3.6 \times 10^{-7}$** | **$1.4 - 5.8 \times 10^{-7}$** |
| **Temperature (°C)** | **810** | **950** (Nakada et al.) |
| **Flow Velocity (m/day)** | **1.1** | **1 – 4** (when ridges formed[6]) |
| **Effusion Rate (m$^3$/s)** | **2.1** | **3** (when ridges formed[6]) |

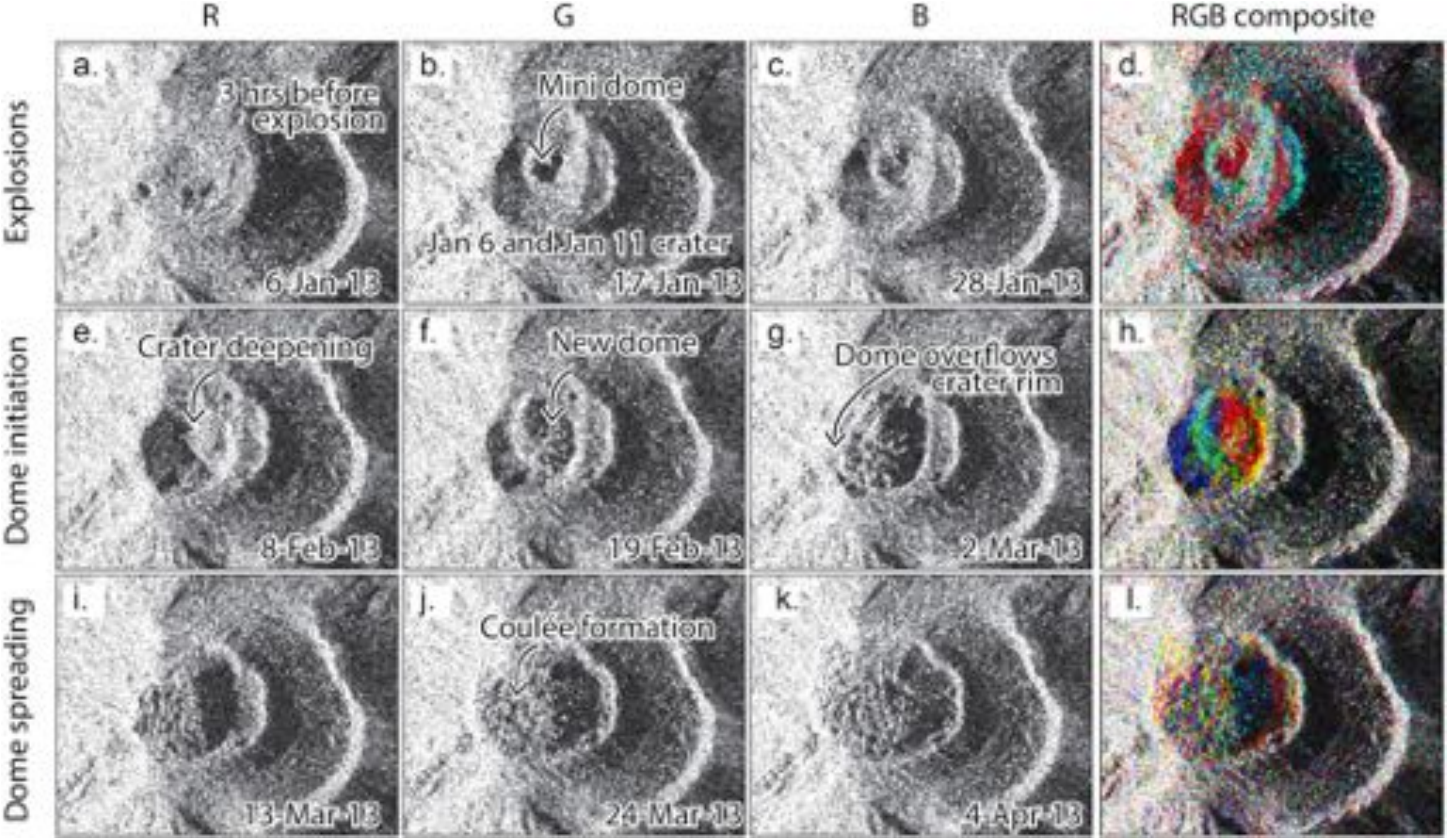
# Radar and SAR Coherence Mapping (SCM)




Dietterich et al., 2012

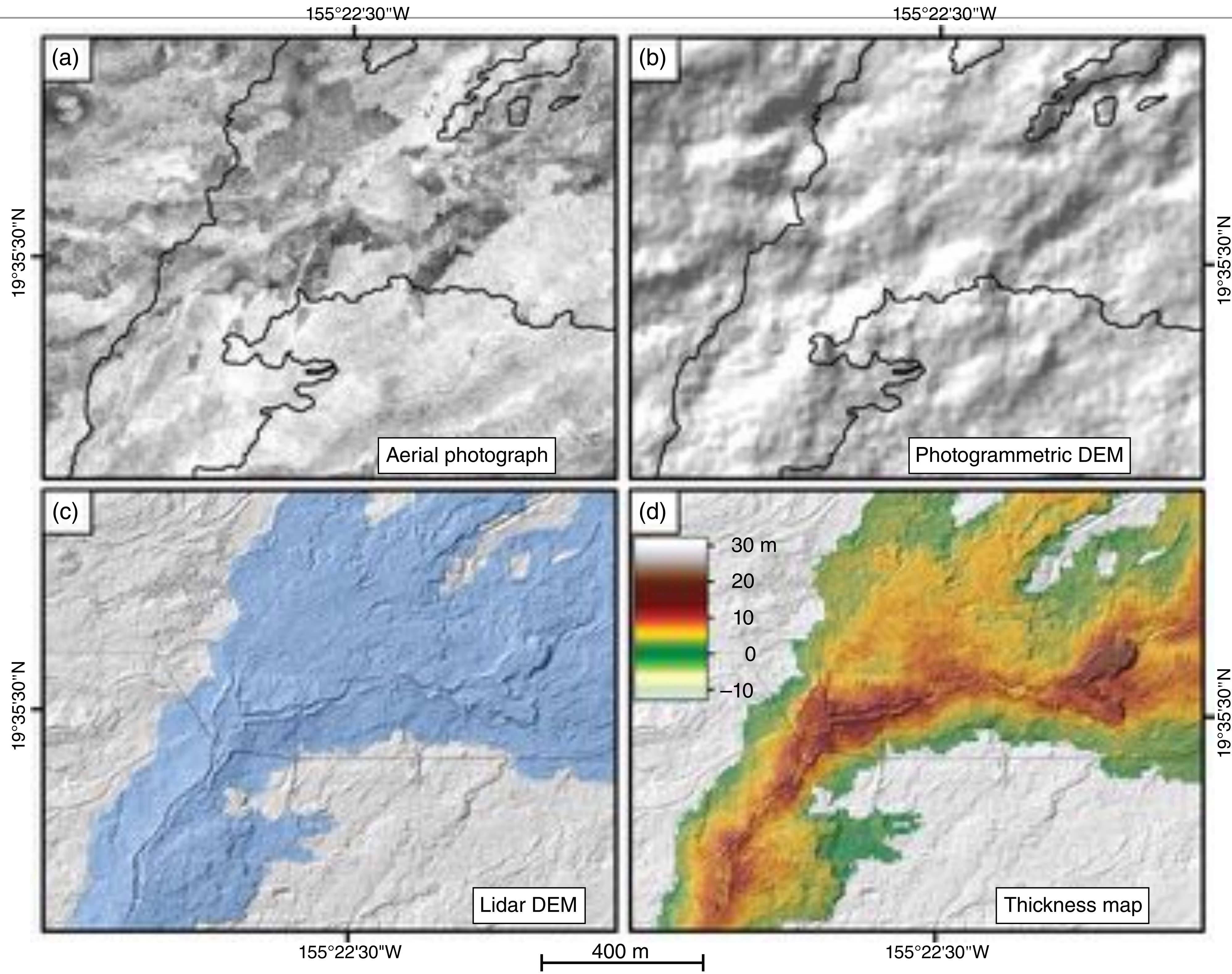



Colima 2013
TerraSAR-X data

**Walter et al., 2019**

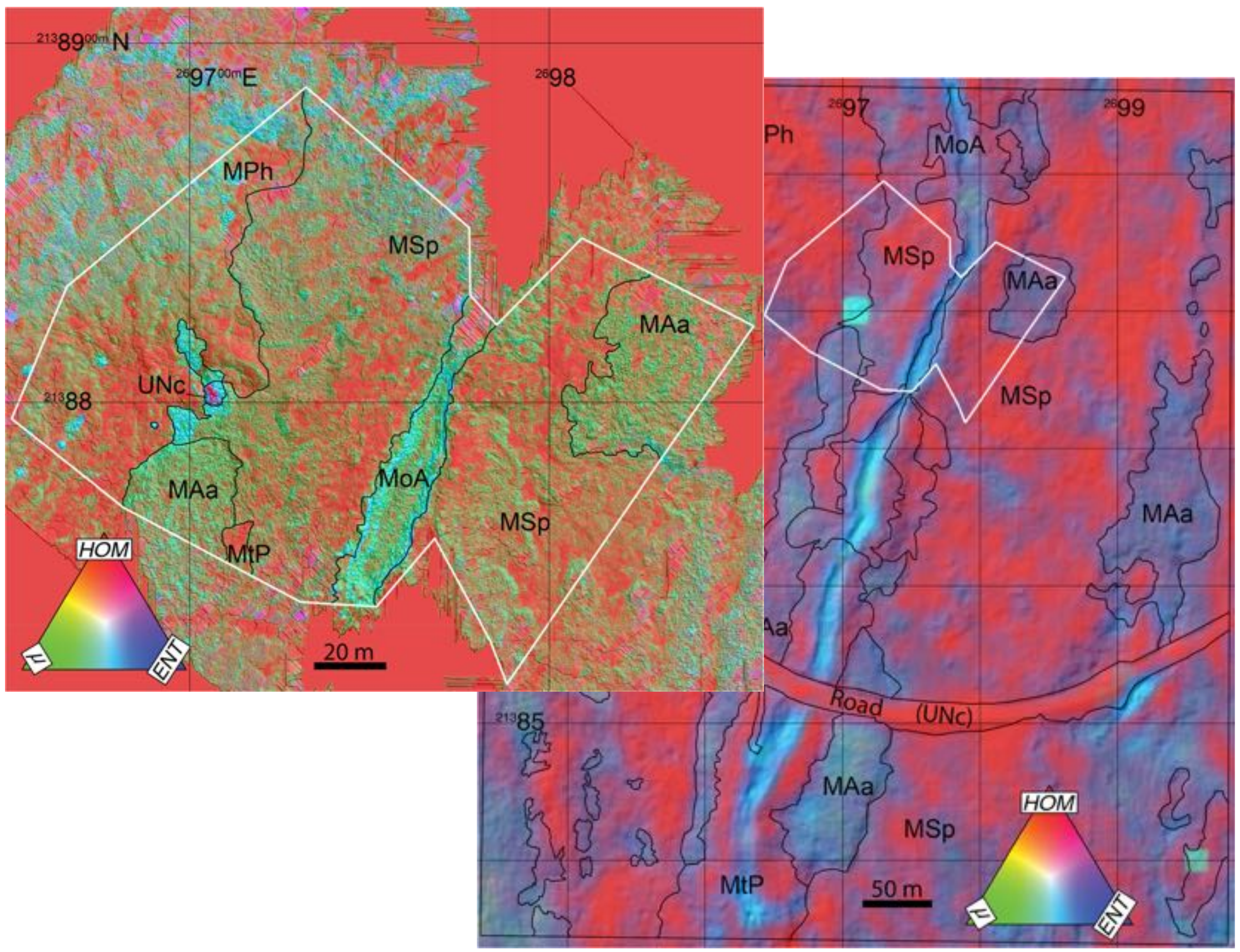
# LiDAR-derived topography

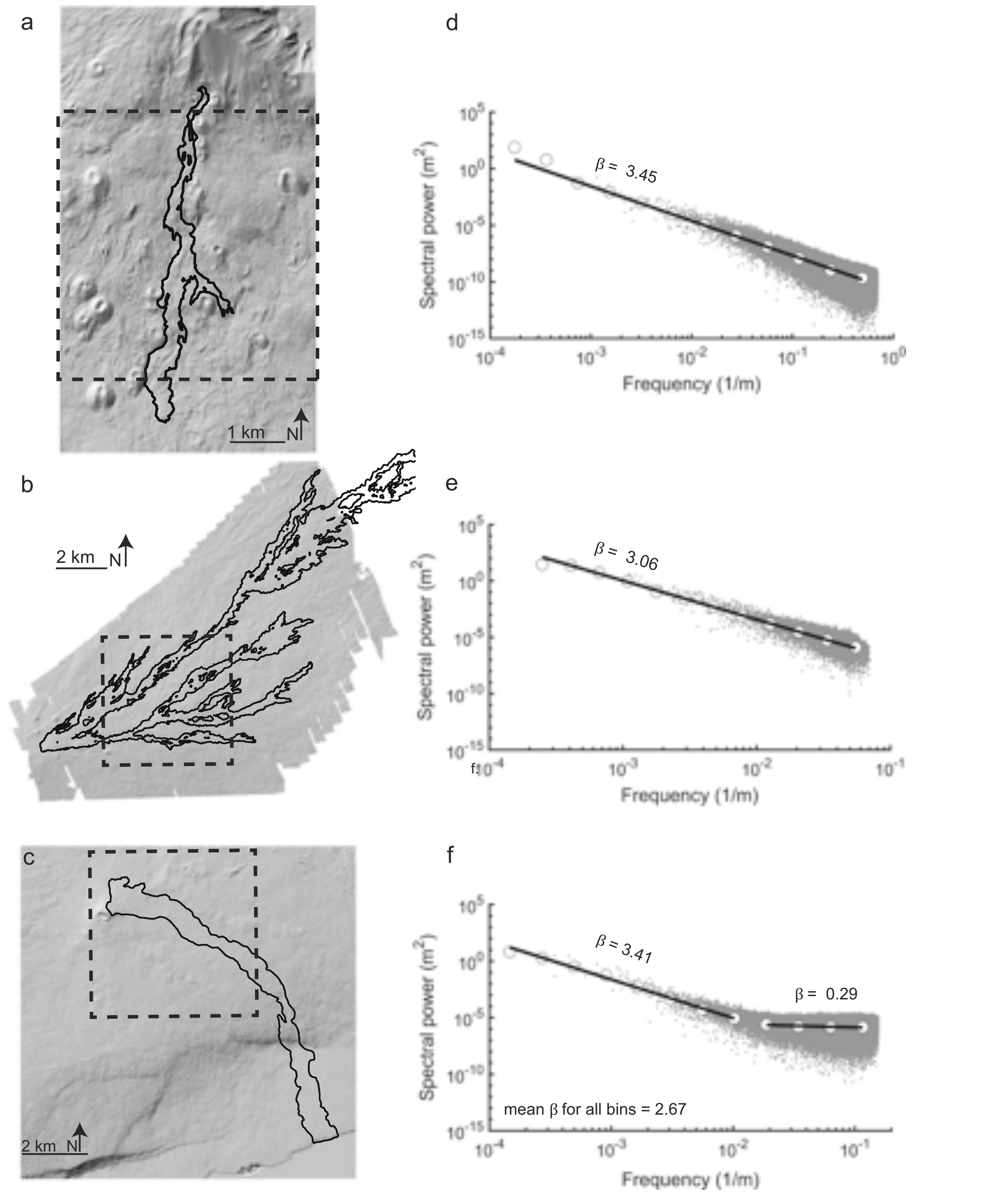
Mauna Loa
1984


**Dietterich et al., 2015**

# Quantifying topographic roughness




r is RMS of elevation offset from fitted plane at a point

| | | | | |
|---|---|---|---|---|
| Mean[a] | $\mu = \frac{\sum r}{W^2}$ | The average of roughness values within the base window | – | |
| Homogeneity[b] | $\mathrm{HOM} = \sum \frac{C_{ij}}{1+\lvert i-j \rvert}$ | Increases with local similarity in $i$ and $j$ | After Zhang (1999) | |
| Entropy | $\mathrm{ENT} = \sum C_{ij} \log C_{ij}$ | Increases with $C_{ij}$ randomness | Clausi (2002) | (5) |

**Whelley et al., 2017**

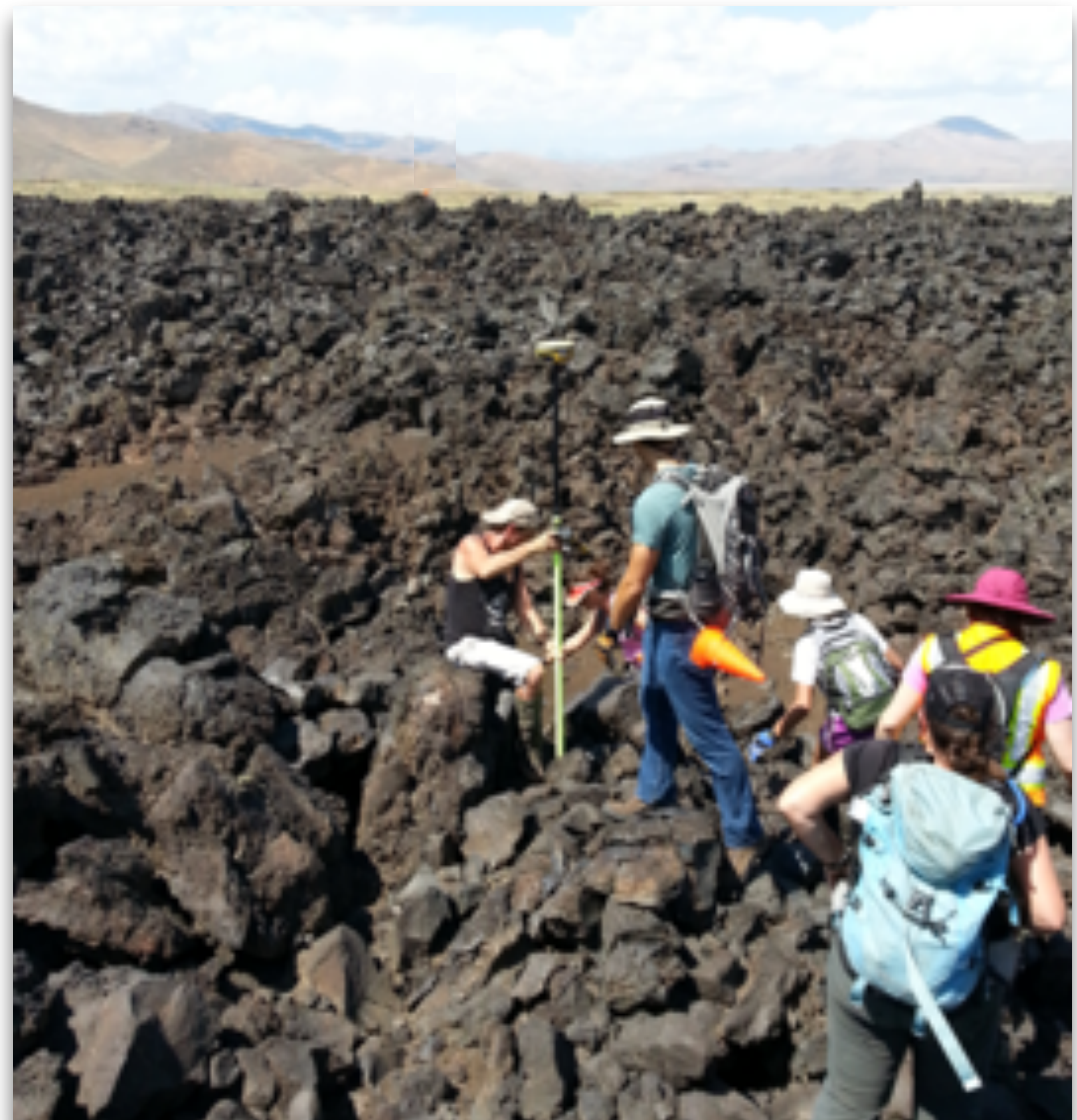
**Richardson and Karlstrom, 2017**

# Measuring roughness and classifying morphology

Kīlauea 1974

Gaddis et al., 1990

Craters of the Moon

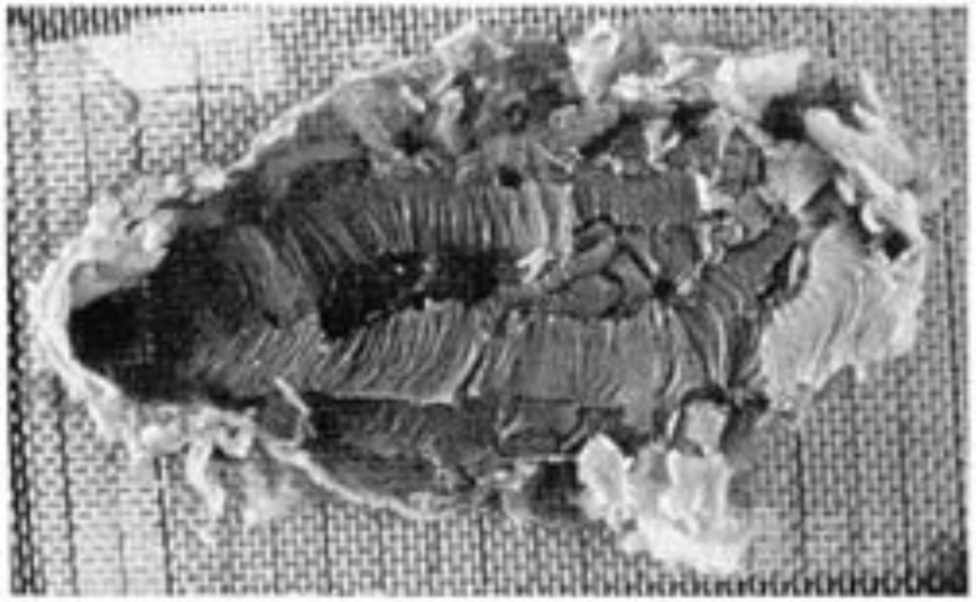


Deepak Dhingra, in 2015

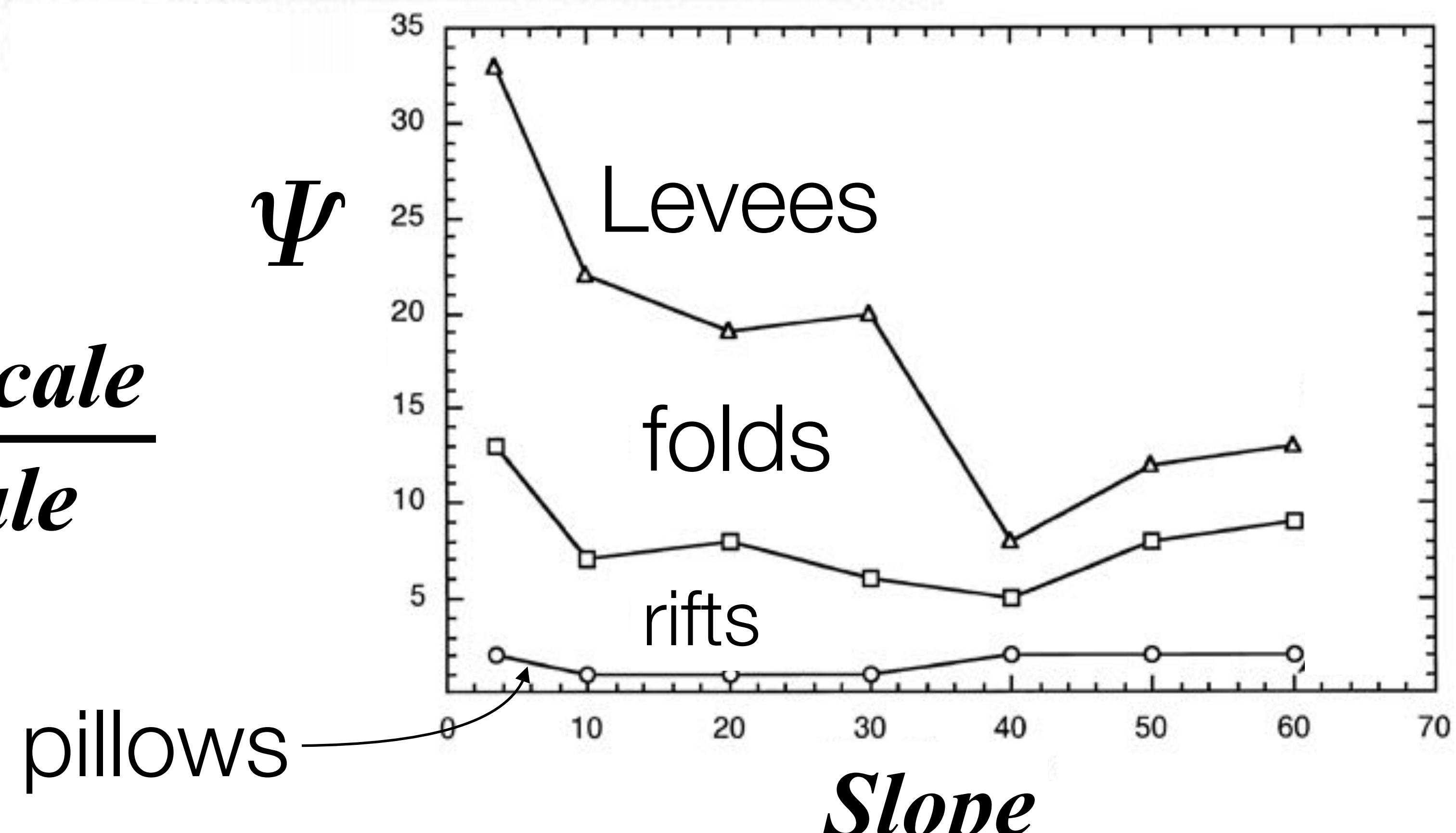
Pillows

Folds

Rifts



Levees

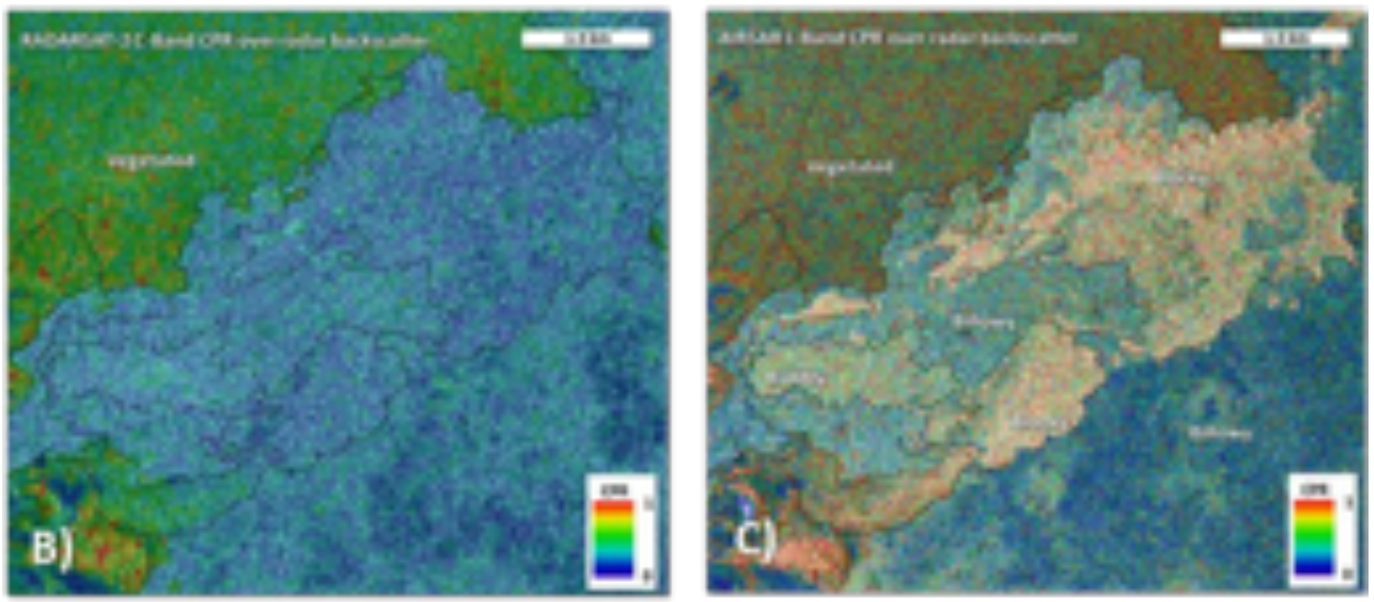


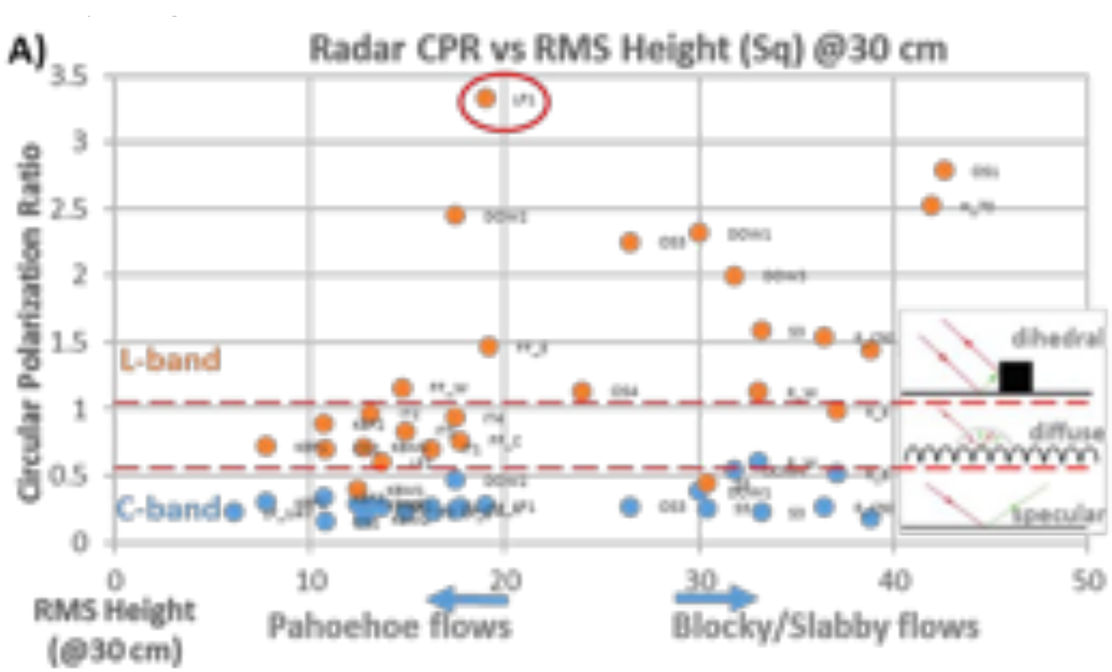

$$\Psi = \frac{\textit{Solidification timescale}}{\textit{Advection timescale}}$$

Gregg and Fink, 2000

# Radar Coherence

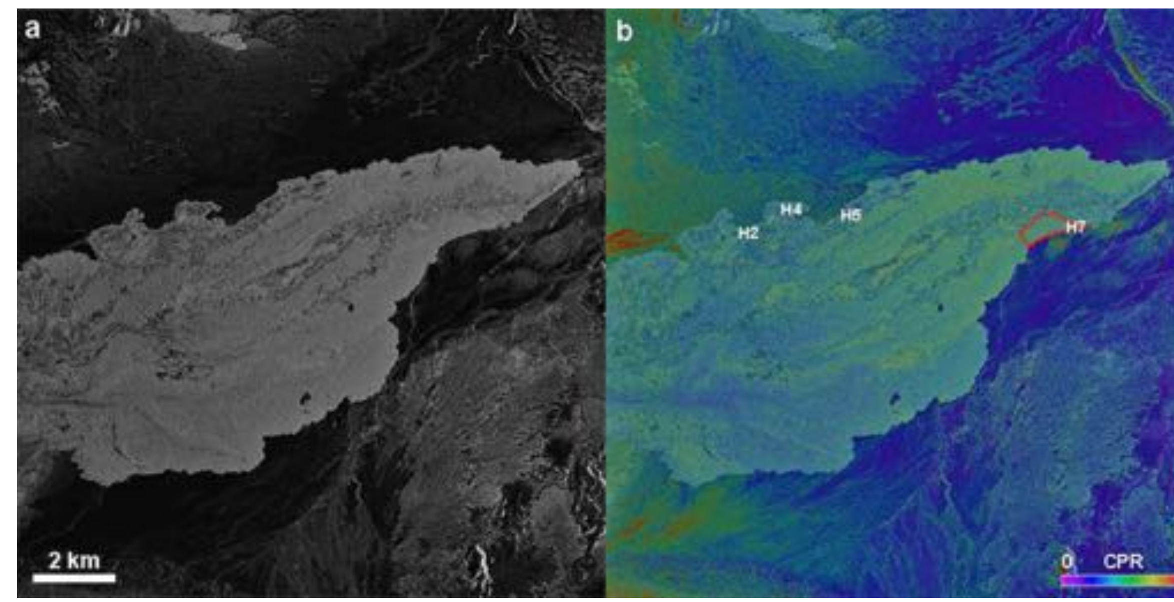
## Craters of the Moon



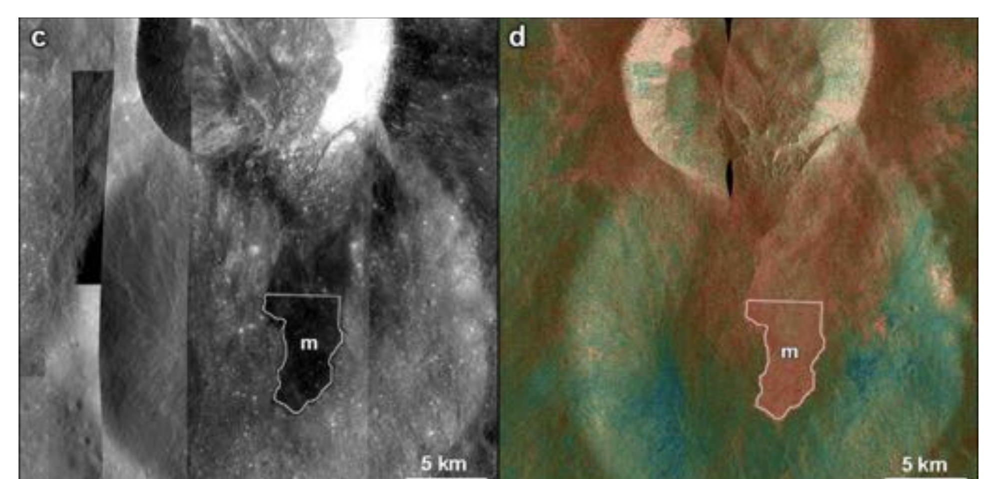




Neish et al., 2016, Zanetti et al., 2018

## Holuhraun 2014-2015

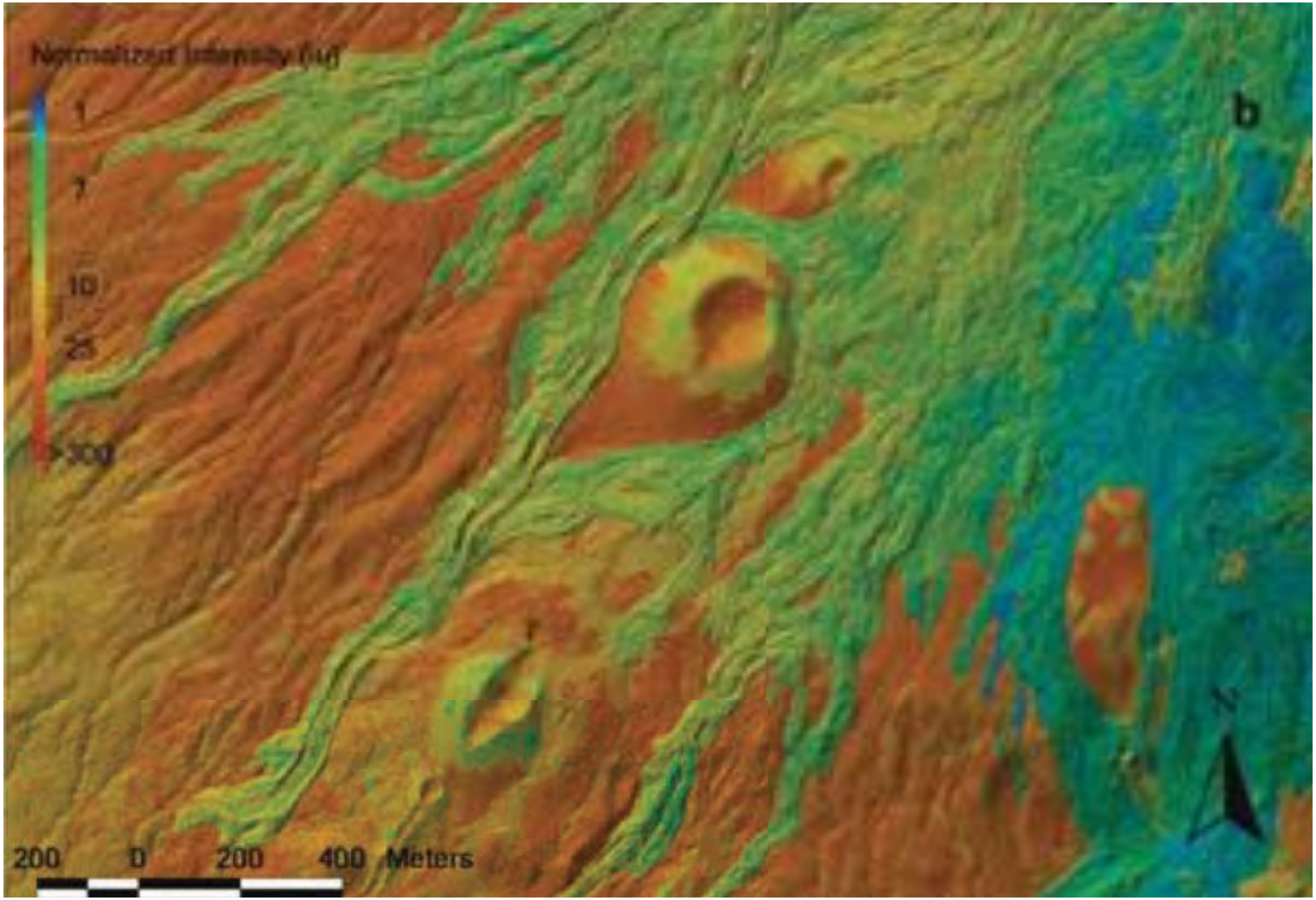



## Korolev X (lunar impact melt)



# LiDAR intensity → Flow Age

Mount Etna

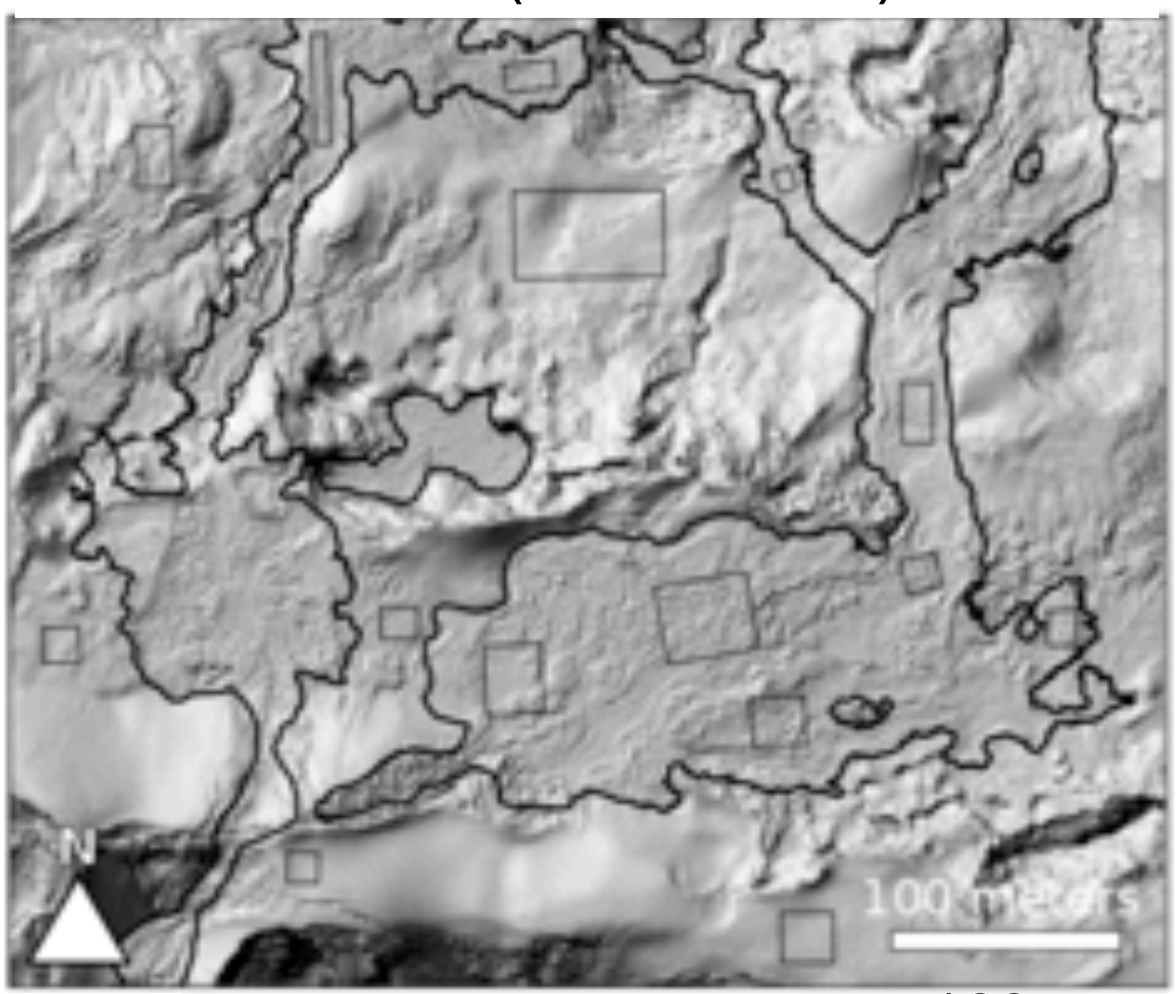



**Mazzarini et al., 2007**

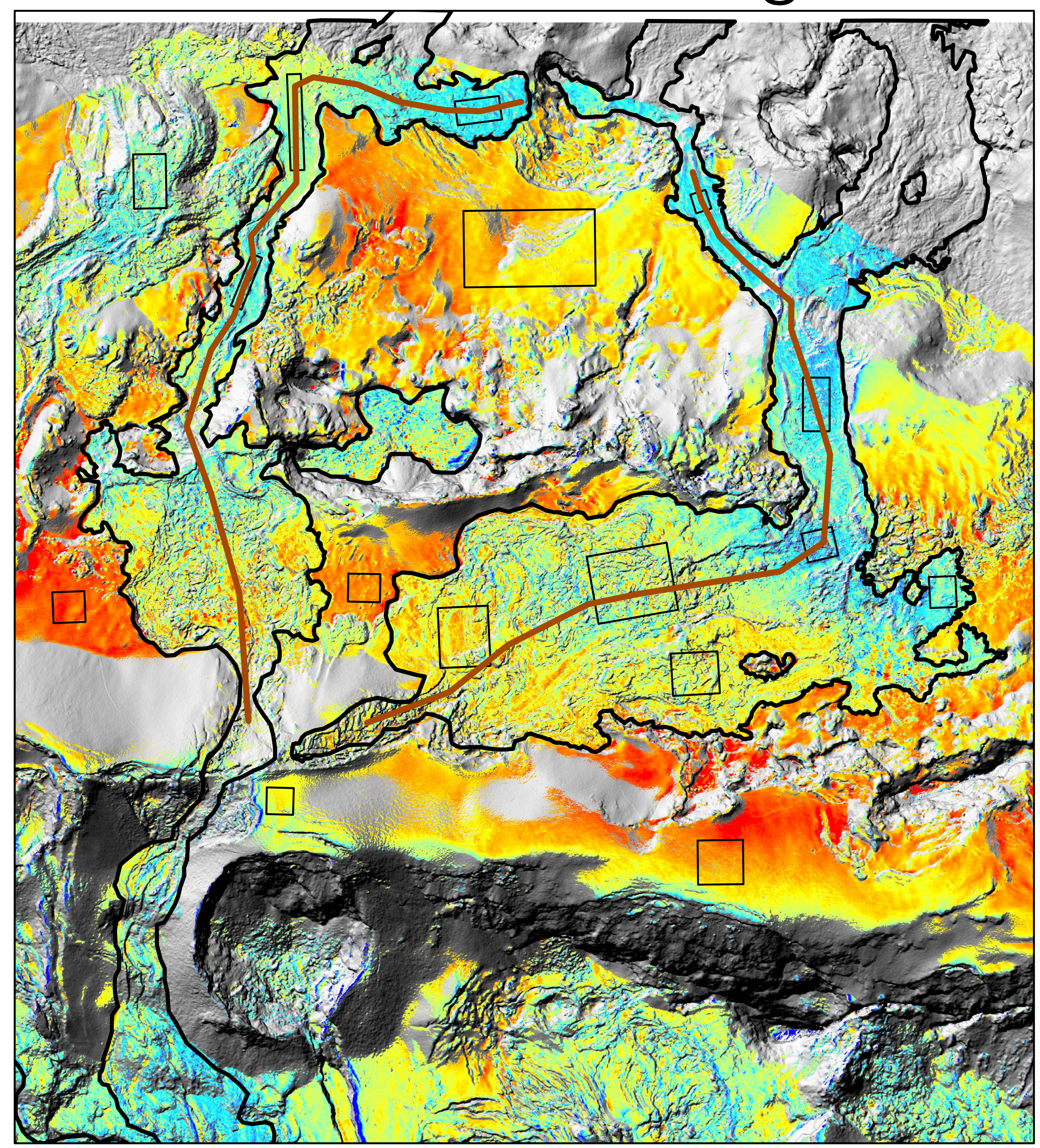
# Morphology classification by multi-sensor surveys

## Sierra Negra (Galapagos) 2018

DEM (hillshade)

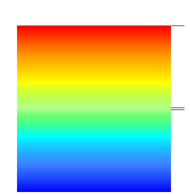



Rate of Heating



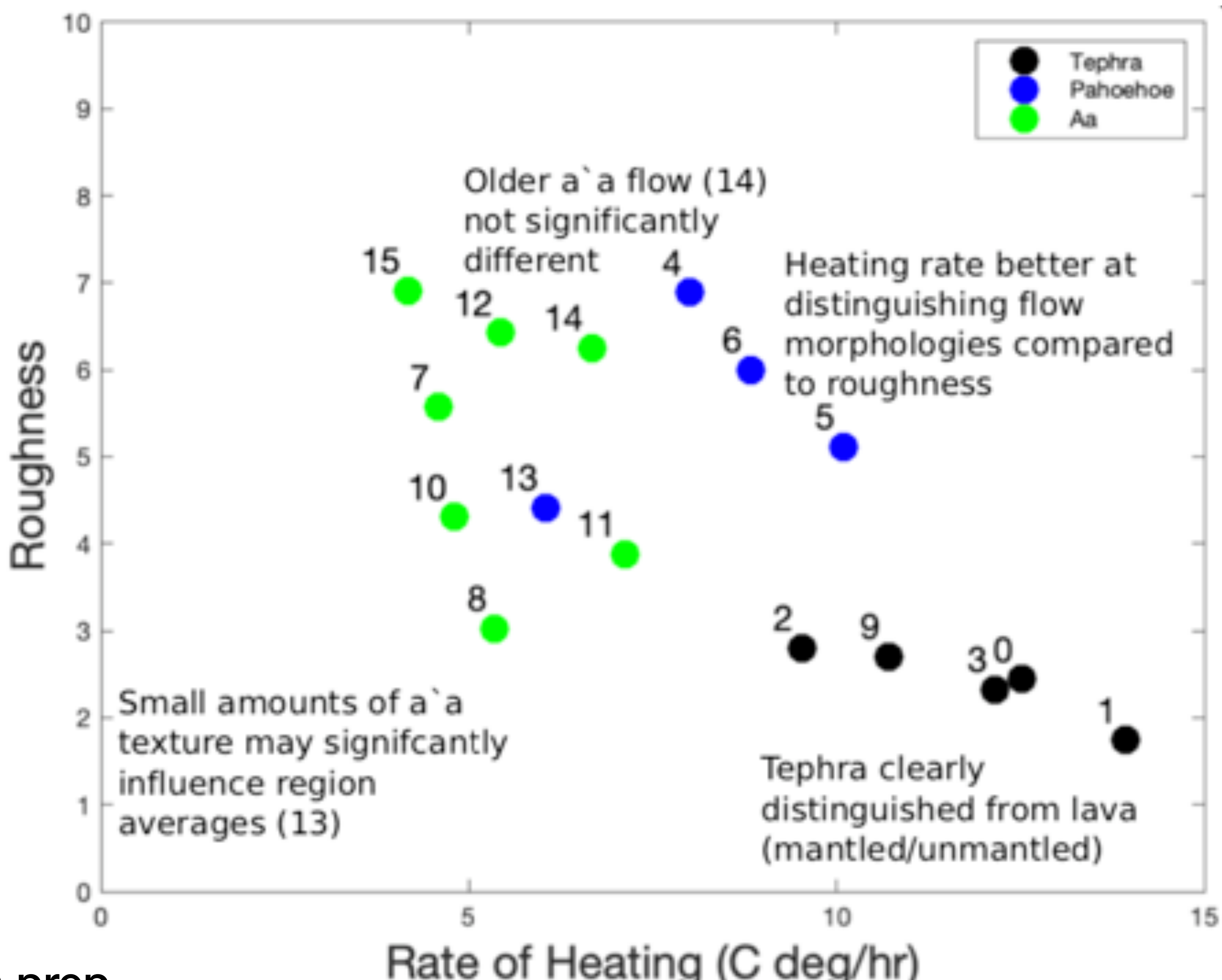
100 m

DJI Matrice 210
Dual-camera setup



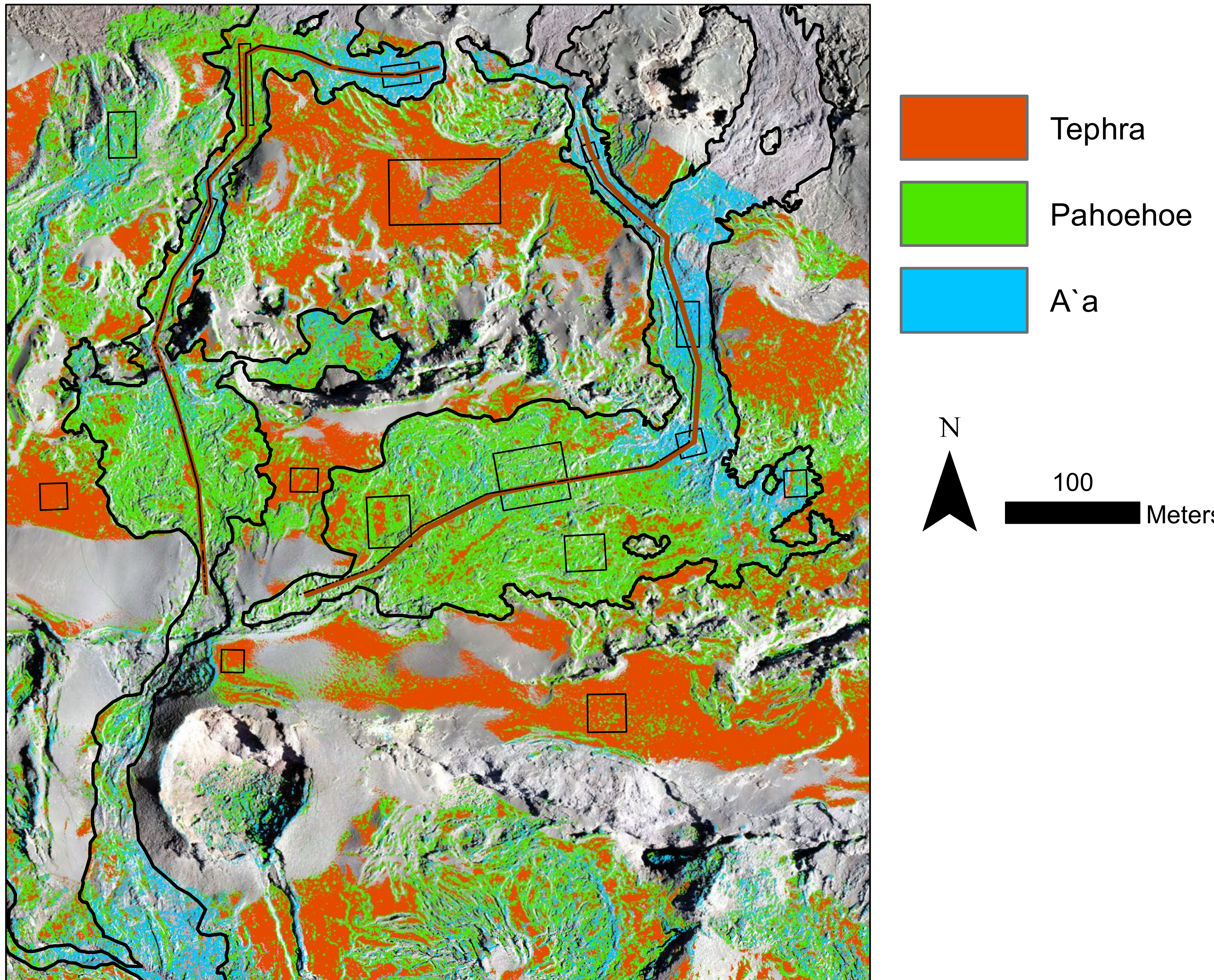

**Carr et al., in prep**

# Morphology classification by multi-sensor surveys




Carr et al., in prep

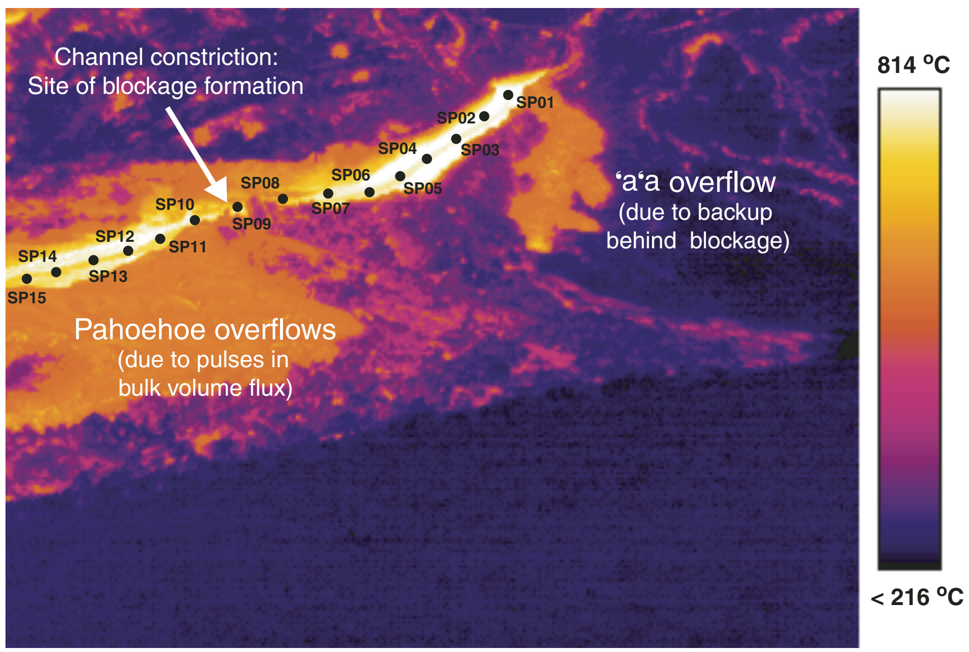
# Morphology classification by multi-sensor surveys

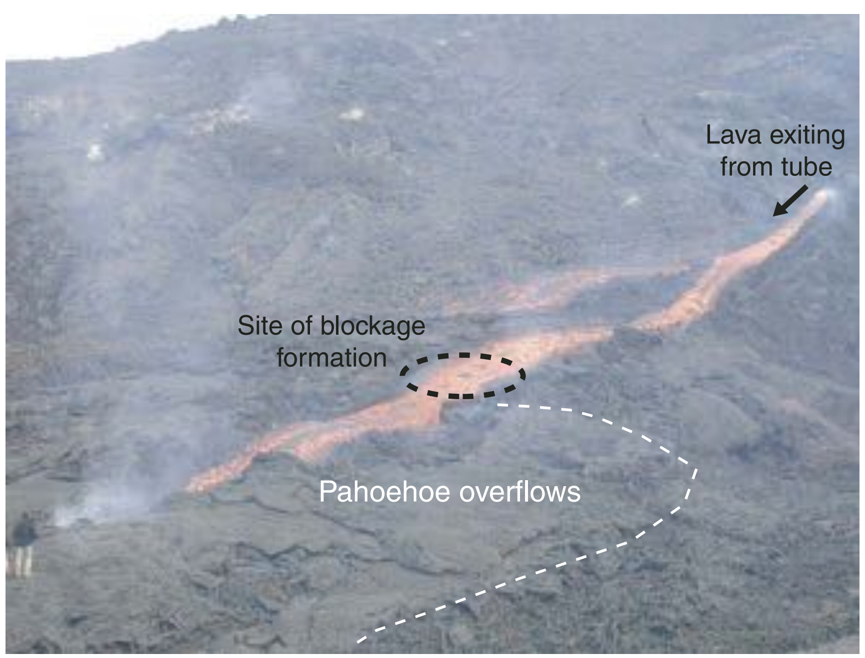



Carr et al., in prep

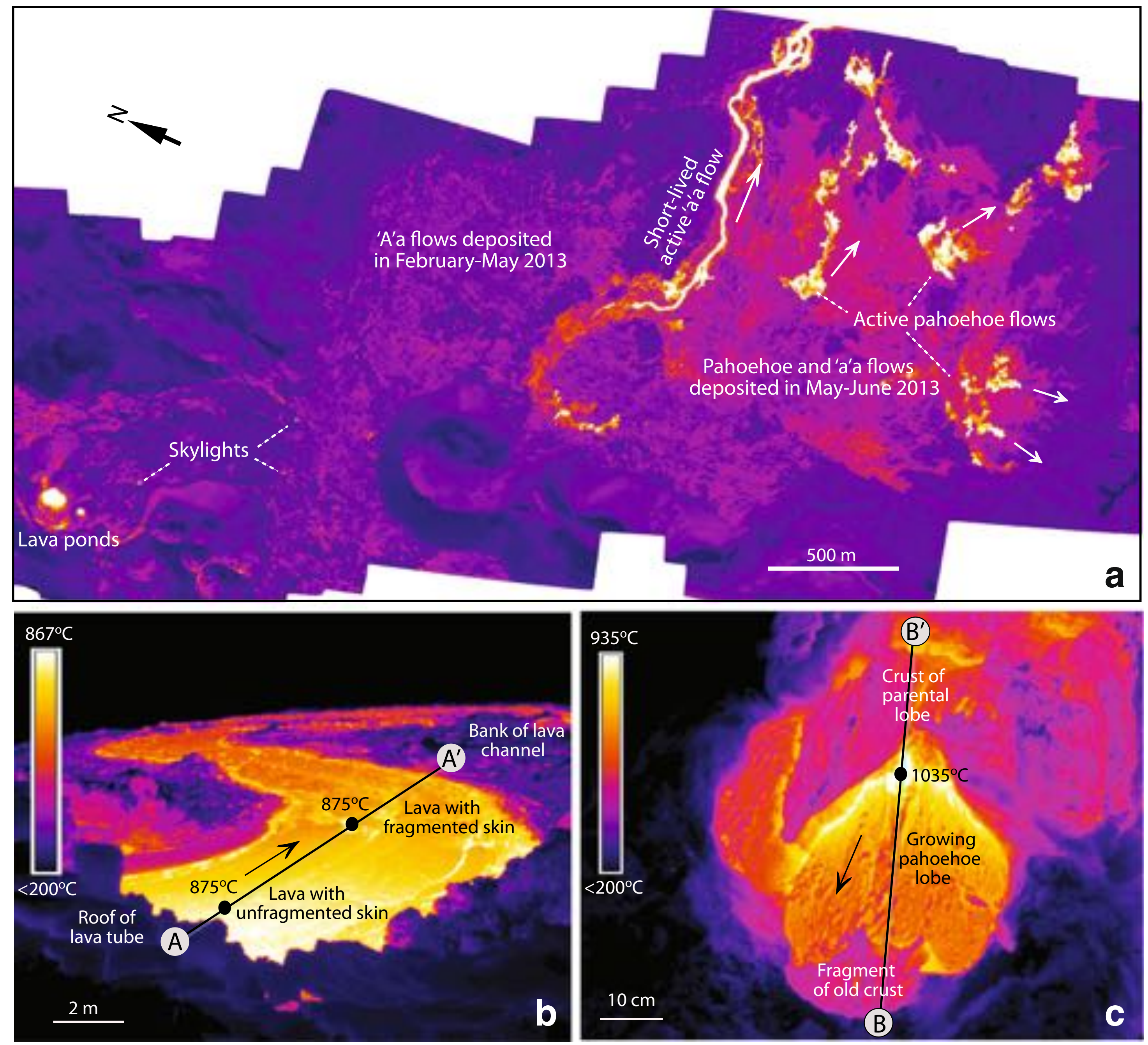
# Thermal cameras

$$Q_{rad} = \sigma \, \varepsilon \, A_{pixel} \, T^4_{hot}$$



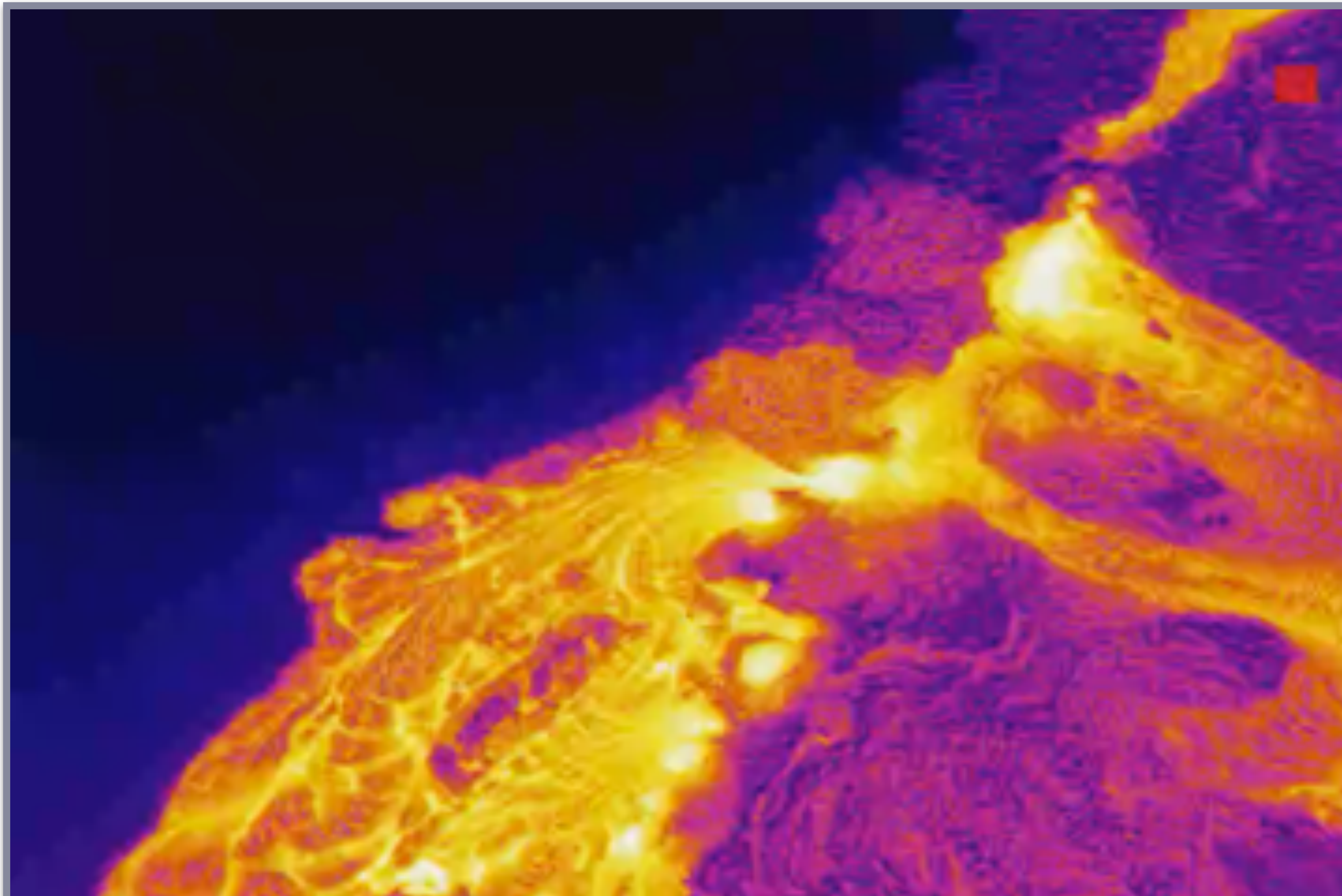

Etna, May 2001



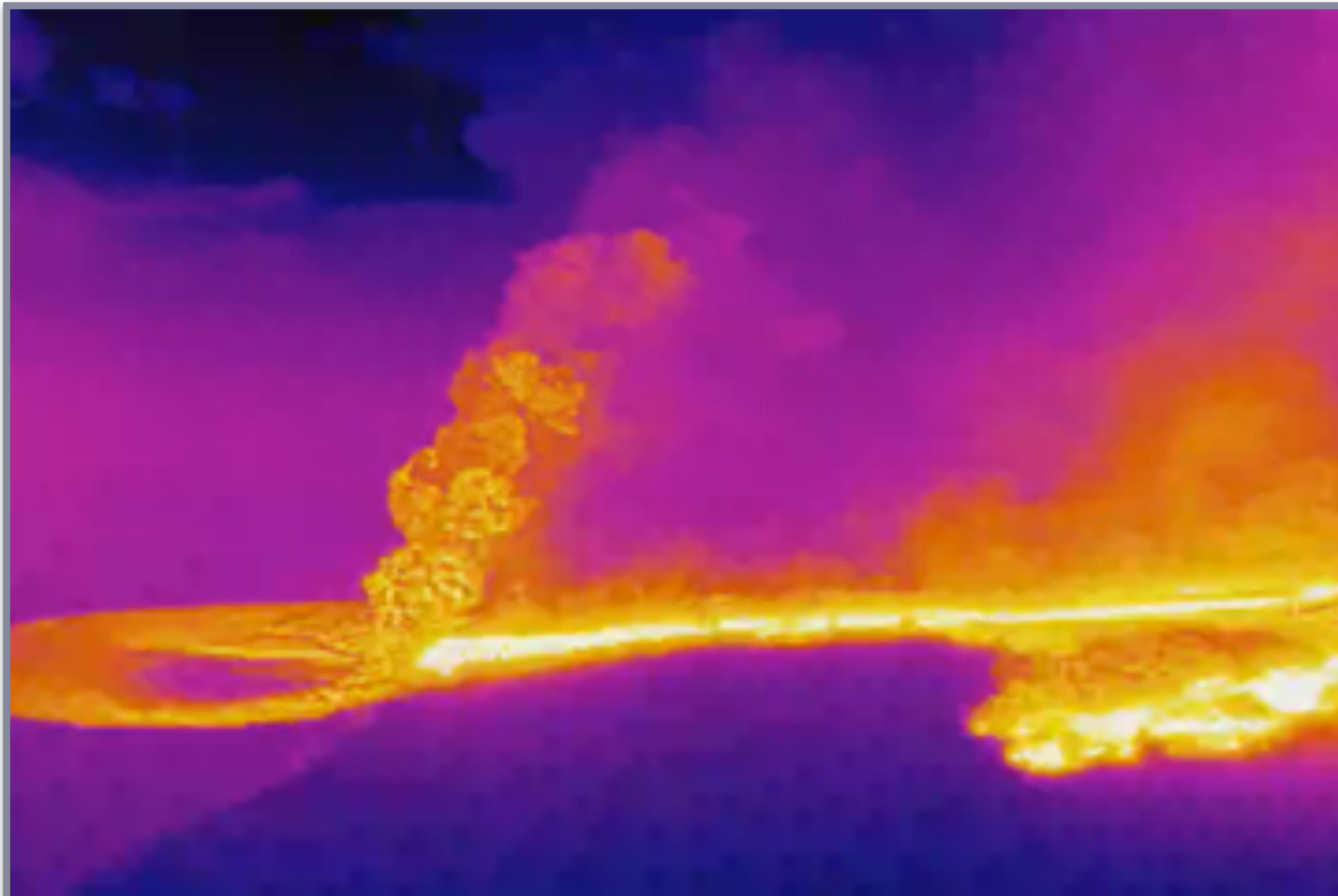

Tolbachik, 2013

**Harris et al., 2005**

**Belousov and Belousova, 2018**



Kīlauea LERZ eruption, 21-May-2018
Taken by DJI210 with Zenmuse XT camera

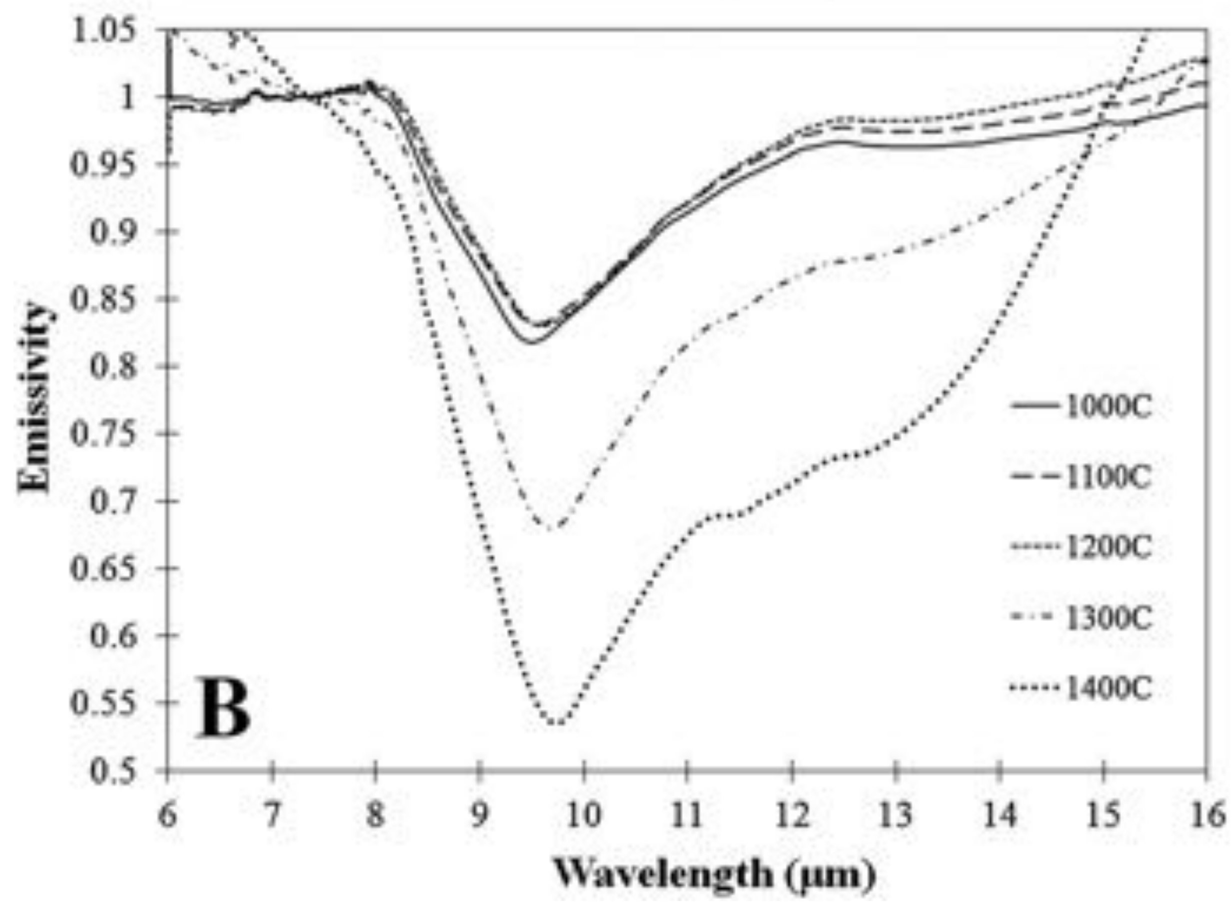


Kīlauea LERZ eruption, 19-May-2018
Taken by DJI210 with Zenmuse XT camera

# Remember:

- The humidity and gases along the path between camera and flow affect the reading

- Emissivity of liquid is lower than of solidified lava




Lee et al., 2013

# For old flows: use thermometry

Glass / liquid composition (Heltz and Thornber 1987, Grove and Juster 1989, Montierth et al. 1995, Sisson and Grove 1993…)

Olivine-liquid equilibrium (e.g., Beattie 1993, Putirka et al. 2007 and 2008)

$$T(^{\circ}\mathrm{C}) = \frac{15294.6 + 1318.8P(\mathrm{GPa}) + 2.4834[P(\mathrm{GPa})]^2}{8.048 + 2.8532\ln D_{\mathrm{Mg}}^{\mathrm{ol/liq}} + 2.097\ln[1.5(C_{\mathrm{NM}}^{\mathrm{L}})] + 2.575\ln[3(C_{\mathrm{SiO_2}}^{\mathrm{L}})] - 1.41\mathrm{NF} + 0.222\mathrm{H_2O} + 0.5P(\mathrm{GPa})} \quad (4)$$

$$T(^{\circ}\mathrm{C}) = \frac{461.29 + 84.9P(\mathrm{GPa}) + 0.588[P(\mathrm{GPa})]^2}{0.355 + 0.06986\ln D_{\mathrm{Fe}}^{\mathrm{ol/liq}} - 0.00435\ln[1.5(C_{\mathrm{NM}}^{\mathrm{L}})] - 0.0523\ln[3(C_{\mathrm{SiO_2}}^{\mathrm{L}})] - 0.0217\mathrm{NF} + 0.000893\mathrm{H_2O} + 0.04P(\mathrm{GPa})} \quad (5)$$

# Assessing lava rheology — 1. Viscometry

Tolbachik, 2013
Penetrometer

$$\eta = \frac{F}{3\pi\ u\ R_{eff}}$$


Kīlauea
Rotational viscometer

$$\tau = \tau_0 + K\dot{\gamma}^n$$

$$\dot{\gamma} = \frac{2\Omega}{n\left(1 - \left(\frac{R_i}{R_o}\right)^{2/n}\right)} \qquad \tau = \frac{M}{2\pi h R_i^2}$$

**Belousov & Belousova 2018**

**Chevrel et al., 2019**

# 2. Kinematics — Analytical channel solutions

Jefferys equation: ***bulk viscosity* = *density* x *g* x *sin(slope)* x *depth*² / (3 x *velocity*)**

General rectangular channel:

$$\eta = \frac{\rho g \sin(\alpha) h^2}{2V} \times \beta$$

$$\beta = 1 - \frac{32}{\pi^3} \sum_{n=1,3,5,\ldots}^{\infty} \frac{1}{n^3} (-1)^{(n-1)/2} \operatorname{sech} \frac{n\pi 2a}{4h}$$

<u>Example (Values from Lipman and Banks 1987):</u>

$V = 5.6$ m/s

$a = 10$ m

$h = 4$ m

} $\beta$=0.96 (for $a$ and $h$)

$\rho = 1.2$–$1.4$g/cm3

$\boldsymbol{\alpha} = 2$-$6°$

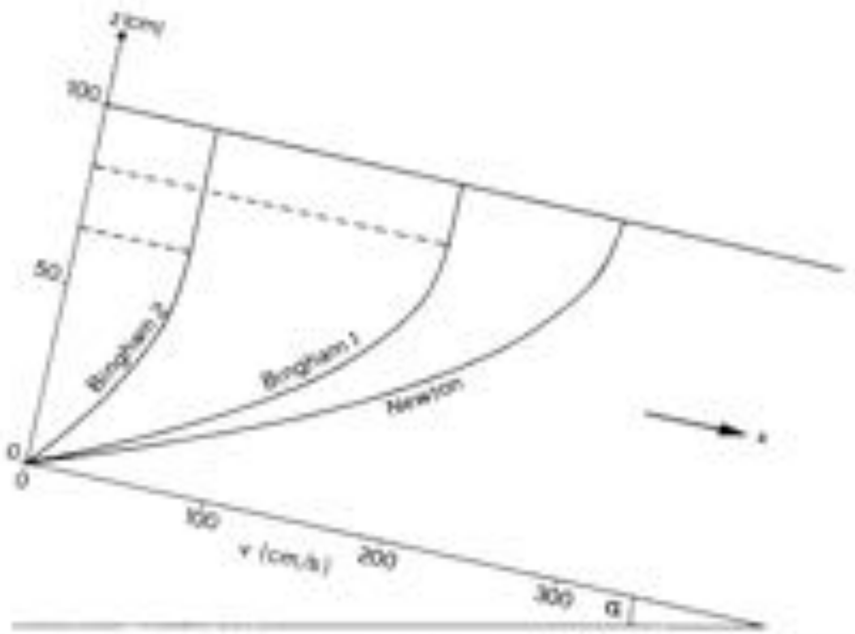
$\eta = 600$–$2000$ Pa s

W. Herzog, “Into the Inferno”, Mauna Loa 1984

# Kinematics — Variations for rheology

Bingham fluid: $$v(z) = \frac{1}{\eta}\left[\frac{\rho g \sin\alpha}{2} z\,(2H - z) - \sigma_Y z\right],\ 0 < z < (H - H_c)$$

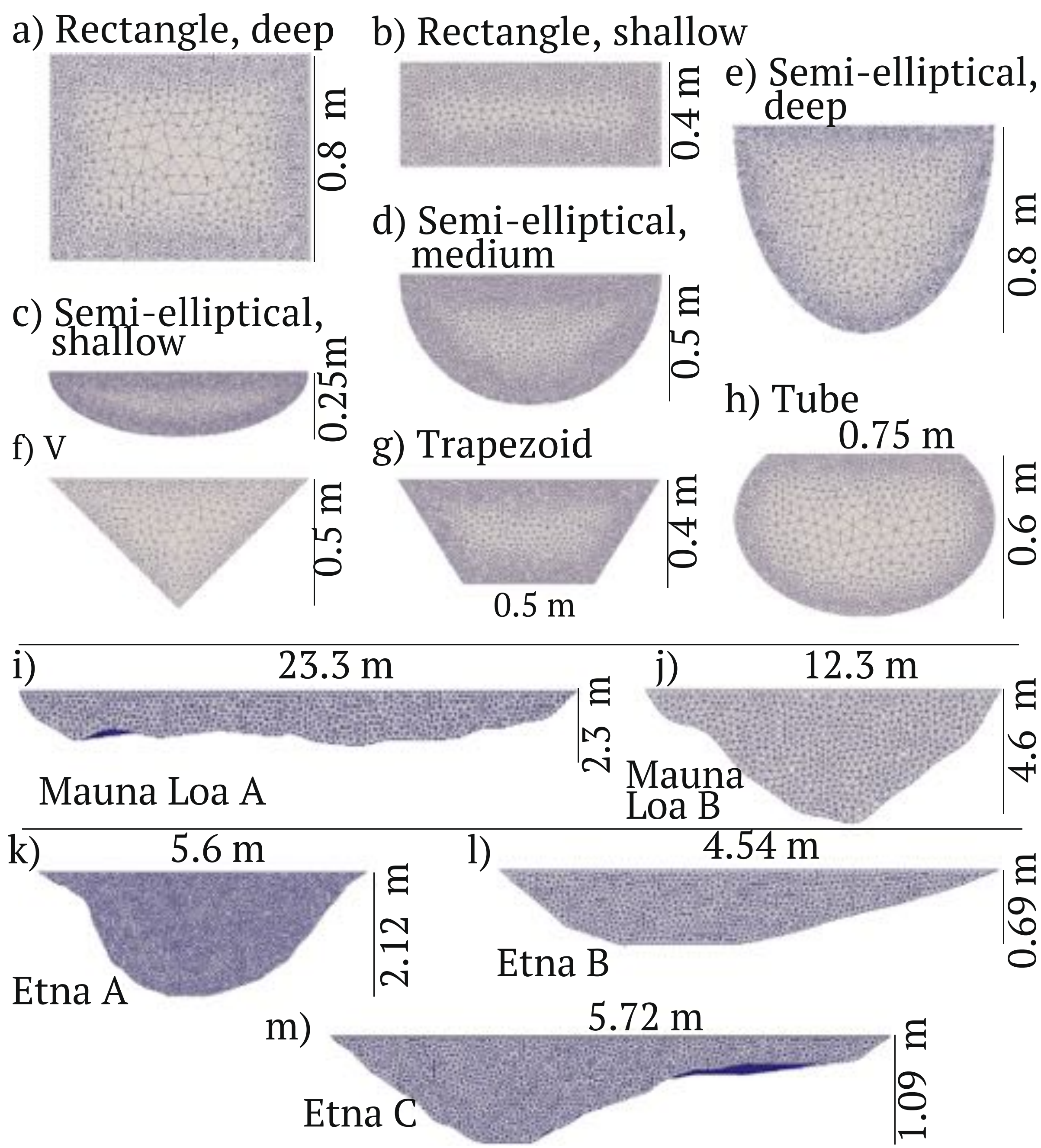
$$H_c = \sigma_Y / (\rho g \sin\alpha)$$

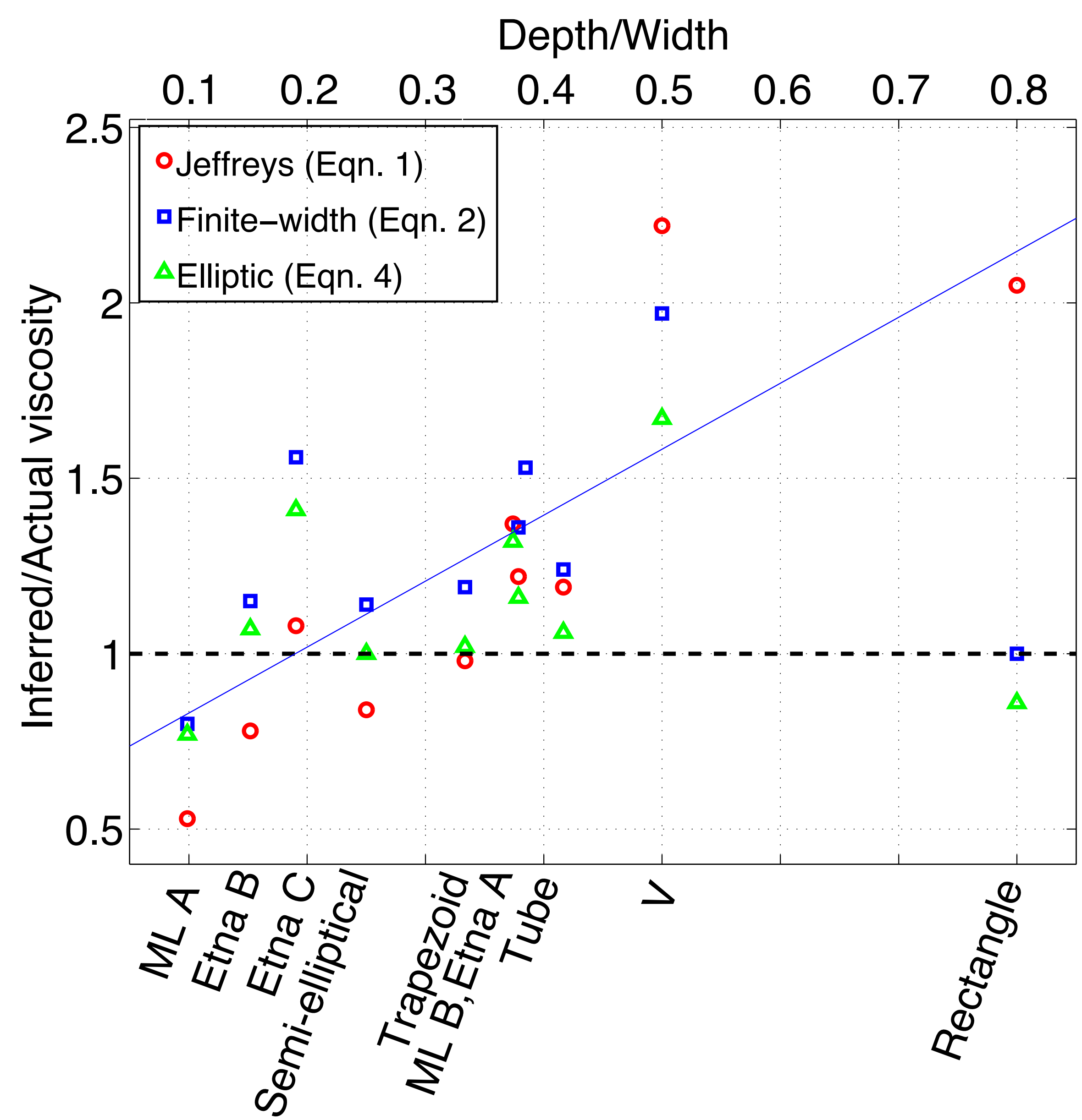



Herschel-Bulkley fluid: $$\overline{u} = \frac{H^2 \rho g \sin\beta}{3K}\left(\frac{3n}{H^3(n+1)}\left(\frac{\rho g \sin\beta}{K}\right)^{\frac{1-n}{n}}\right) \times \left(H(H - h_c)^{\frac{n+1}{n}} - \frac{n}{2n+1}(H - h_c)^{\frac{2n+1}{n}}\right).$$

**Dragoni et al., 1986; Castruccio et al., 2010; Castruccio et al., 2014**

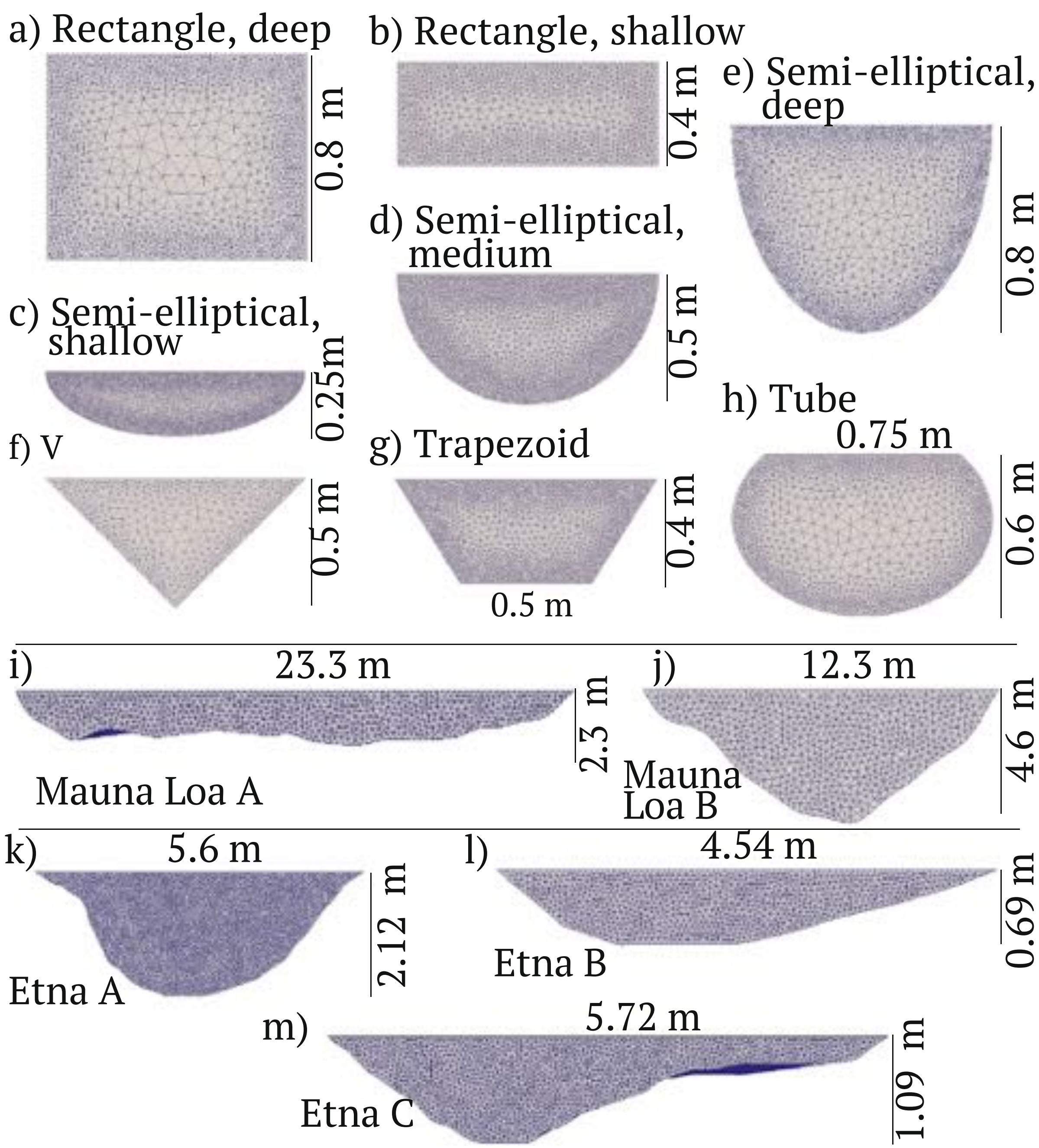
# Kinematics — Impact of channel shape

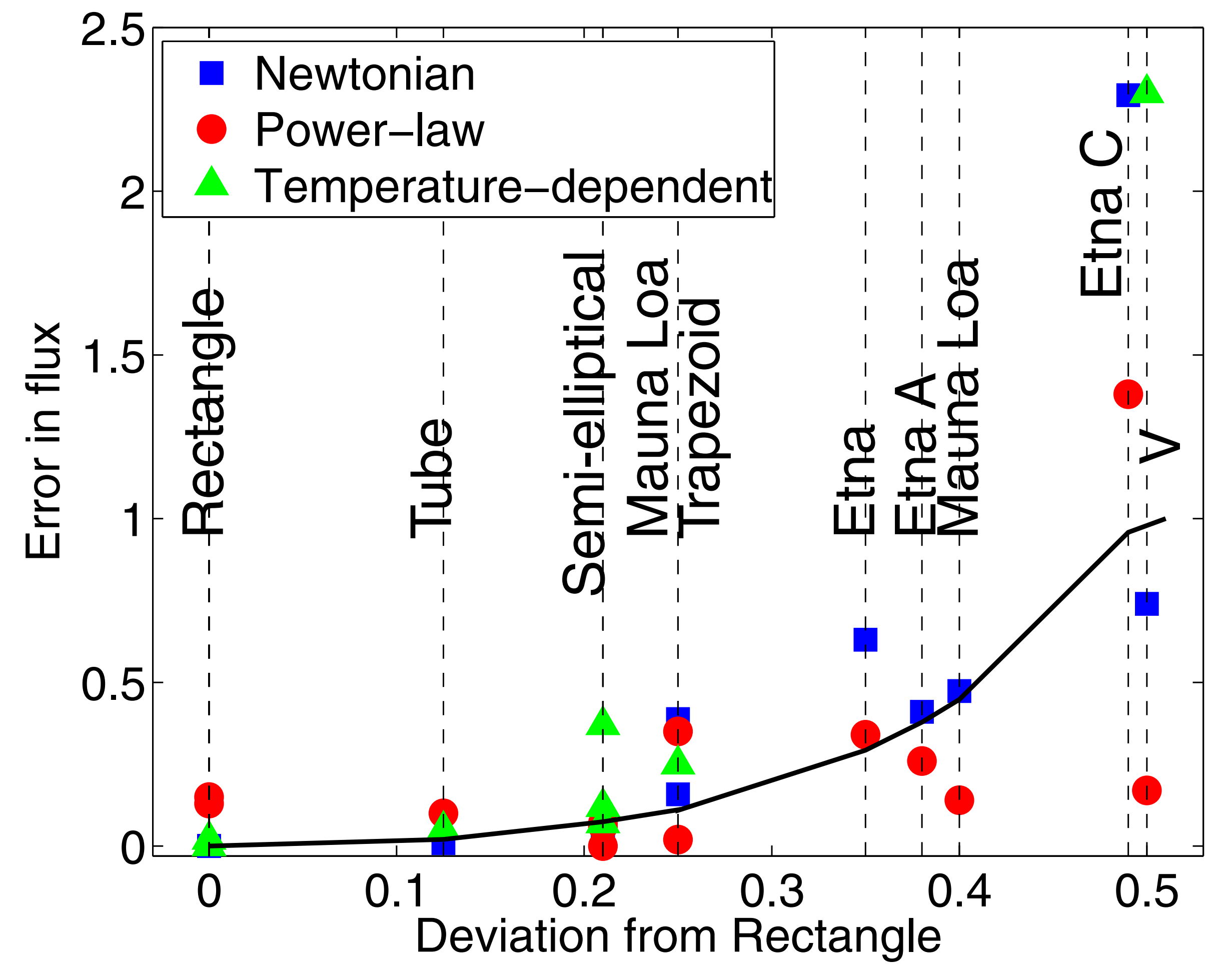



Lev and James, 2012

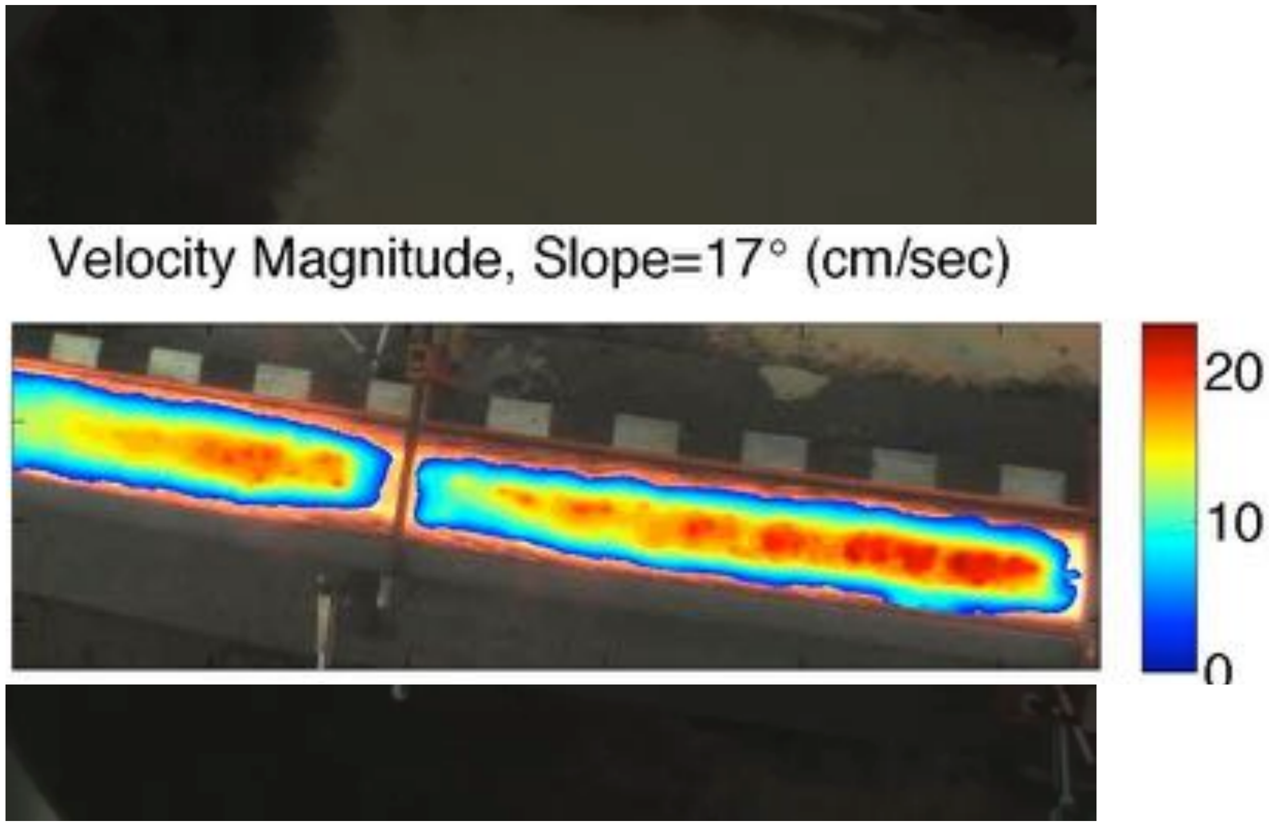
# Kinematics — Impact of channel shape

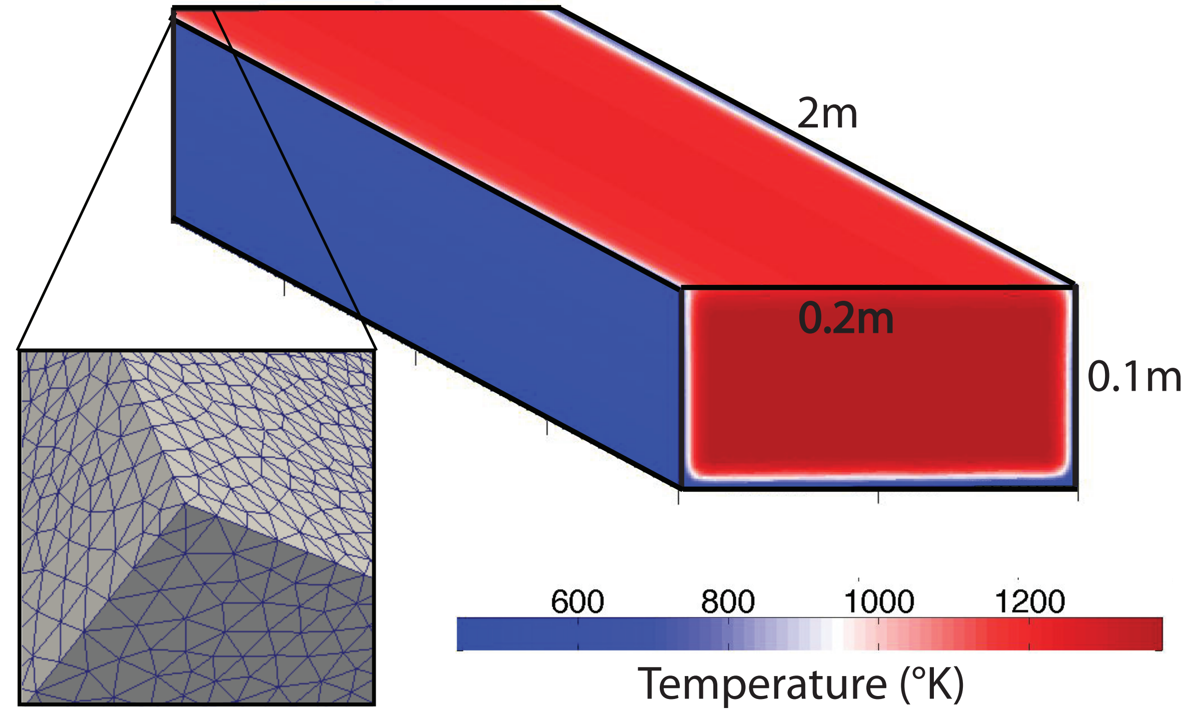


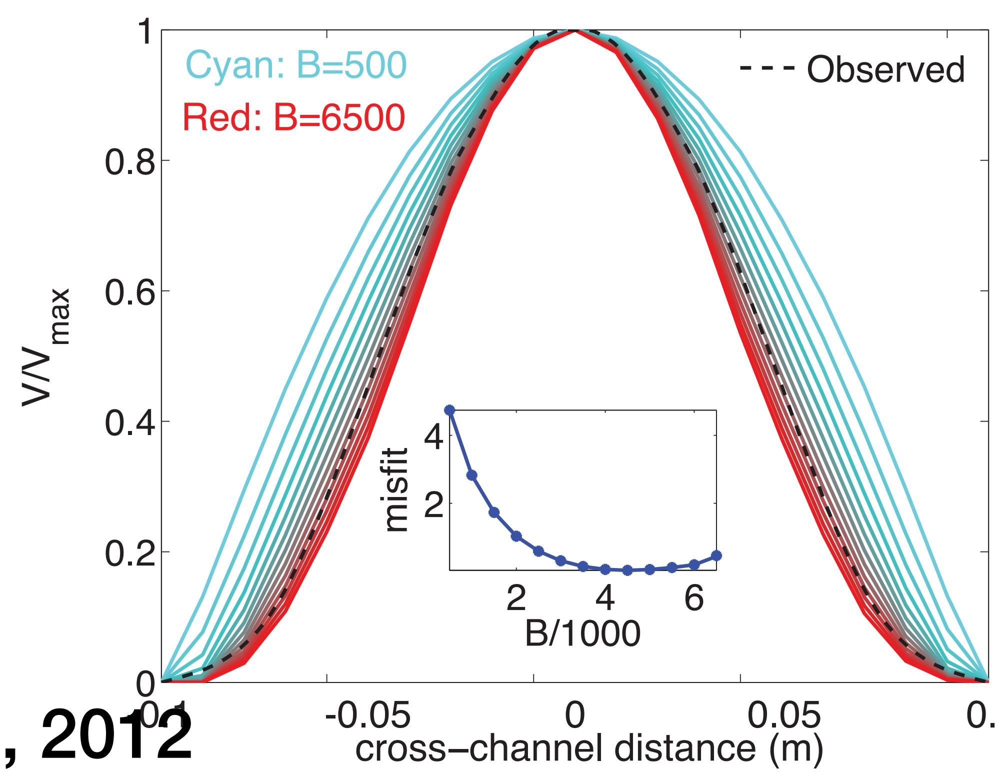

Lev and James, 2012

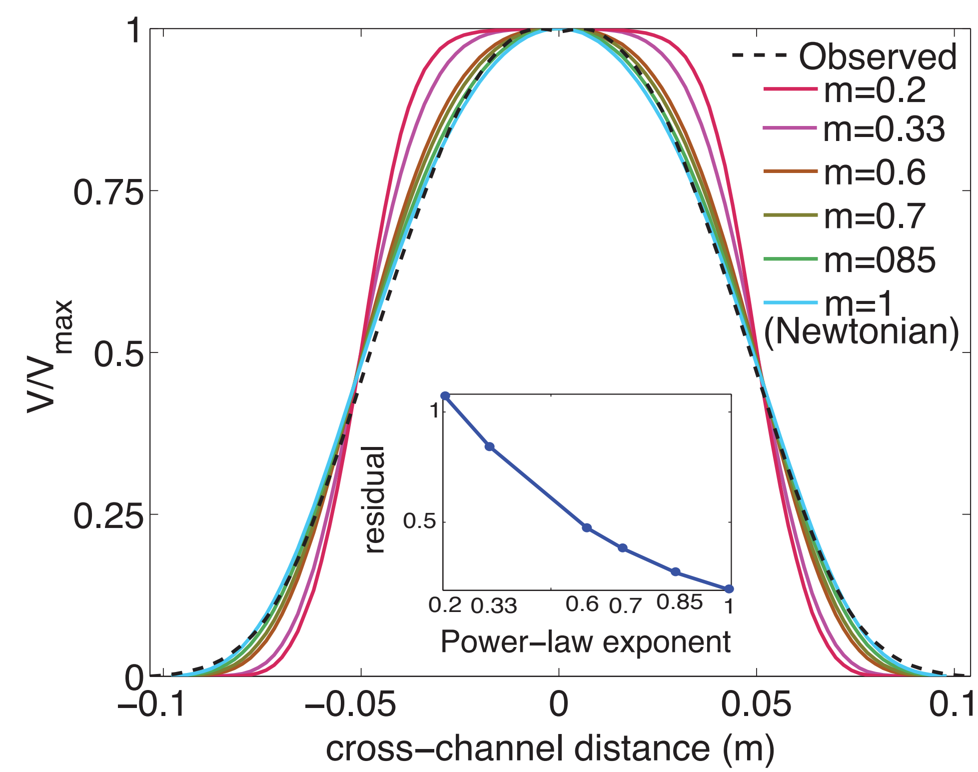
# Using the full surface velocity information — Velocimetry based assessments



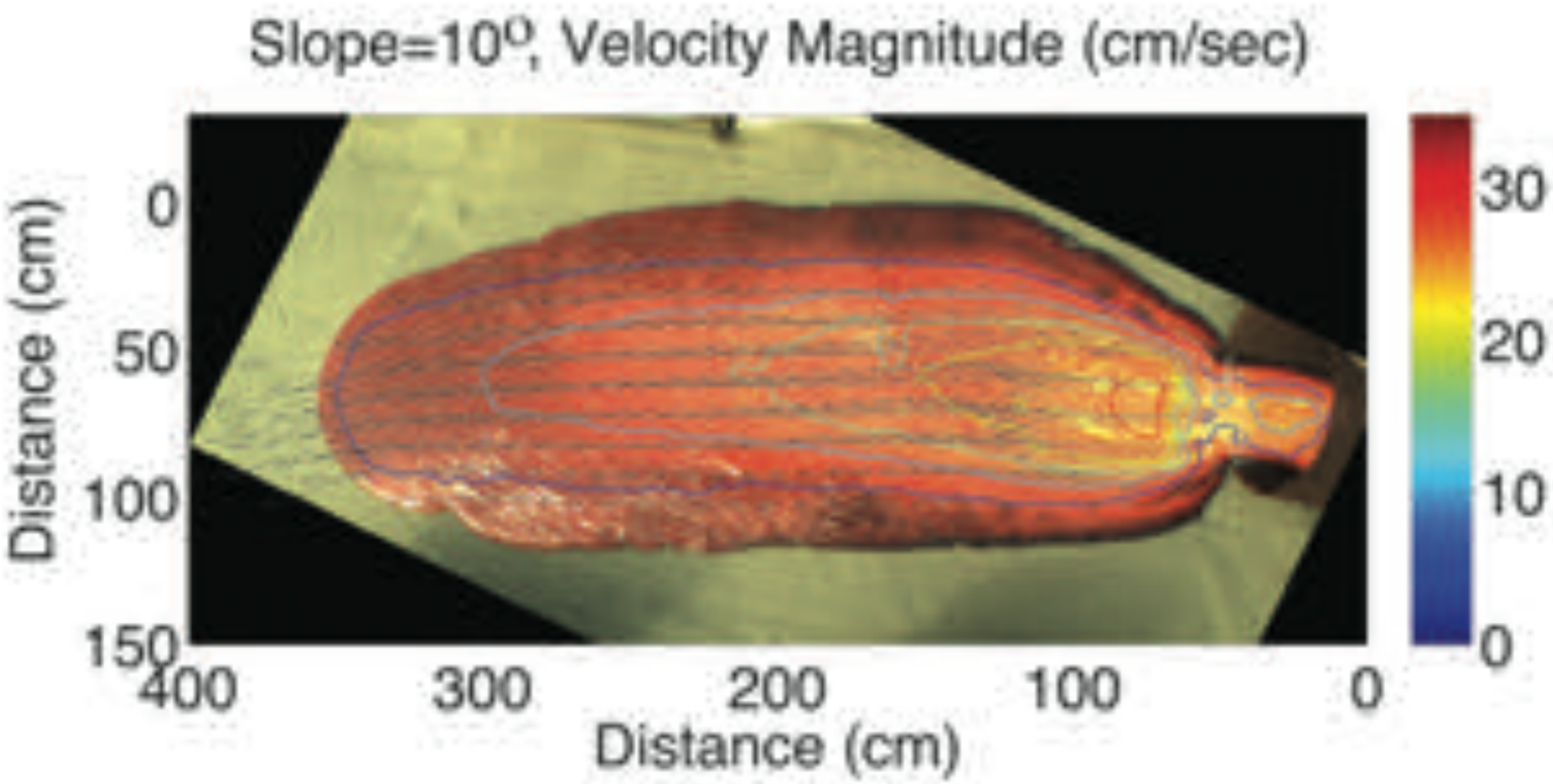

B)

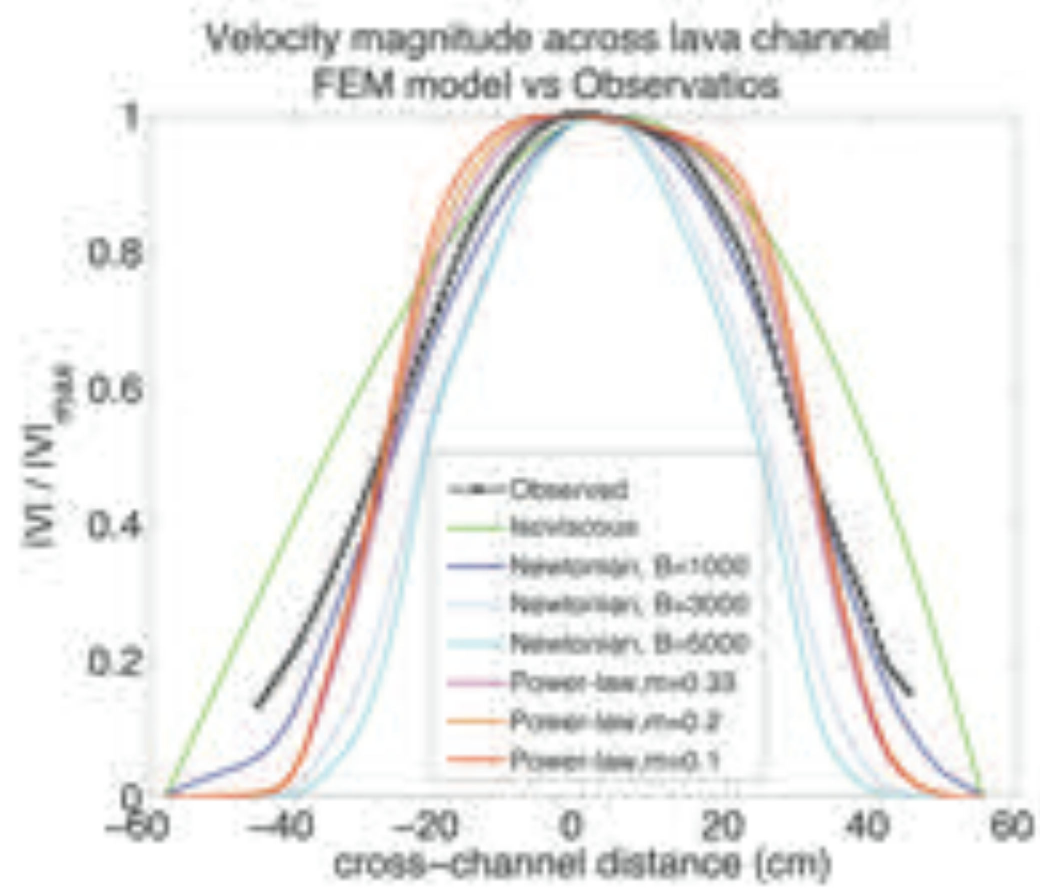



Lev et al., 2012

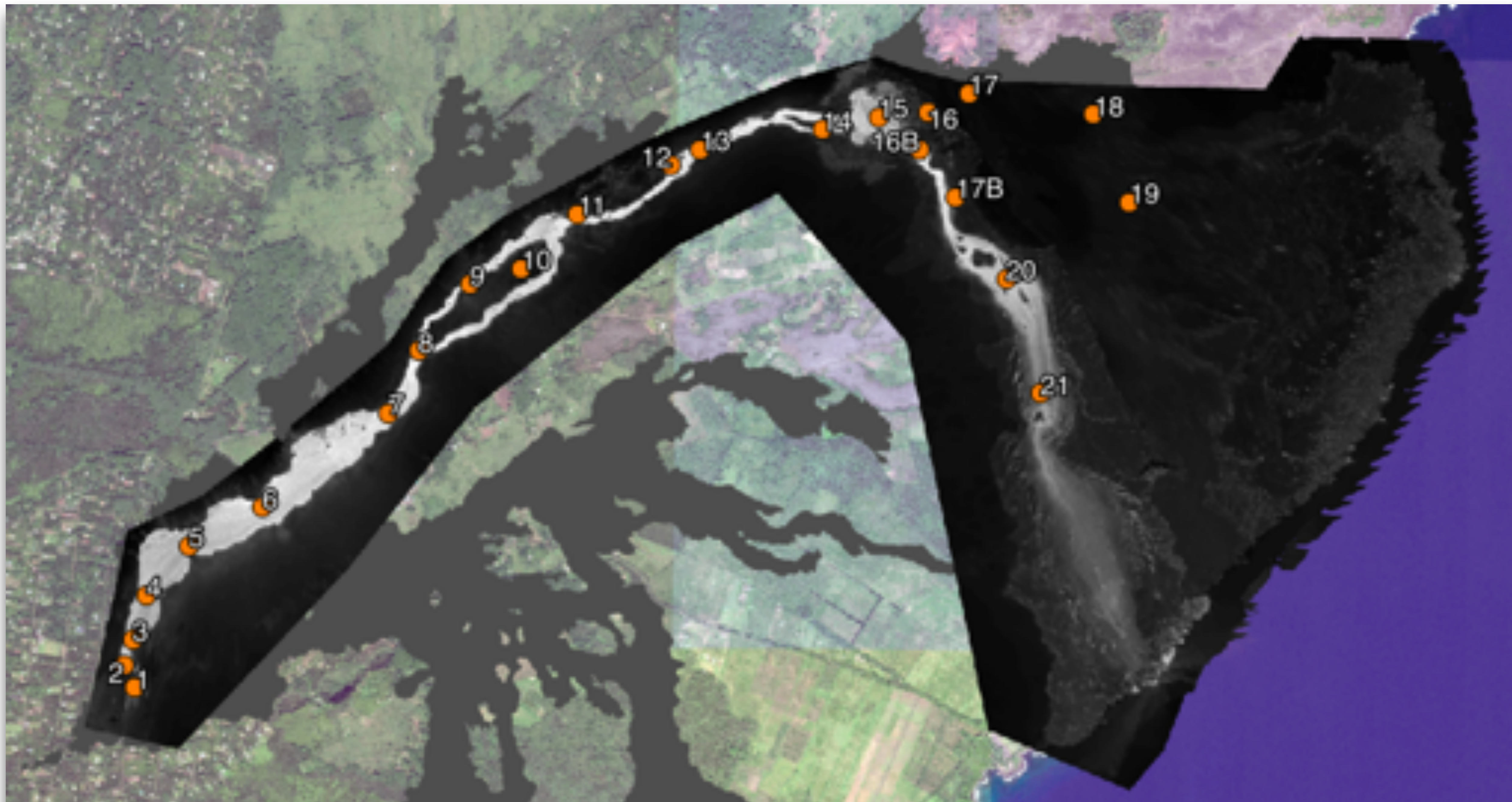
# Velocimetry-based assessments



# Velocimetry-based assessments — in the field

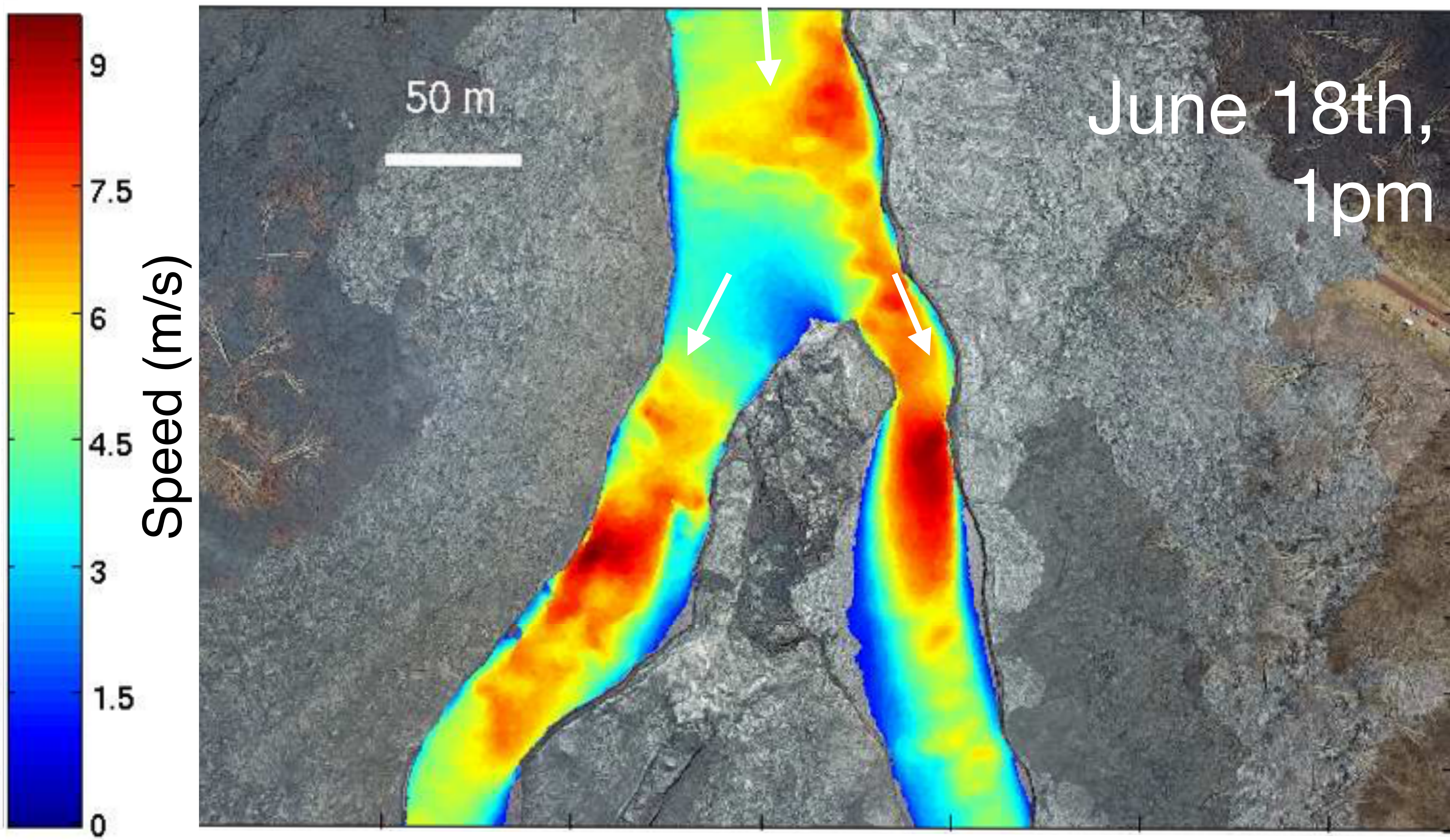
## Kīlauea 2018 sUAS hover sites



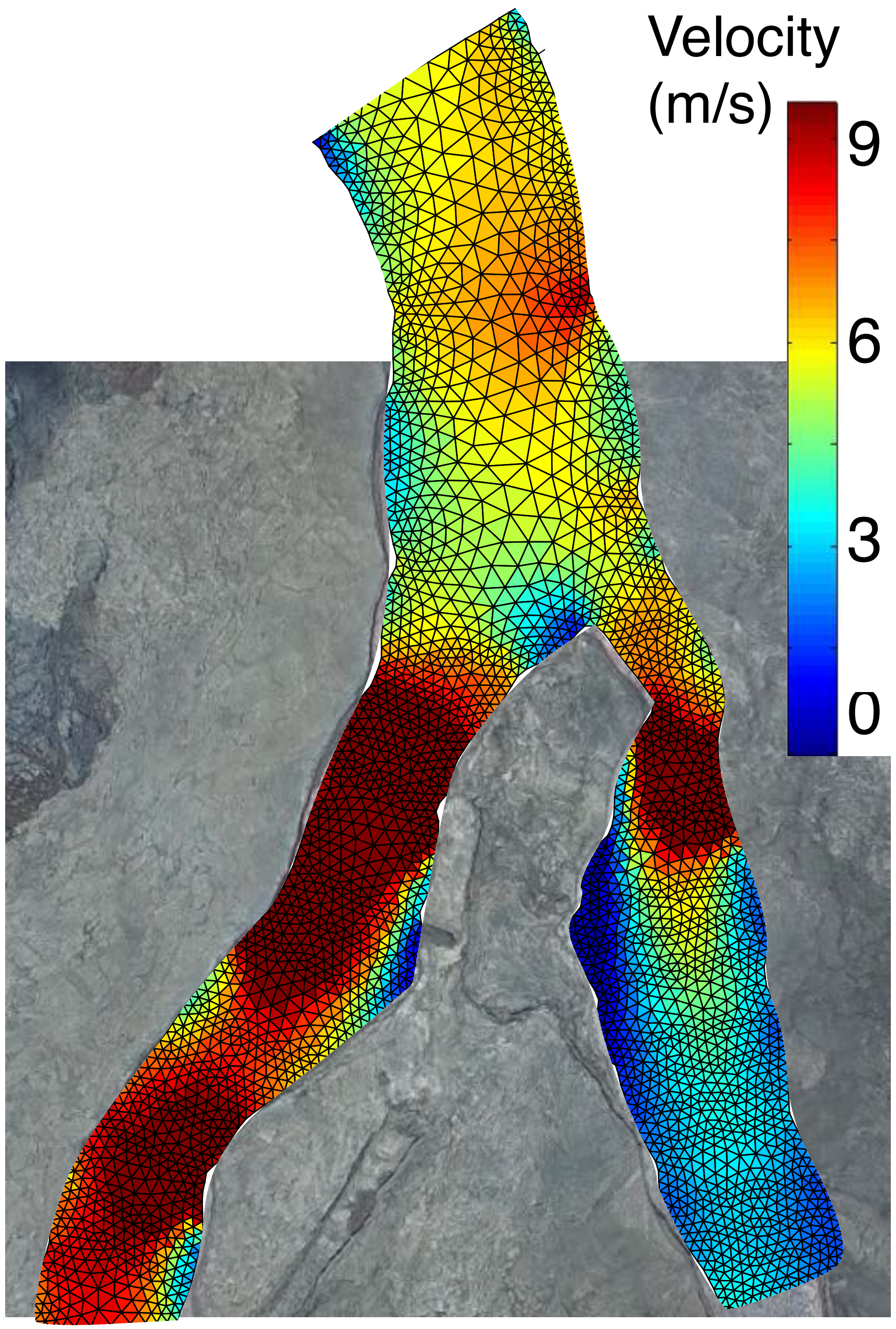

**USGS (Dietterich, Diefenbach… )**

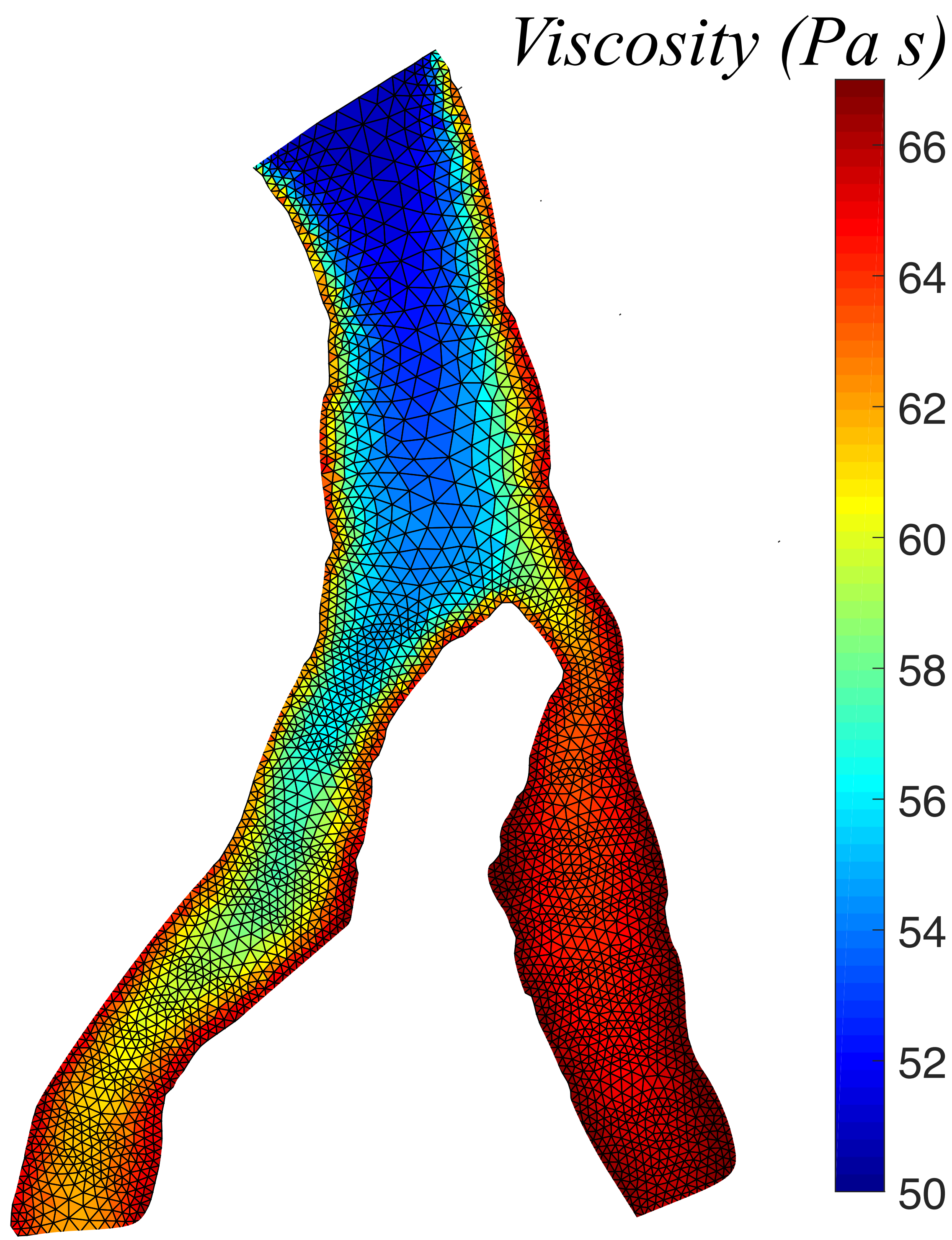
# Velocimetry-based assessments — in the field

# Velocimetry-based assessments — in the field

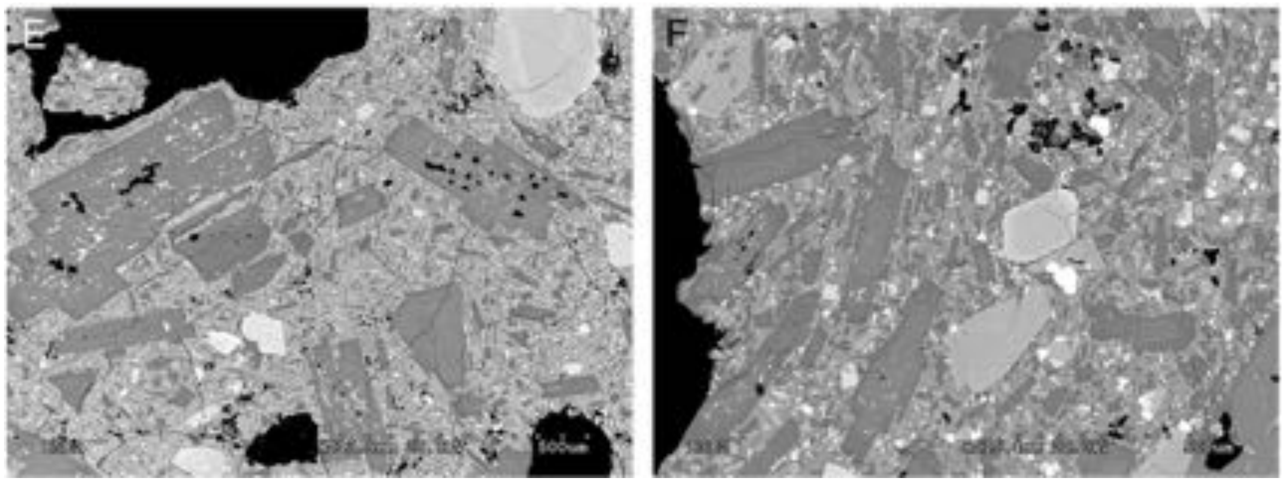


# Velocimetry-based assessments — in the field



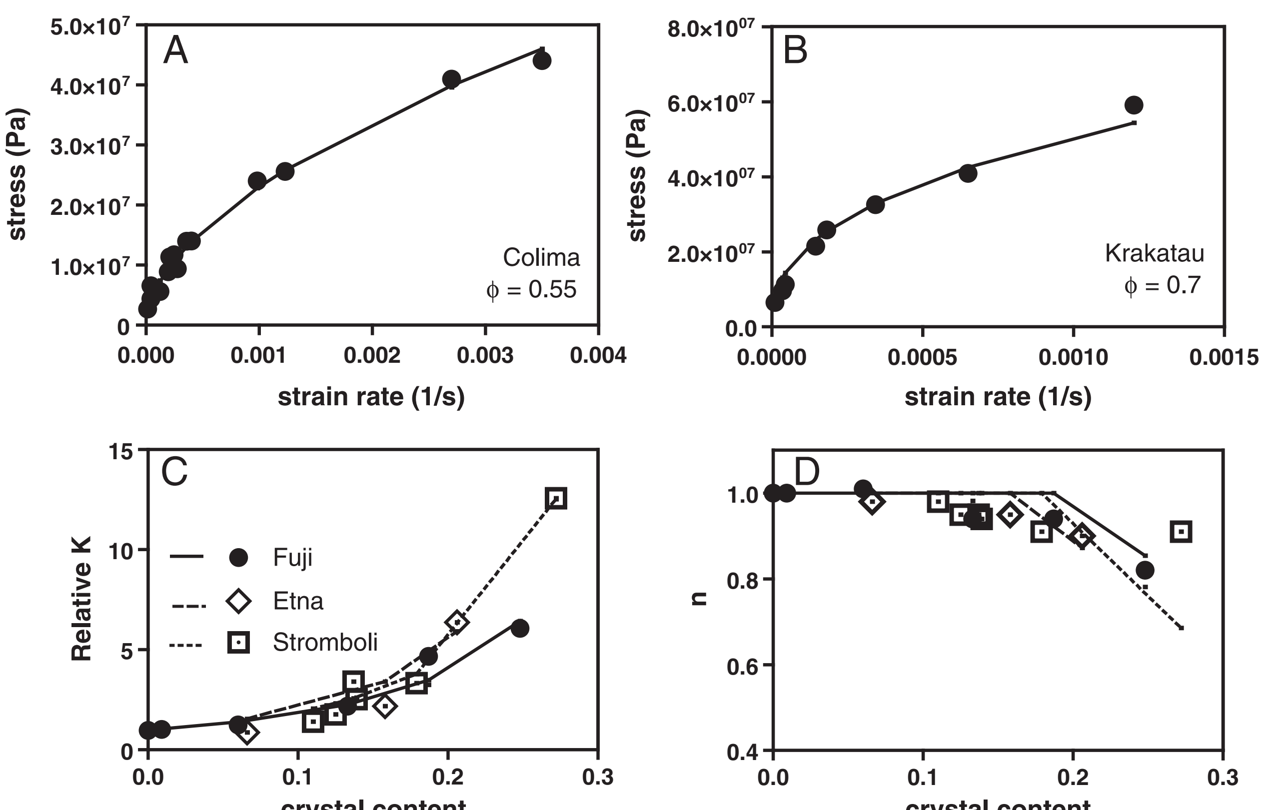



# Comparing with microstructure




**Colima**
**phi_m= 0.69**

**Krakatau**
**phi_m= 0.77**



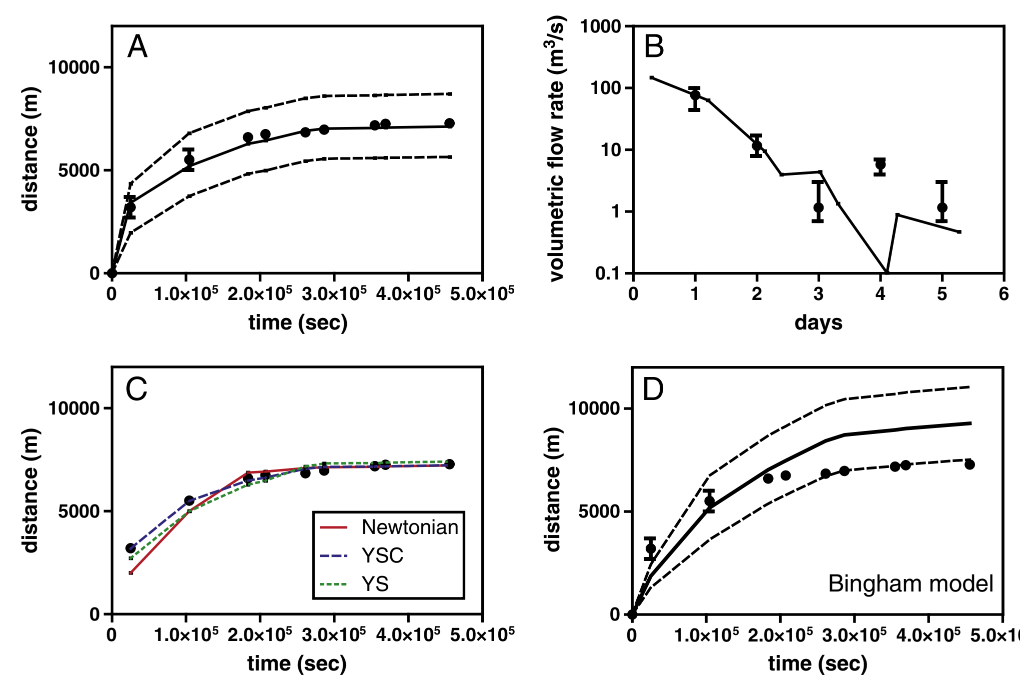

Castruccio et al., 2014

$$K(\phi) = K_o\left(1 - \frac{\phi}{\phi_m}\right)^{-2.3}$$

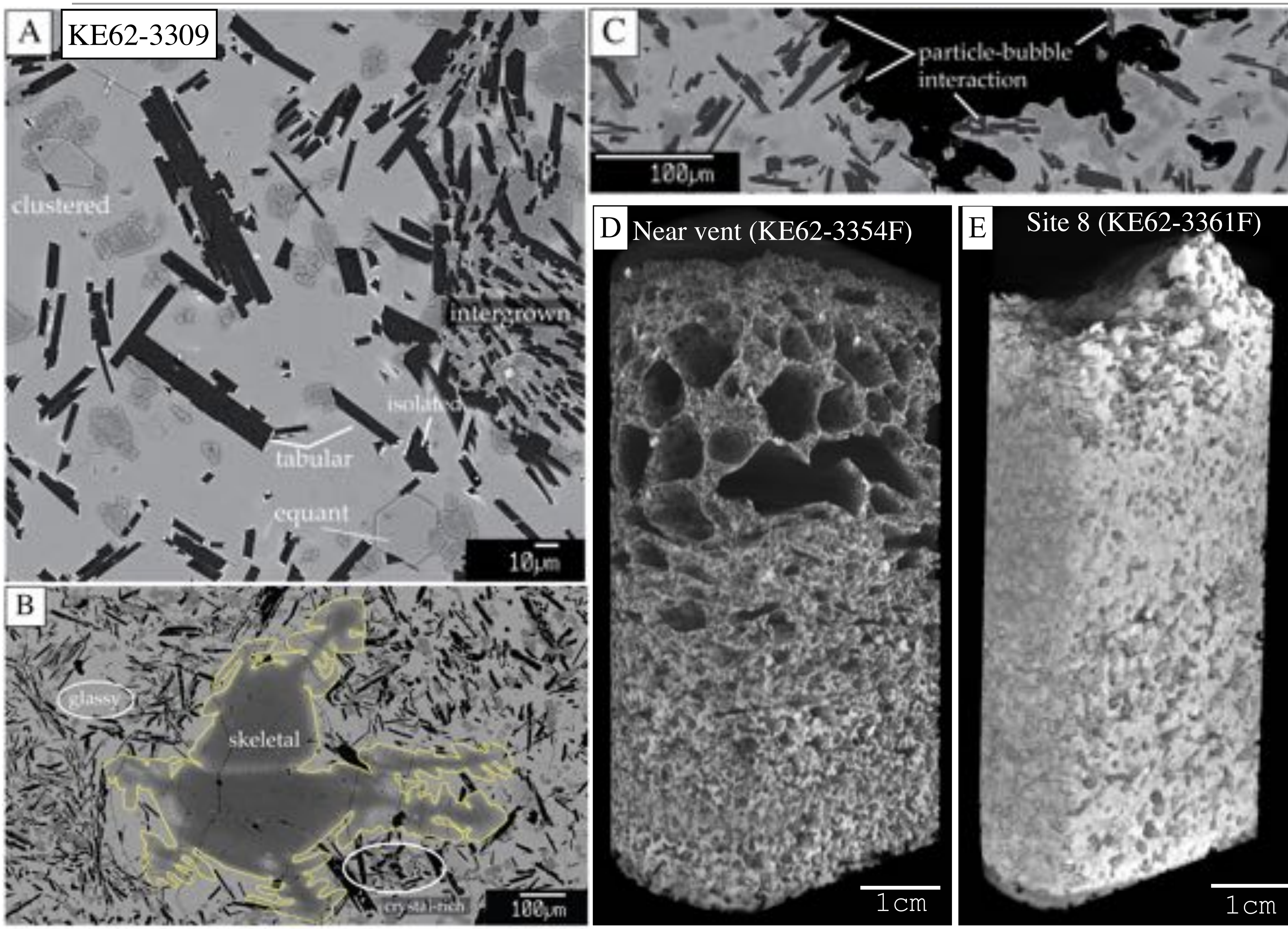
$$n(\phi) = \begin{cases} 1 & \phi \leq \phi_c \\ 1 + 1.3\left(\frac{\phi_c - \phi}{\phi_m}\right) & \phi > \phi_c \end{cases}$$

$$\tau_y(\phi) = \begin{cases} 0 & \phi \leq \phi_c \\ D(\phi - \phi_c)^8 & \phi > \phi_c \end{cases}$$

**Etna 2002**



# Comparing with microstructure




For solid particles:

$$K(\phi) = K_o\left(1 - \frac{\phi}{\phi_m}\right)^{-2.3}$$

$$n(\phi) = \begin{cases} 1 & \phi \leq \phi_c \\ 1 + 1.3\left(\frac{\phi_c - \phi}{\phi_m}\right) & \phi > \phi_c \end{cases}$$

$$\tau_y(\phi) = \begin{cases} 0 & \phi \leq \phi_c \\ D(\phi - \phi_c)^8 & \phi > \phi_c \end{cases}$$

**Alan Whittington, Julia Hammer**

# How lava flows are currently modeled?

- Goals of flow modeling
- Classes of models:
  - Probabilistic vs. Deterministic models
  - Physics-based vs. Rule-based models
- Testing and evaluating models
- Analog (physical) modeling

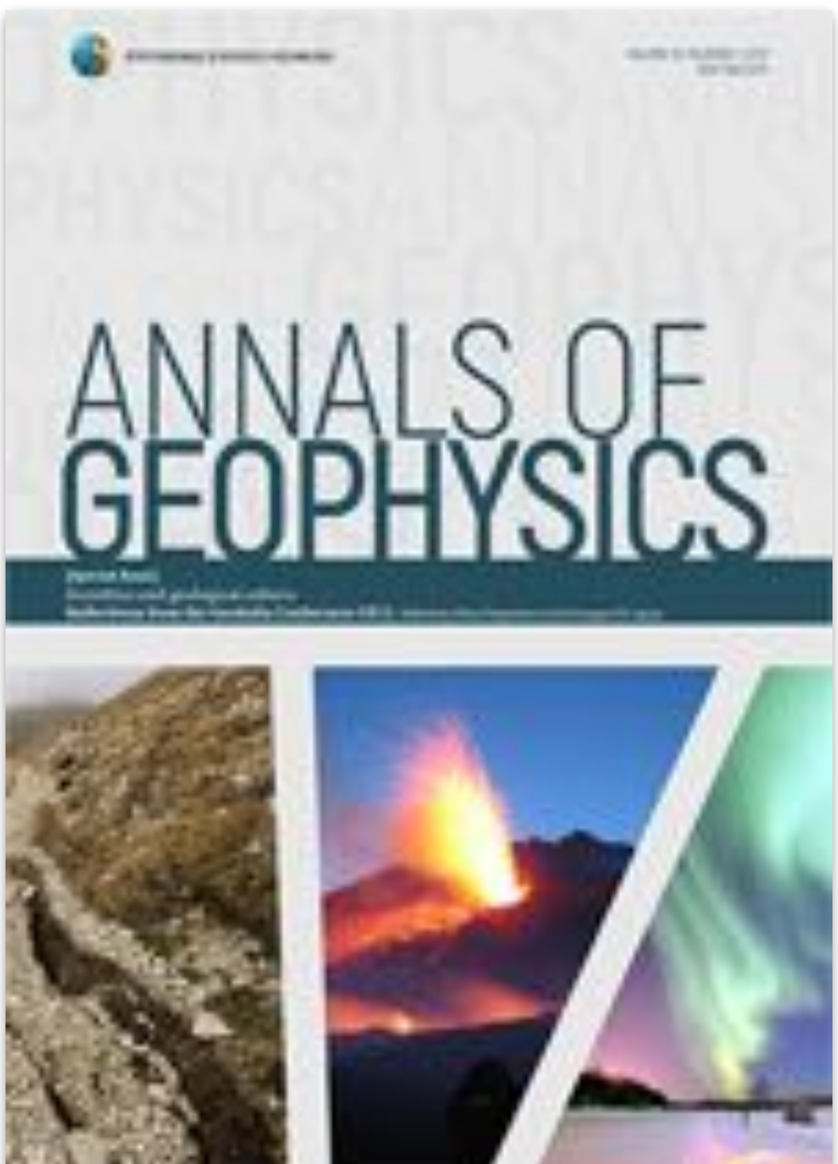
# Two$^2$ classes of models

- Deterministic — same result every time the model is run
- Probabilistic / Stochastic — include randomness

- Physics based — use viscosity, stress, temperature…
- Rule based — e.g., “go in steepest direction”

Lots of useful information in two recent special volumes:

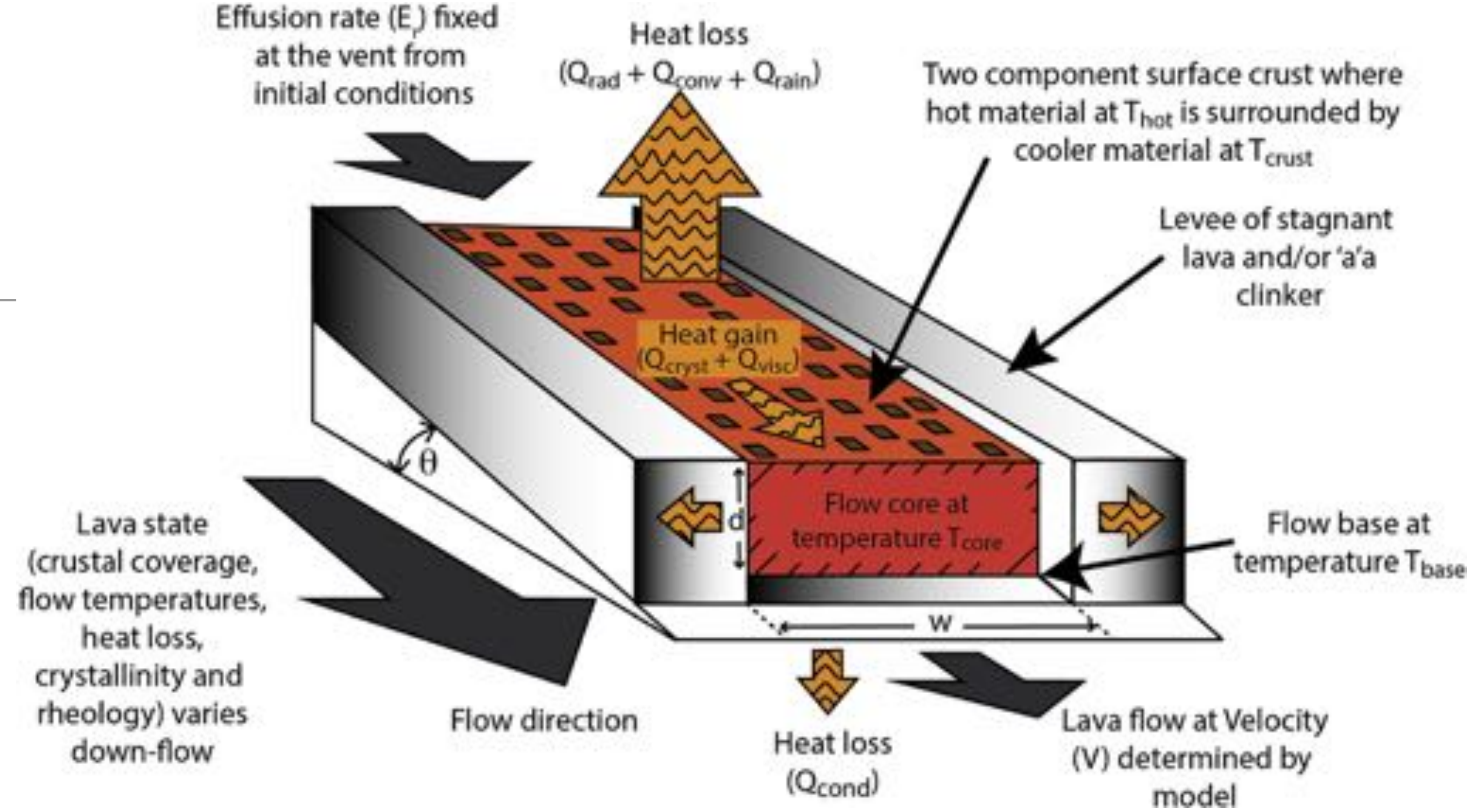
- 2015 Geological Society
- 2018 Annals of Geophysics




# FlowGO / pyFlowGo

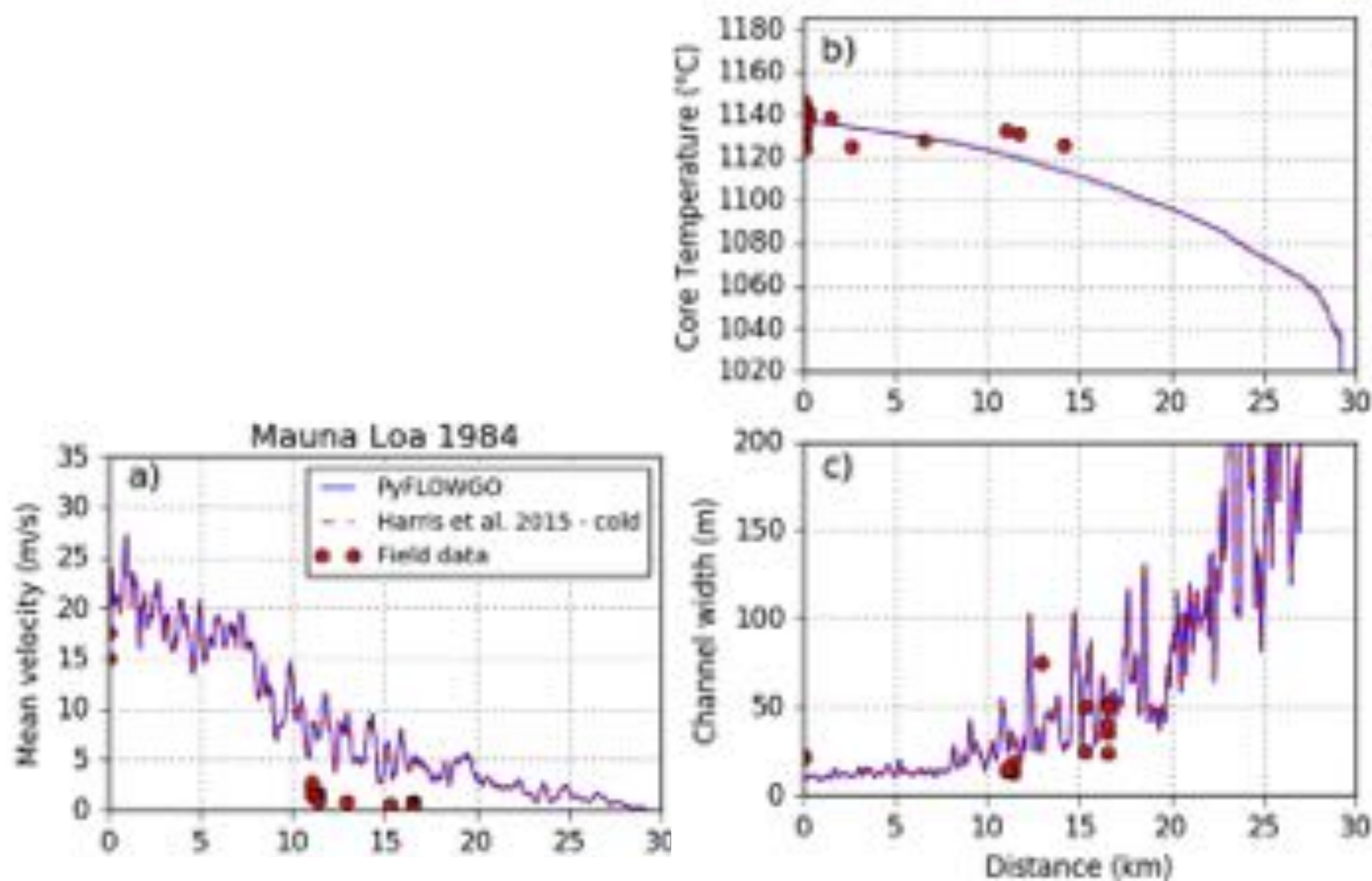
1D along-track deterministic, physics-based model

Original in Excel, now in Python, free on GitHub




- Slopes along track
- Initial: channel width and thickness, temperature, crystallinity, and composition

- Along track evolution of: velocity, width, thickness, crystallinity, viscosity, temperature.
- Maximum length



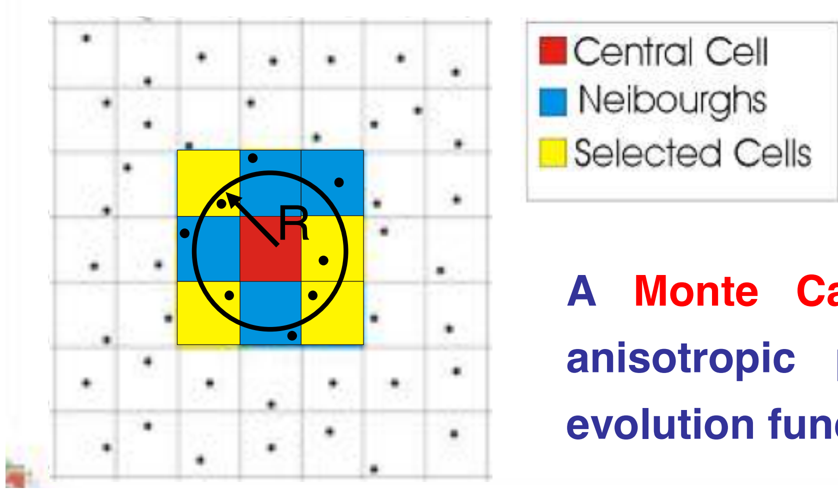
# Cellular Automata models (MAGFLOW, SCIARA…)

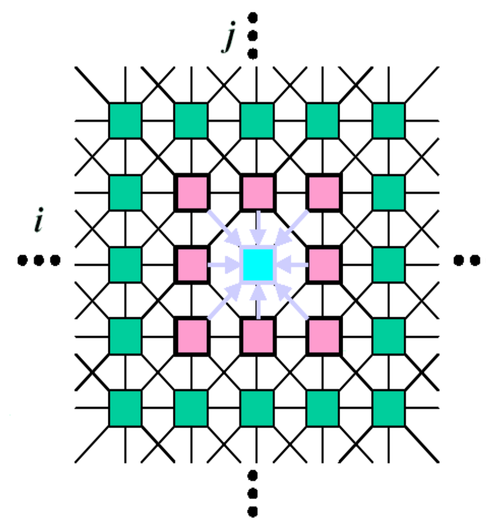
- Deterministic, (simple) physics-based

**The MAGFLOW model is based on a Cellular Automata structure, defined by a regular mesh with square cells. Two state variables are defined for each cell: thickness of lava and quantity of heat.**

**The evolution function of the CA is a steady state solution of Navier-Stokes equation in the case of a Bingham fluid that flows on an inclined plane.**

**The viscosity and the yield strength of lavas depend on the temperature and water content (Giordano and Dingwell, 2003; Ishiara et al., 1990).**



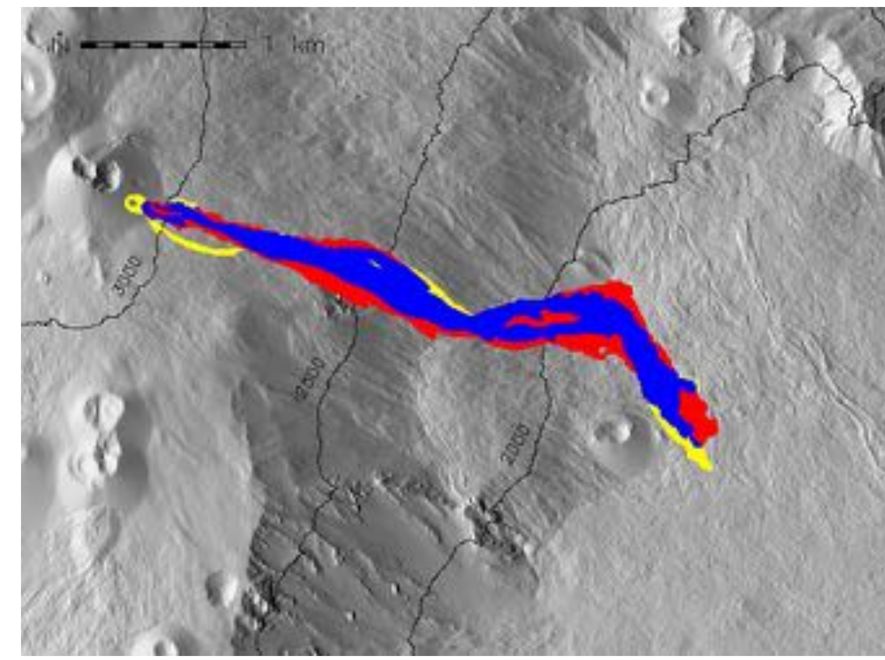
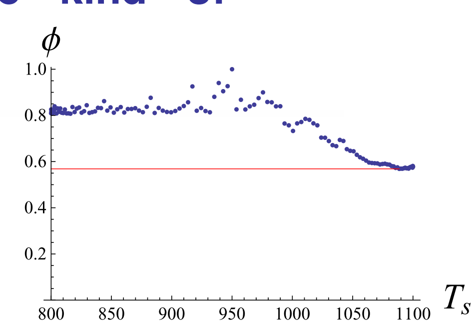
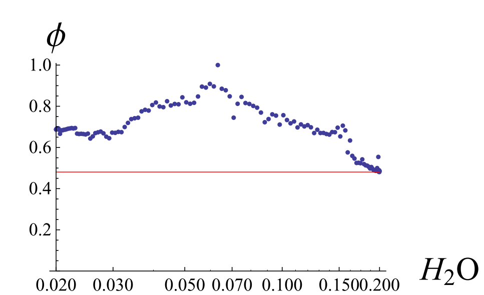




Fig. 3. Graphical representation of fitness computation obtained overlaying a test simulation with an actual emplacement (reference). Blue (0.58 km$^2$) denotes common invasion areas, yellow (0.08 km$^2$) denotes underestimated areas (in the reference but not in the tested simulation), red (0.03 km$^2$) denotes overestimated areas (in the tested simulation but not in the reference). Fitness is computed as the ratio between the blue area and the union of all the areas, and in this case would be $\phi = 0.58/(0.58 + 0.08 + 0.03) = 0.8406$ ($e_1 = 0.9168$). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

**A Monte Carlo approach is used to solve the anisotropic problem, deriving from the kind of evolution function used.**

$$\phi(A, B) = \frac{|A \cap B|}{|A \cup B|}.$$



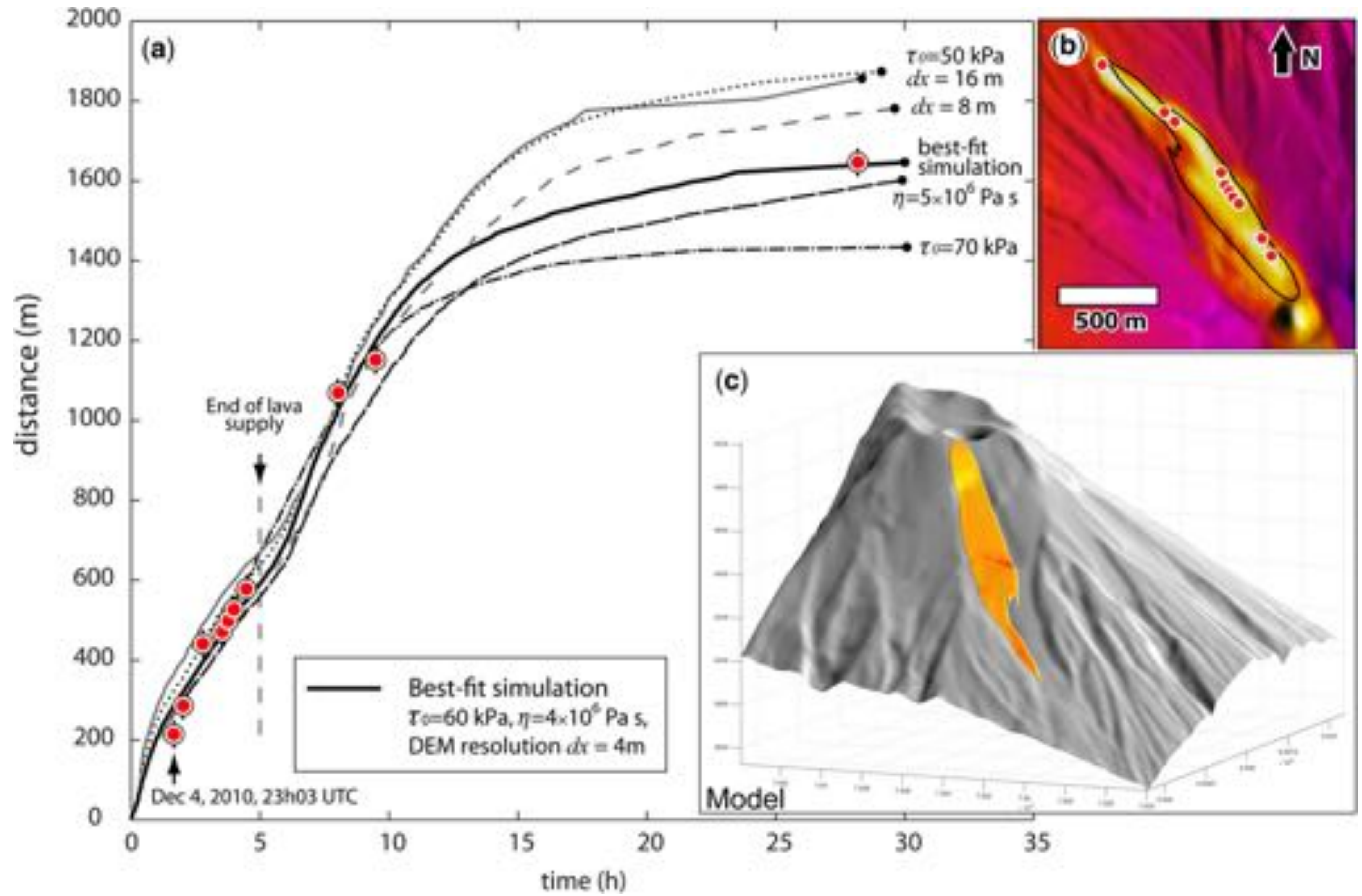
# VolcFLOW

- Depth-averaged approach that solves mass (1) and momentum (2-3) conservation equations (Deterministic, Physics-based)
- A Matlab executable

$$\frac{\partial h}{\mathrm{d}t} + \frac{\partial}{\partial x}(hu) + \frac{\partial}{\partial y}(hv) = \frac{\partial h_s}{\mathrm{d}t} \qquad (1)$$

$$\frac{\partial}{\partial t}(hu) + \frac{\partial}{\partial x}(hu^2) + \frac{\partial}{\partial y}(huv) = gh\sin\alpha_x - \frac{1}{2}\frac{\partial}{\partial x}(gh^2\cos\alpha) + \frac{\tau_x}{\rho} \qquad (2)$$

$$\frac{\partial}{\partial t}(hv) + \frac{\partial}{\partial x}(hvu) + \frac{\partial}{\partial y}(hv^2) = gh\sin\alpha_y - \frac{1}{2}\frac{\partial}{\partial y}(gh^2\cos\alpha) + \frac{\tau_y}{\rho}. \qquad (3)$$



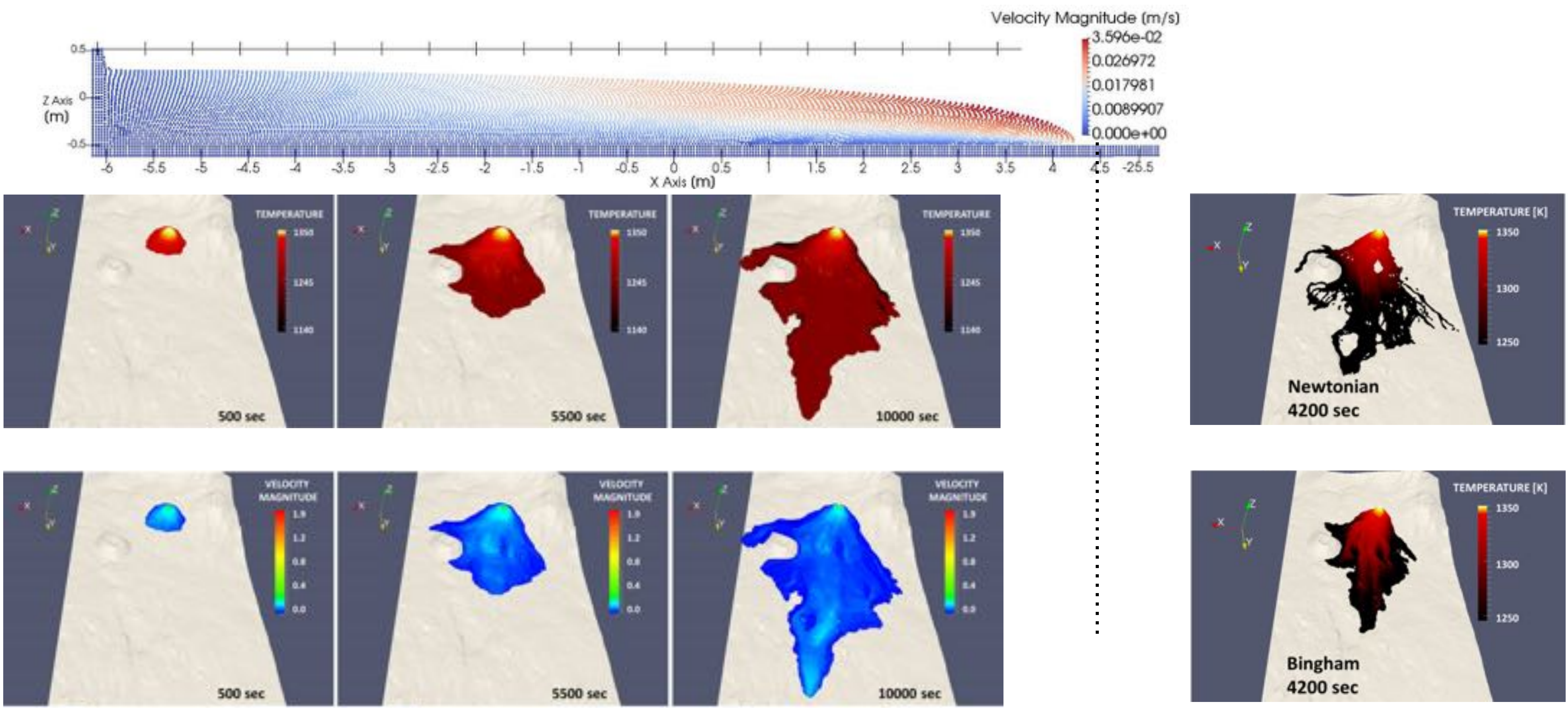

Test case:Tungurahua (Ecuador), 2010

Kelfoun and Vallejo-Vargas, 2015

# CFD models

GPUSPH – smoothed particle hydrodynamics.

Deterministic, physics based

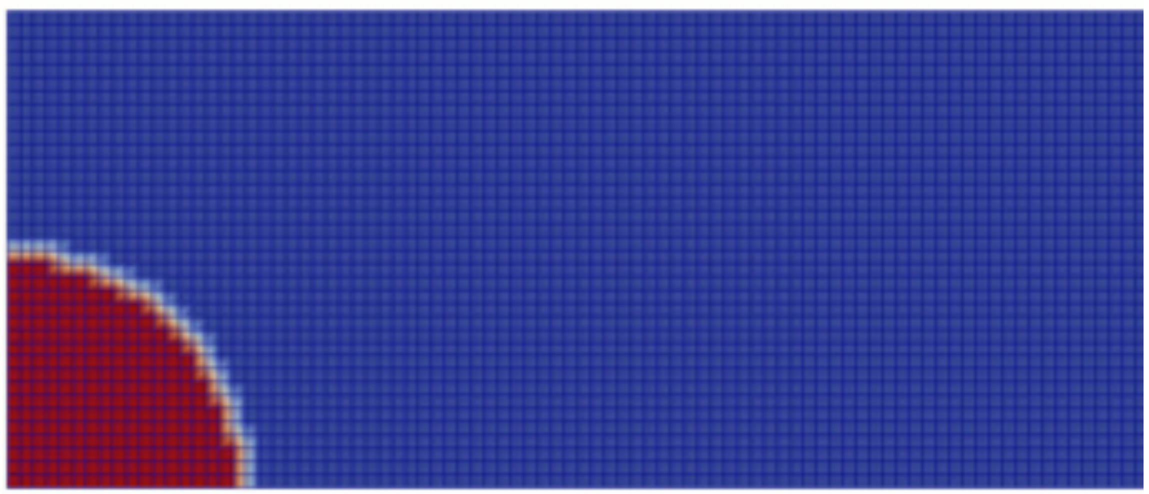


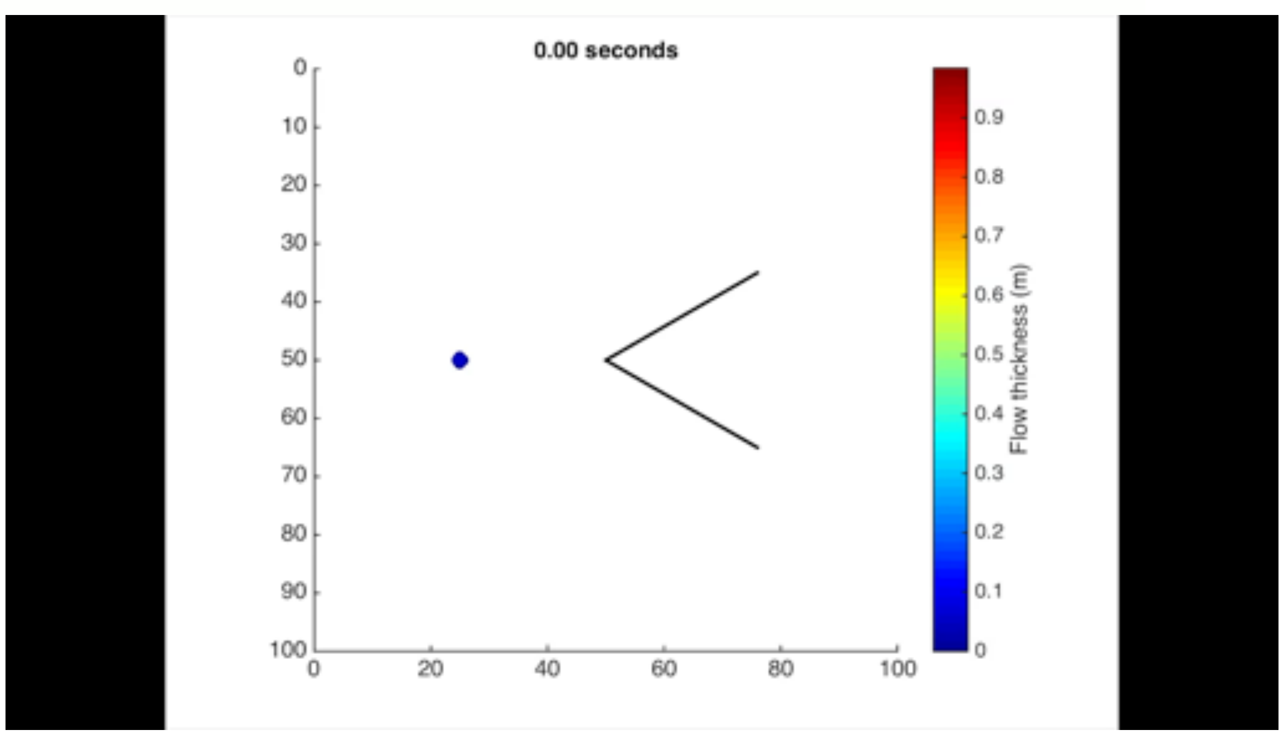

Bilotta et al., 2016

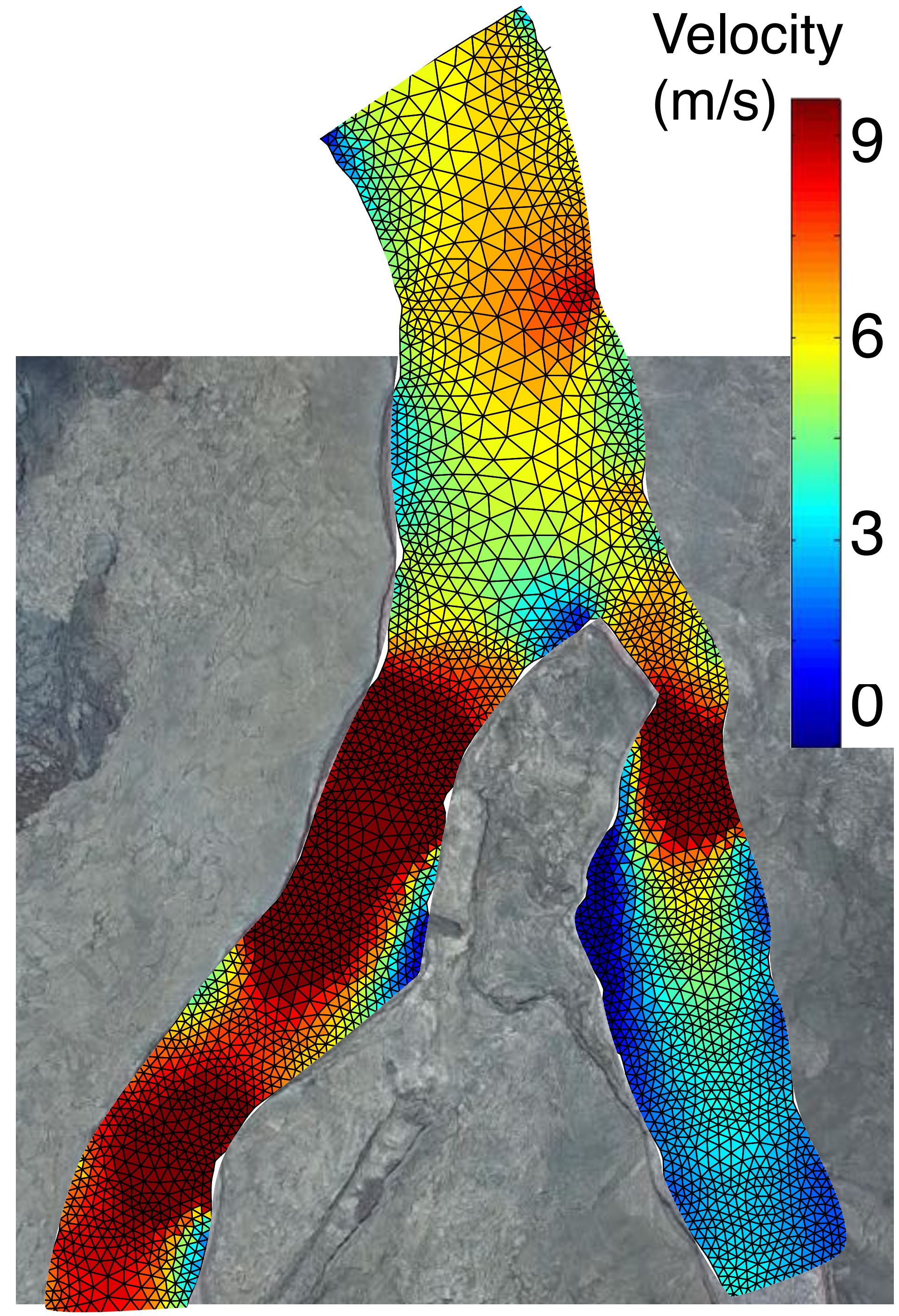
# CFD models

Finite Elements/Volumes: OpenFOAM, Flow3D, COMSOL, new LDEO code

Deterministic, physics-based



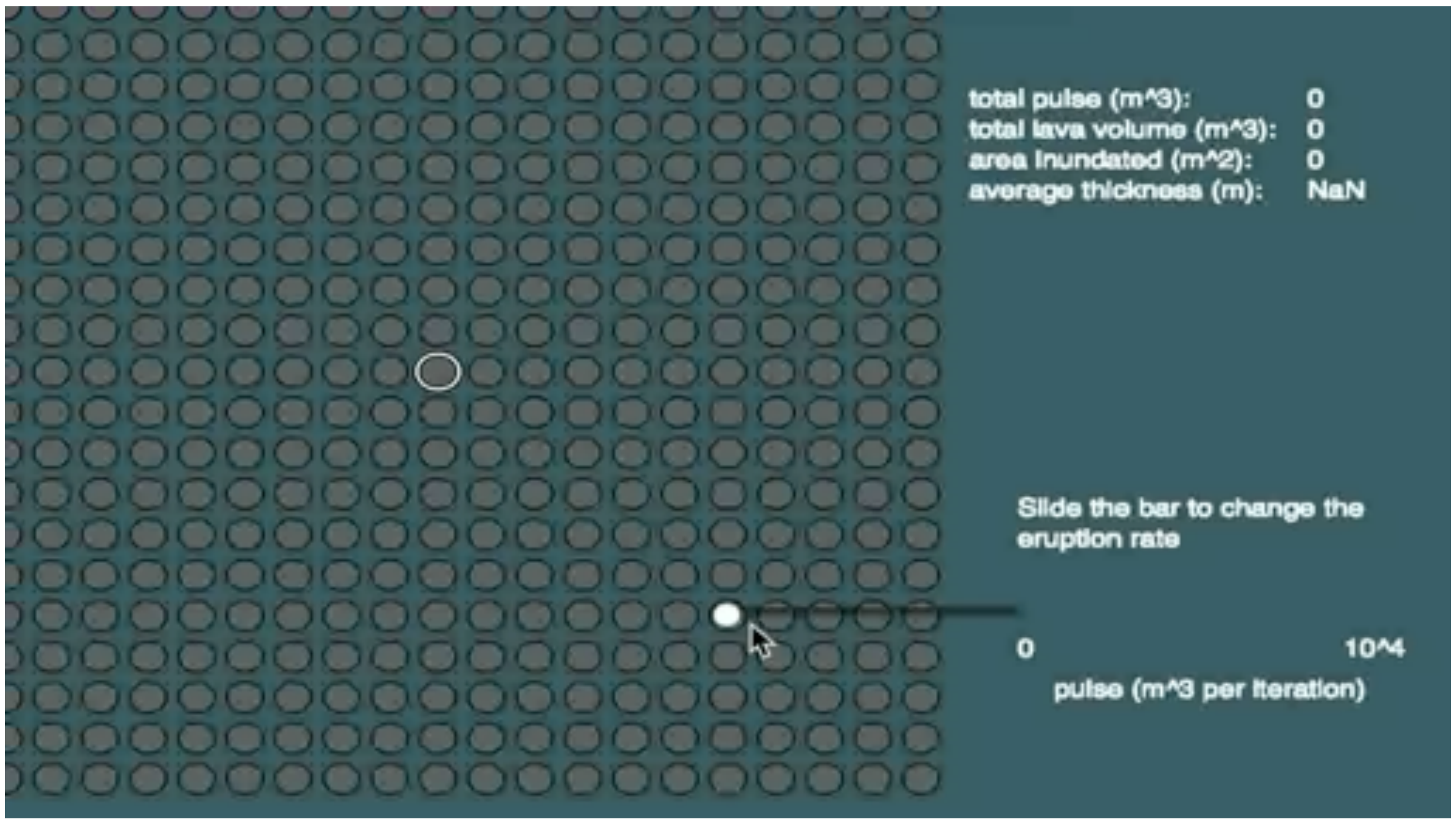


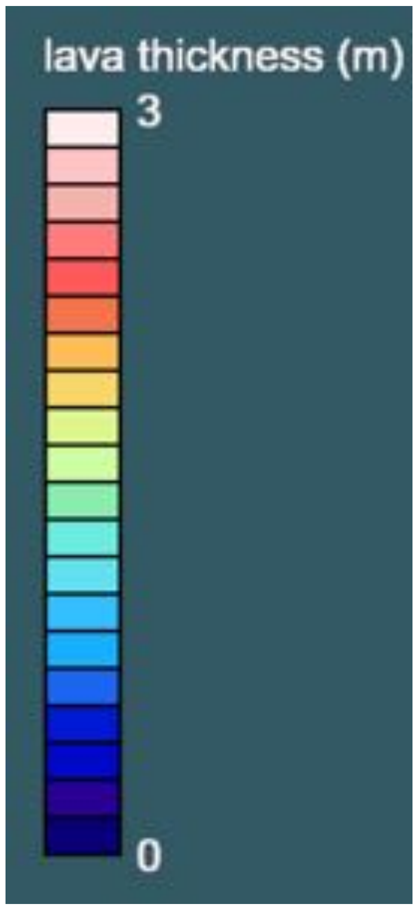



# That’s just too much physics…

# MOLASSES

- Deterministic, rule-based



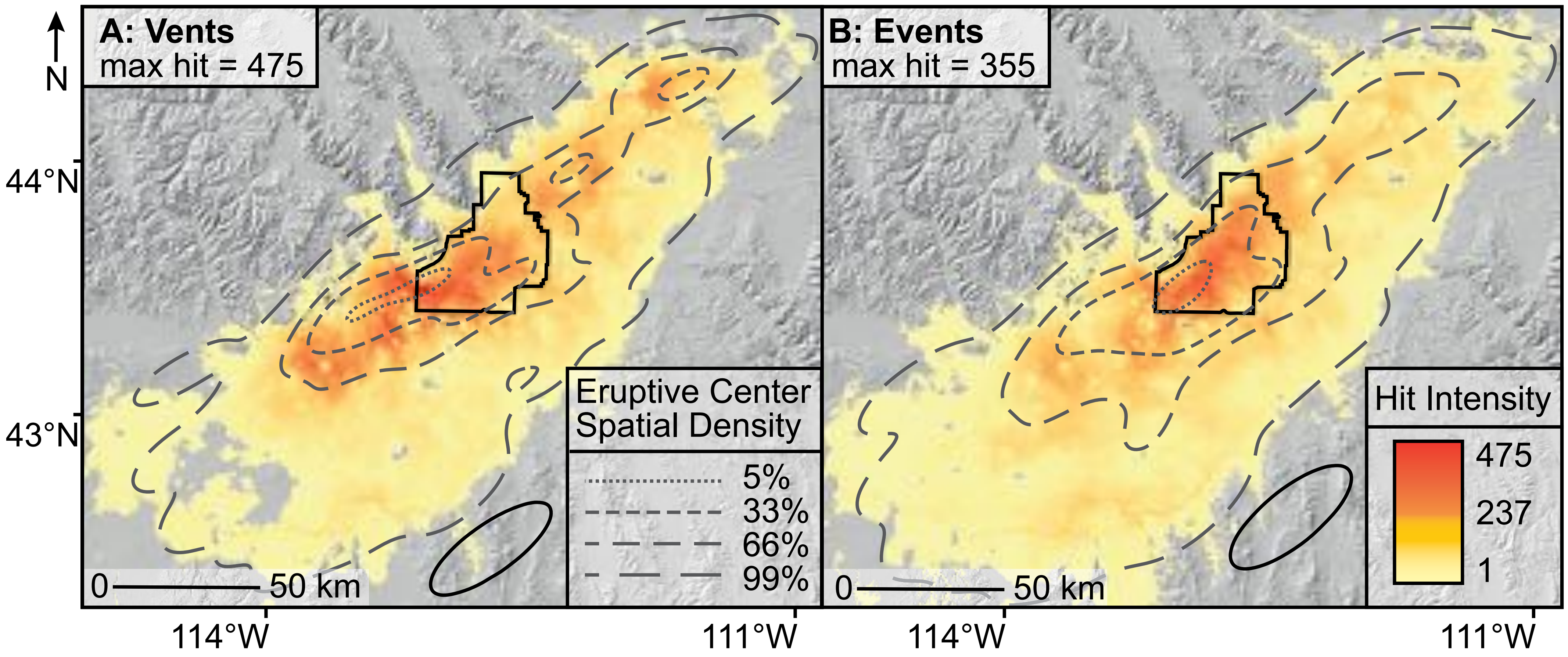




https://github.com/USFvolcanology/molasses

**http://www.cas.usf.edu/~cconnor/lava_sandbox2.html**

# MOLASSES—> INL hazard map

- Combine:
  - prolific geologic mapping and differs from earlier works by incorporating novel models of ESRP volcanism,
  - a new method of clustering vents into eruptive events, probabilistic selection of input parameters,
  - computational lava flow simulations,
  - analysis of activity recurrence intervals to report unconditional probabilities of future hazards



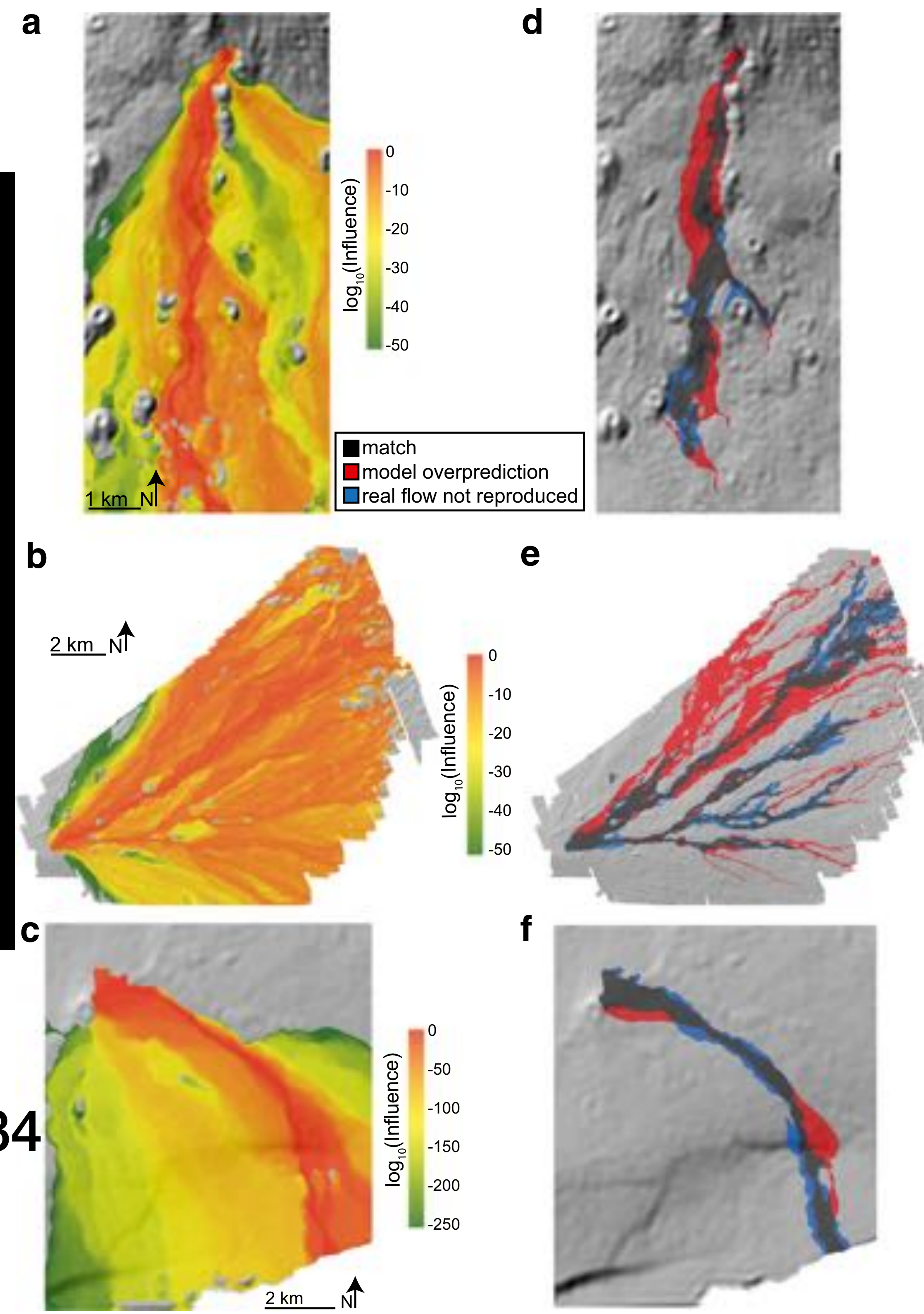
# MULTIFLOW

## Deterministic, rule-based

1. Take a DEM and put a vent somewhere
2. Starting at the vent, disperse lava to neighboring cells in proportion to relative slope:

$$I_i = \frac{S_i^p}{\sum_{k=1}^{n} S_k^p}.$$

3. Summarize results: Total "influence" at each location

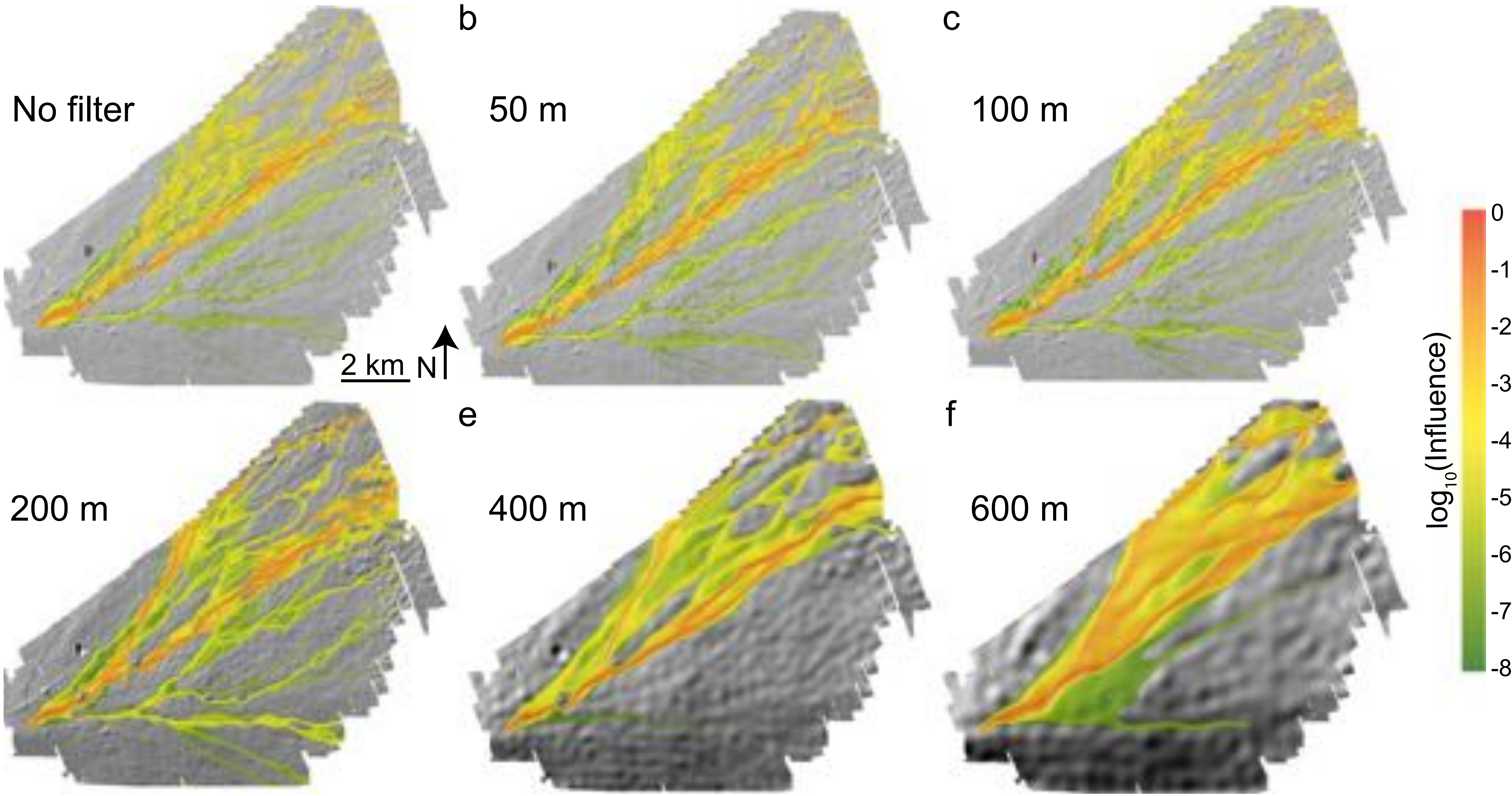



Etna 2006
Mauna Loa 1984
Kīlauea 2011

Richardson and Karlstrom 2019

# MULTIFLOW

## Effect of low-pass filtering of the DEM

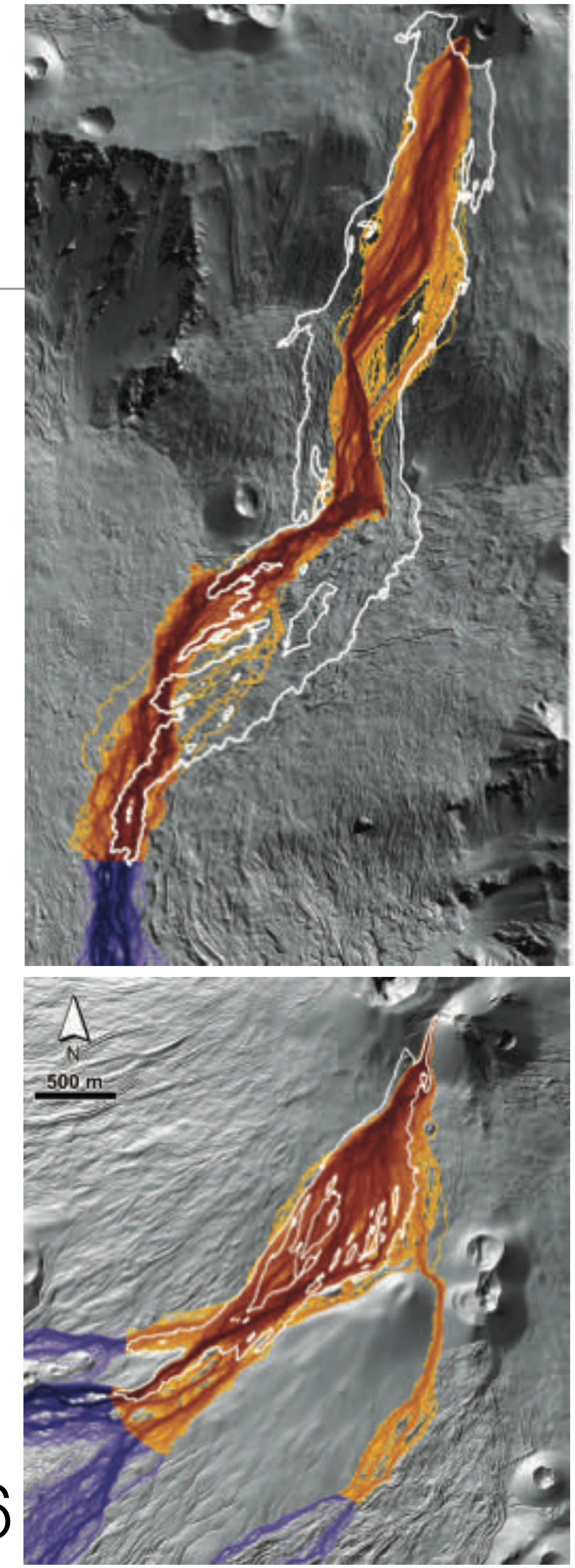



Richardson and Karlstrom 2019

# DOWNFLOW

## Stochastic, rule-based

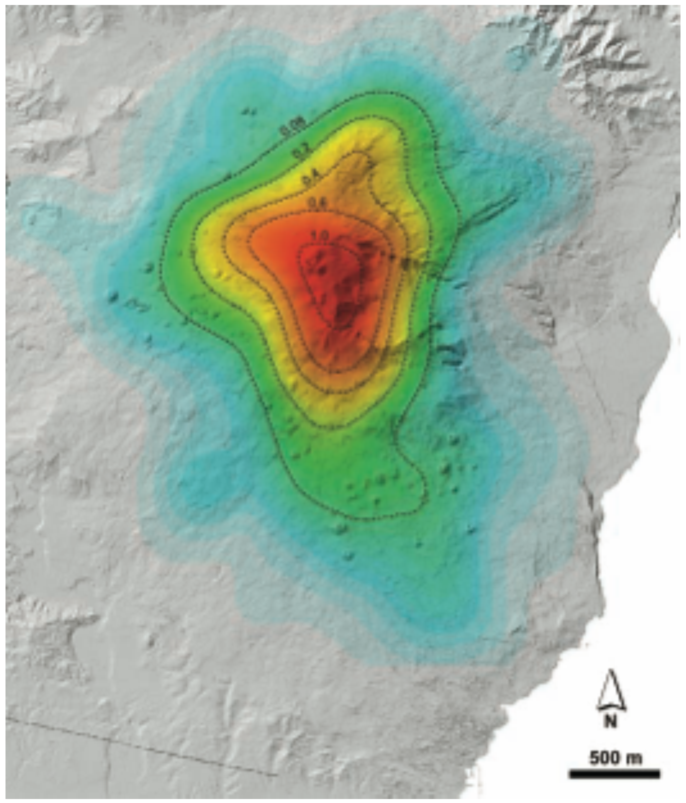
1. Take a DEM and put a vent somewhere
2. For N iterations:
    1. Modify the elevation at each DEM point by a random value $\pm\Delta h$
    2. Trace a steepest decent path from the vent through the DEM
    3. Optional: end the trace at a given length
3. Summarize results: probability of inundation for each grid point




Etna 2006

Favalli et al., 2005, 2009, 2011

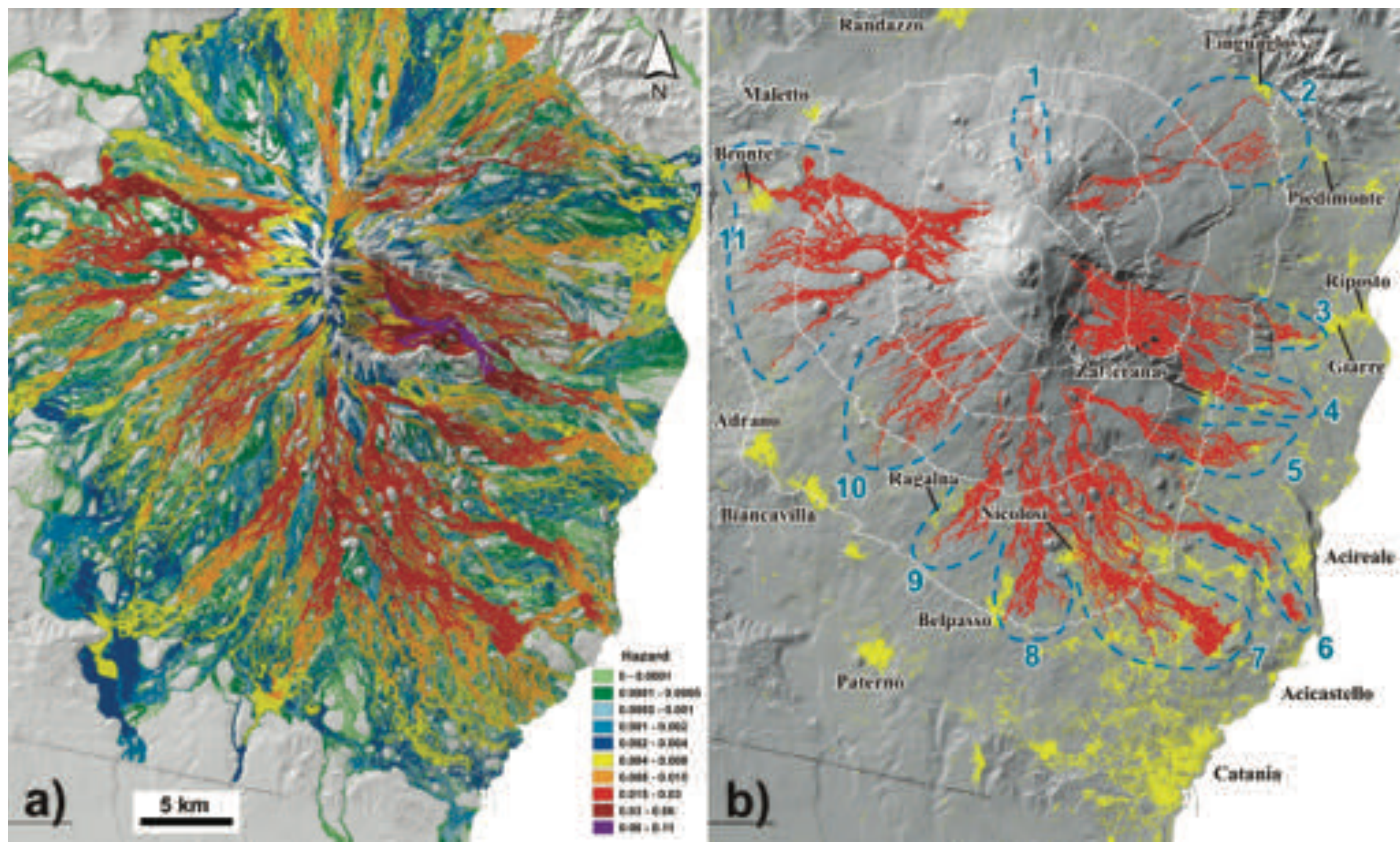
# DOWNFLOW → Hazard map



Vent opening density function

$$P(x,y) = \iint P_{DOWNFLOW}(x,y;\, x',y') \cdot P_L(h,L) \cdot p_v(x',y')\, dx'dy' \qquad (2)$$

Probability to occur in *Y* years assuming Poisson distribution of vent openings




Favalli et al., 2005, 2009, 2011

# Model assessment

- Benchmarking
- Model Inter-comparison

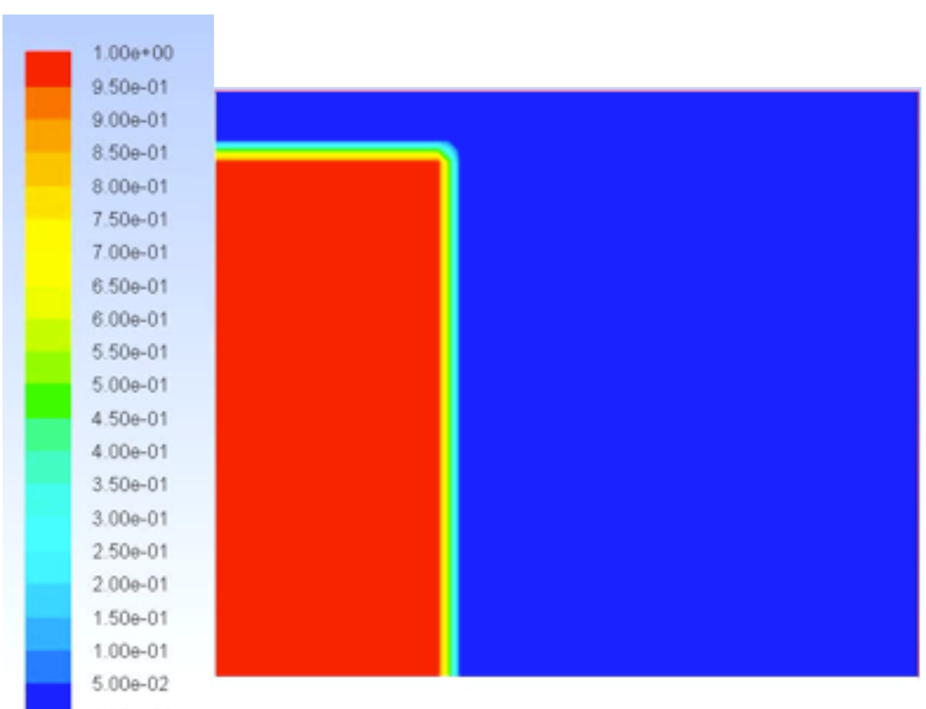
(Also must think about verification and validation)

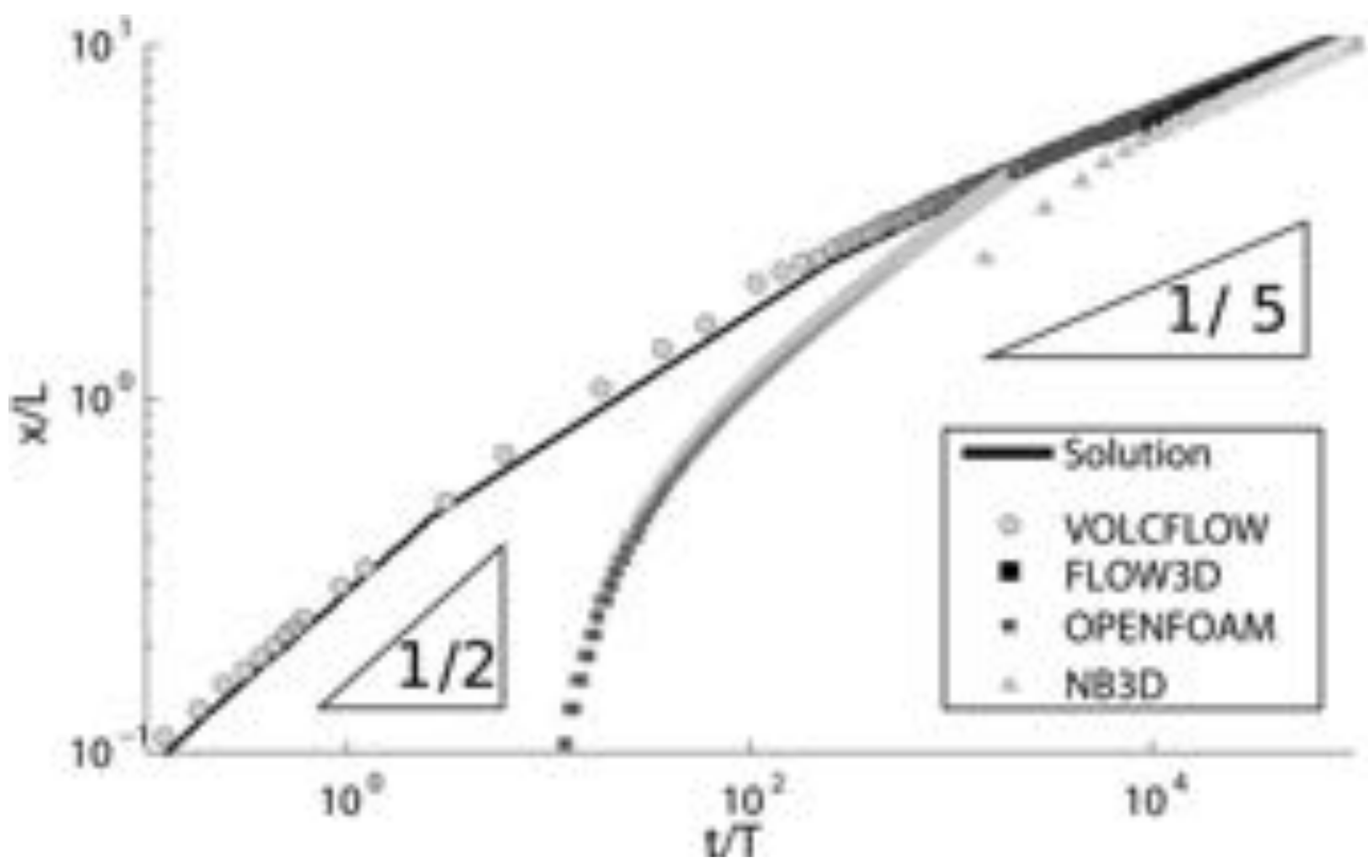
**Cordonnier et al., 2015; Dietterich et al., 2017**

# Model assessment

- Benchmarking — BM1

$$\frac{x_f(t)}{L} \approx \begin{cases} 0.284\left(\frac{t}{T}\right)^{1/2} & \text{if } t < 2.5T \\ 1.133\left(\frac{t}{T} + 1.221\right)^{1/5} - 1 & \text{otherwise} \end{cases}$$

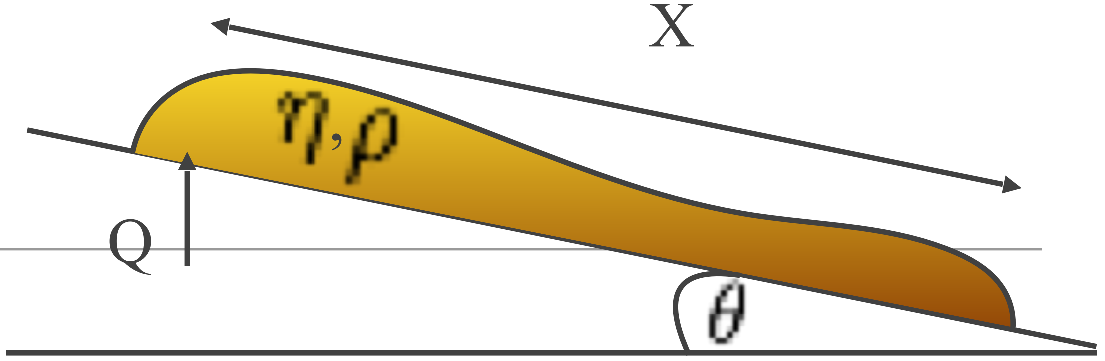


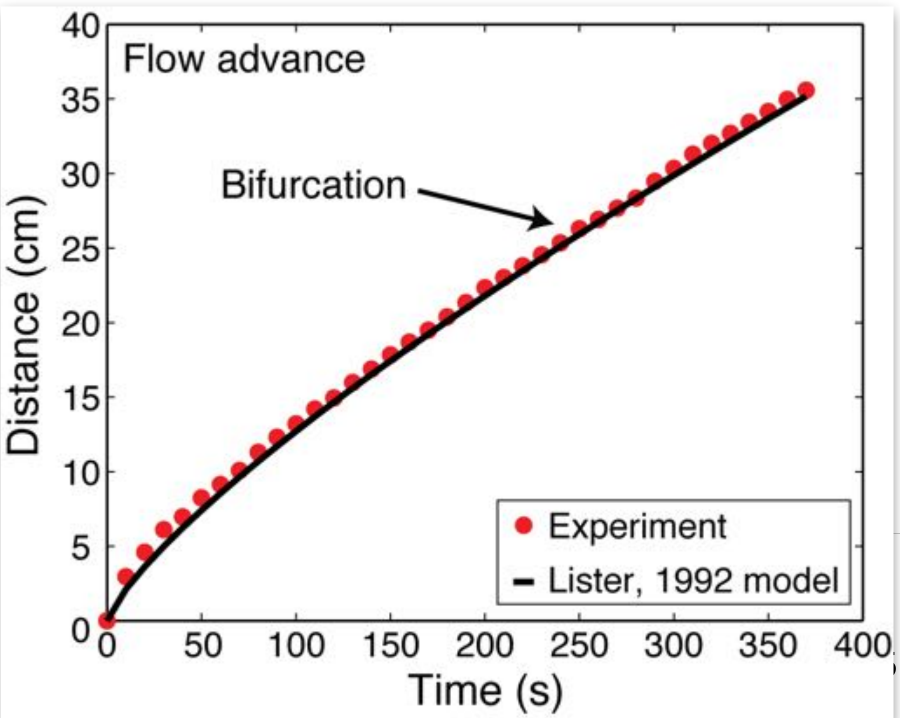




Cordonnier et al., 2015; Dietterich et al., 2017

# Model assessment

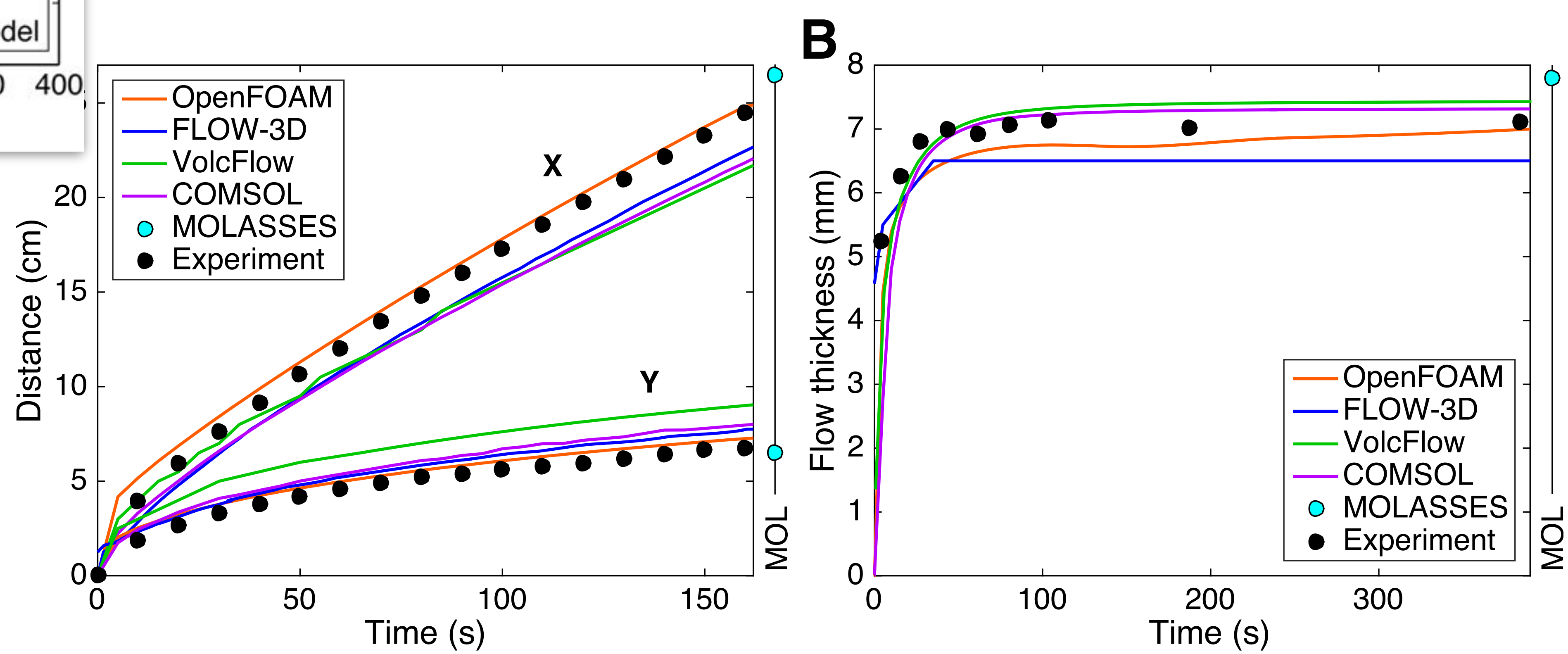
- Benchmarking — BM2



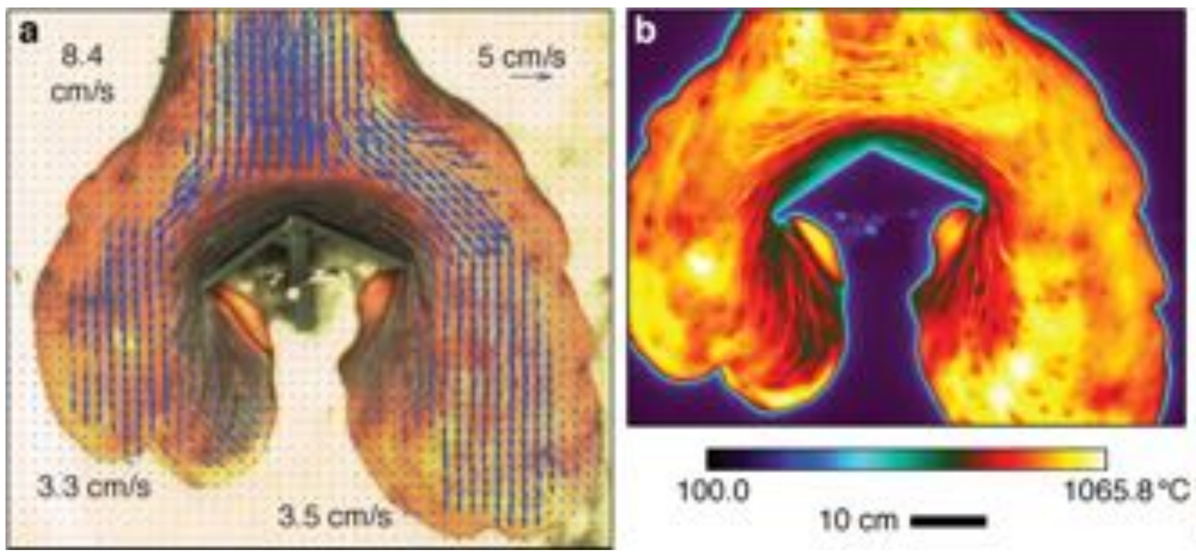

**Lister, 1992**

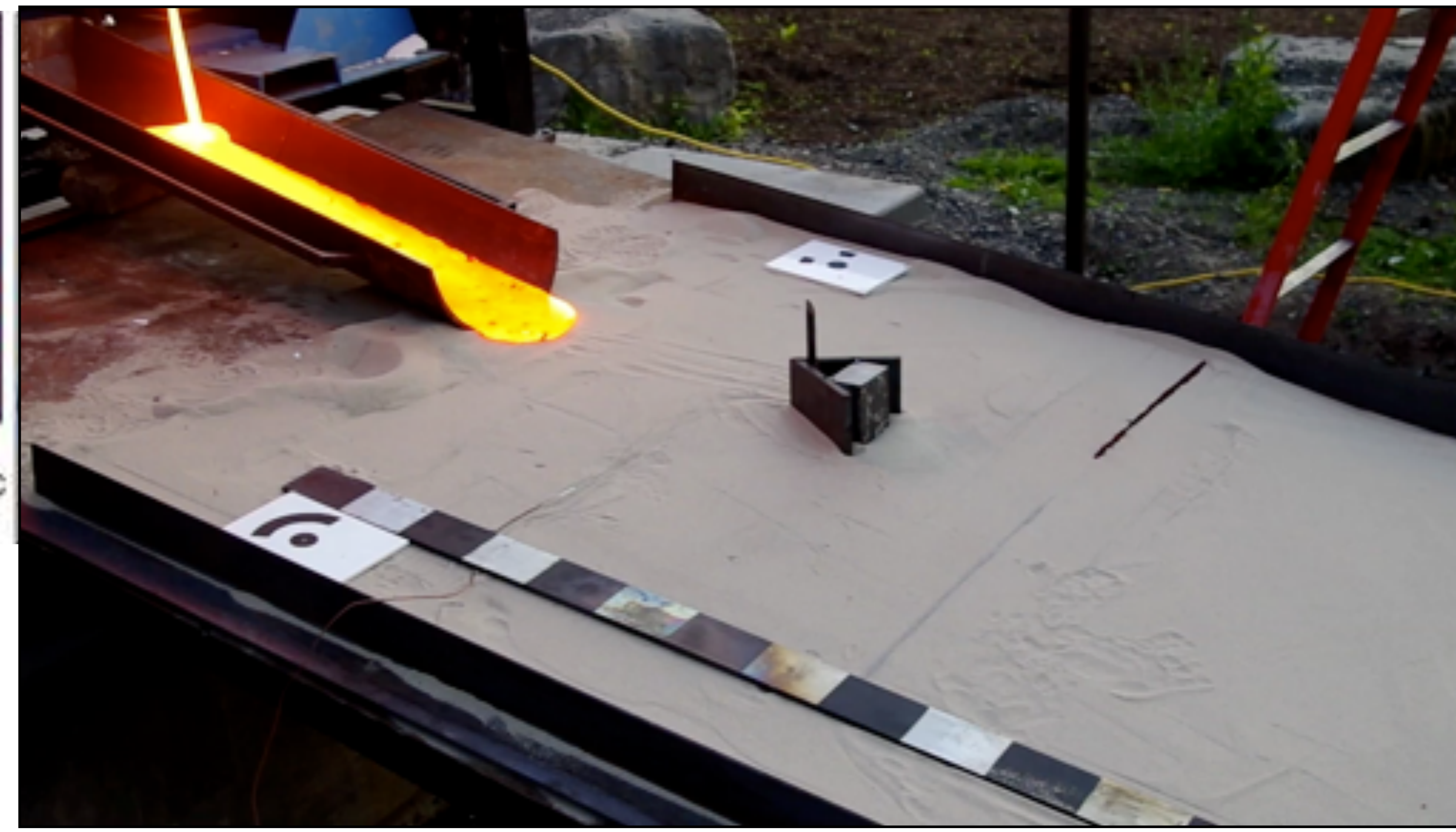
$$X \sim \left( \frac{(\rho g)^3 Q^4 \sin^5\theta}{(3\eta)^3 \cos^2\theta} \right)^{1/9} t^{7/9}$$

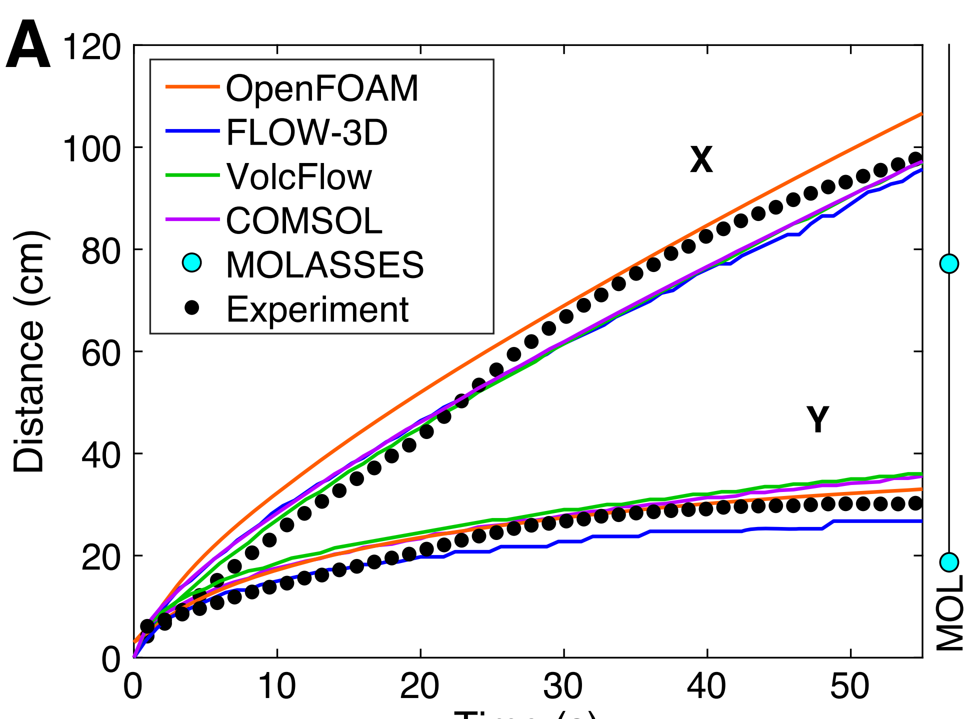


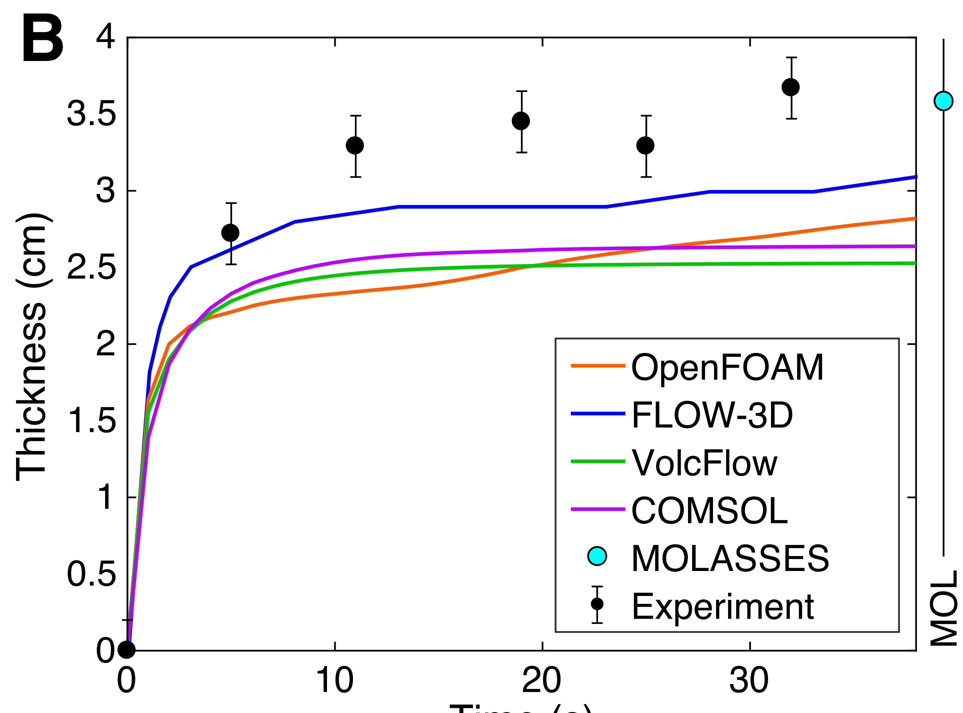

Cordonnier et al., 2015; Dietterich et al., 2017

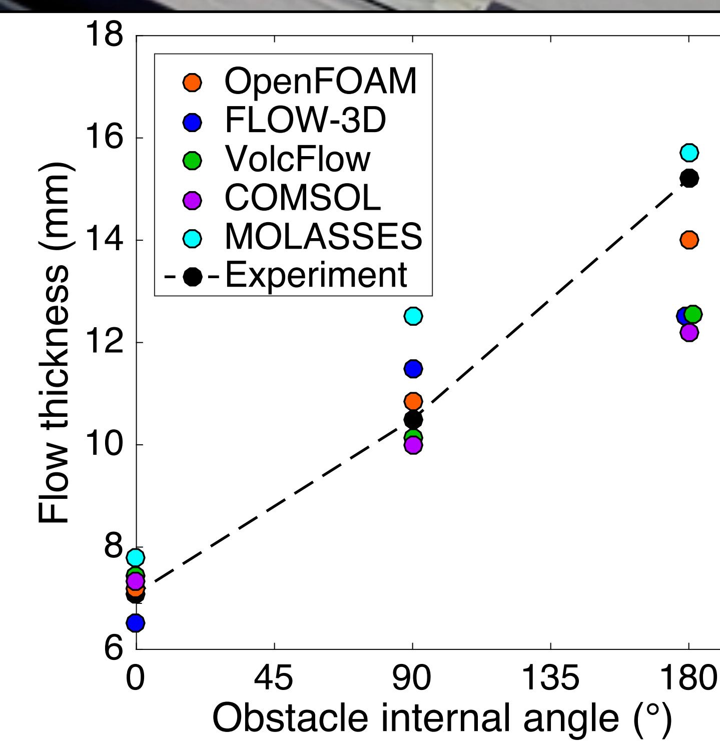
# Benchmarking — Basalt lab experiment





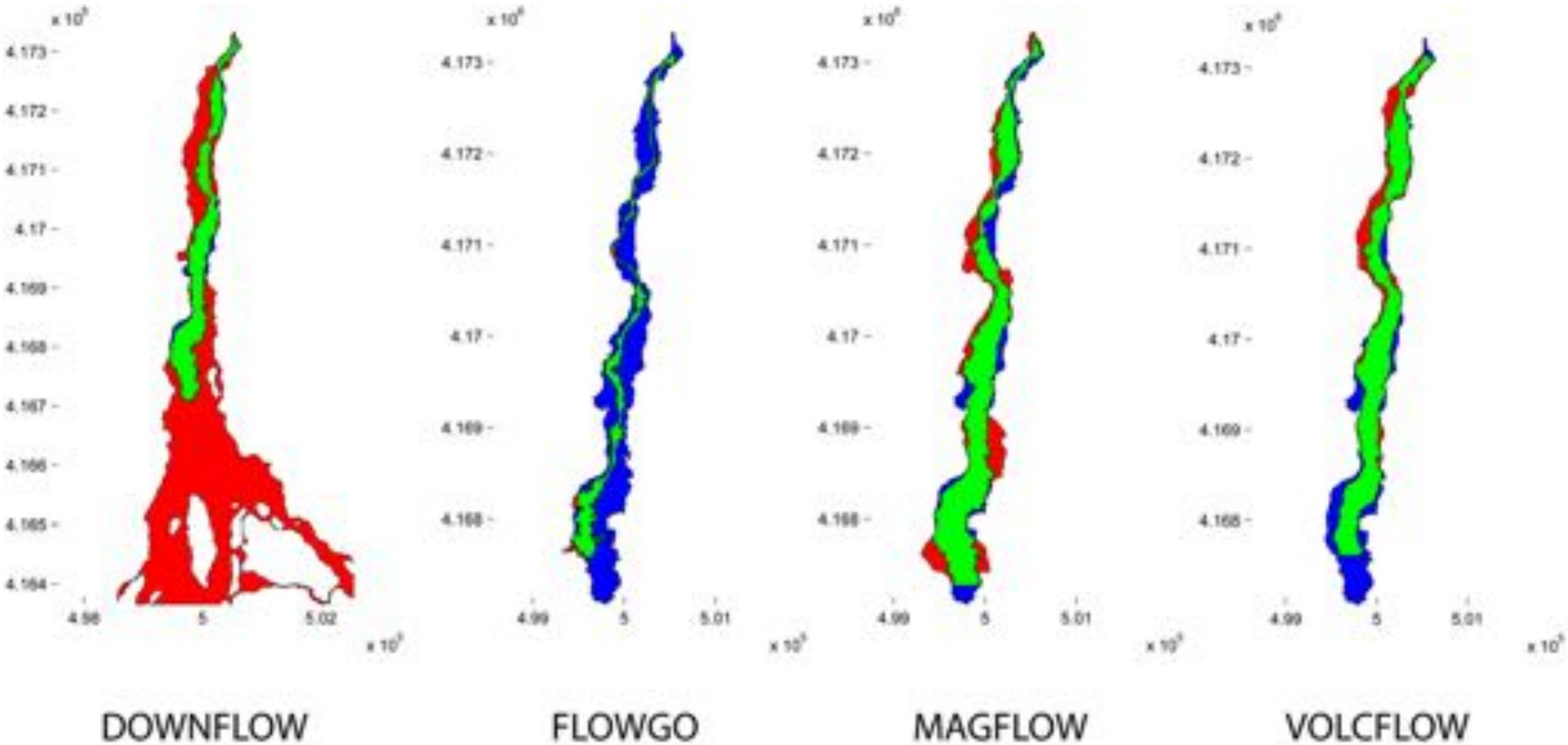
# The Lava Lab

A collaborative inter-disciplinary initiative at Syracuse University

Similar initiatives at SUNY Buffalo and elsewhere… stay tuned!

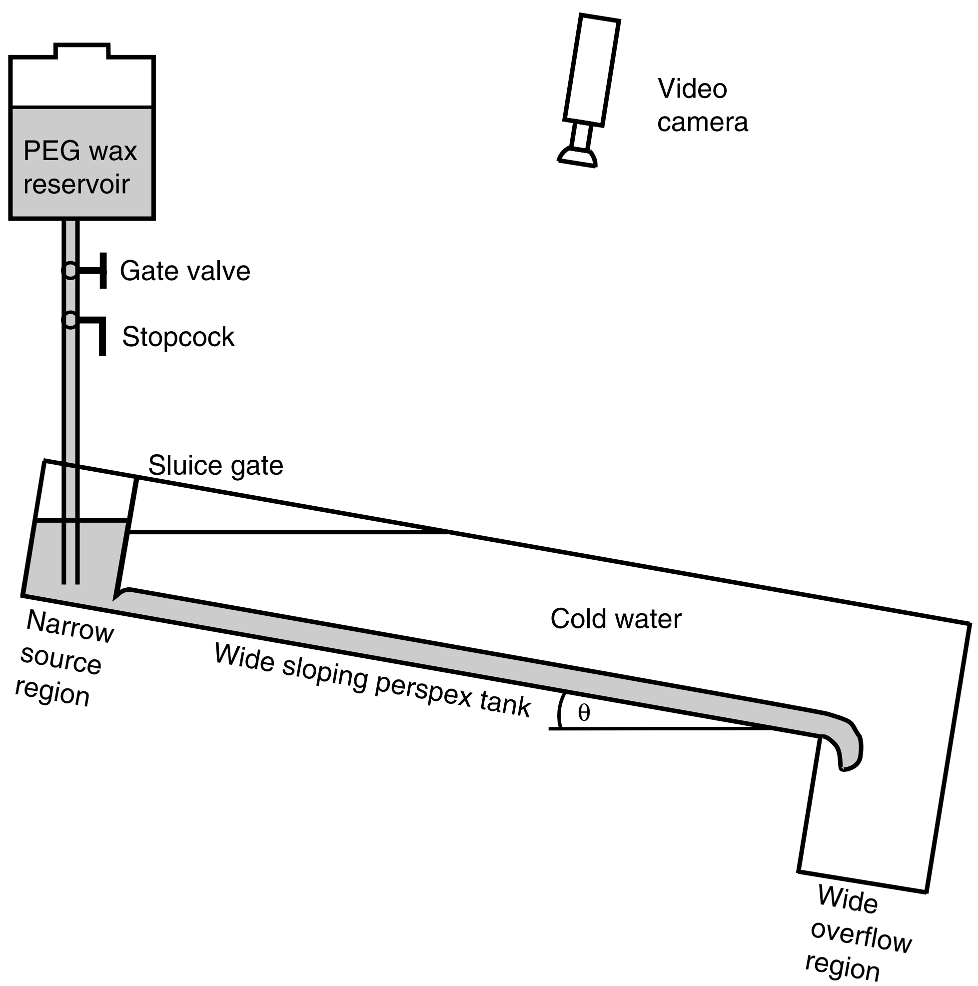
# Model inter-comparison — Inundation area

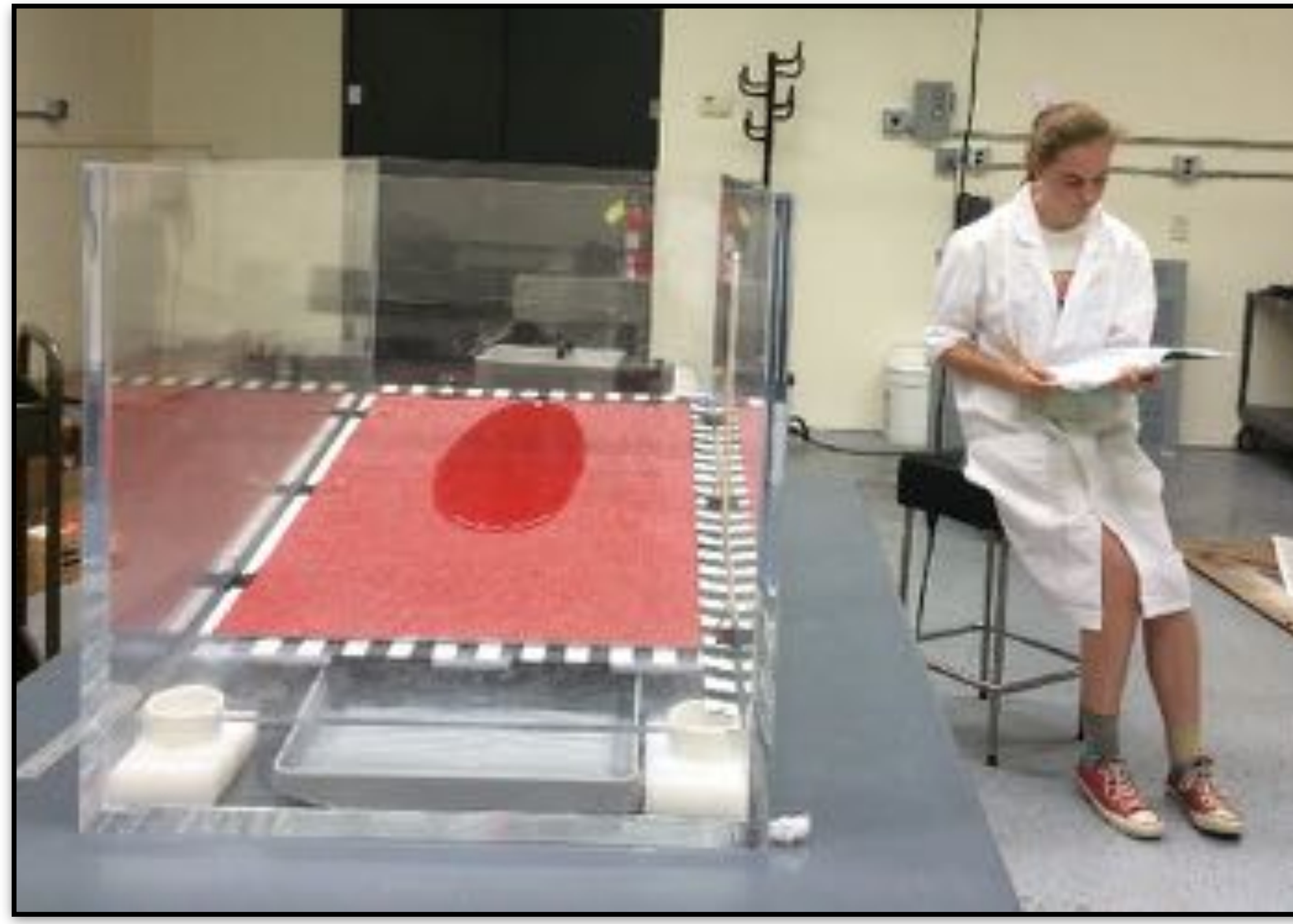
Input to all models: DEM, vent, flux, temperature



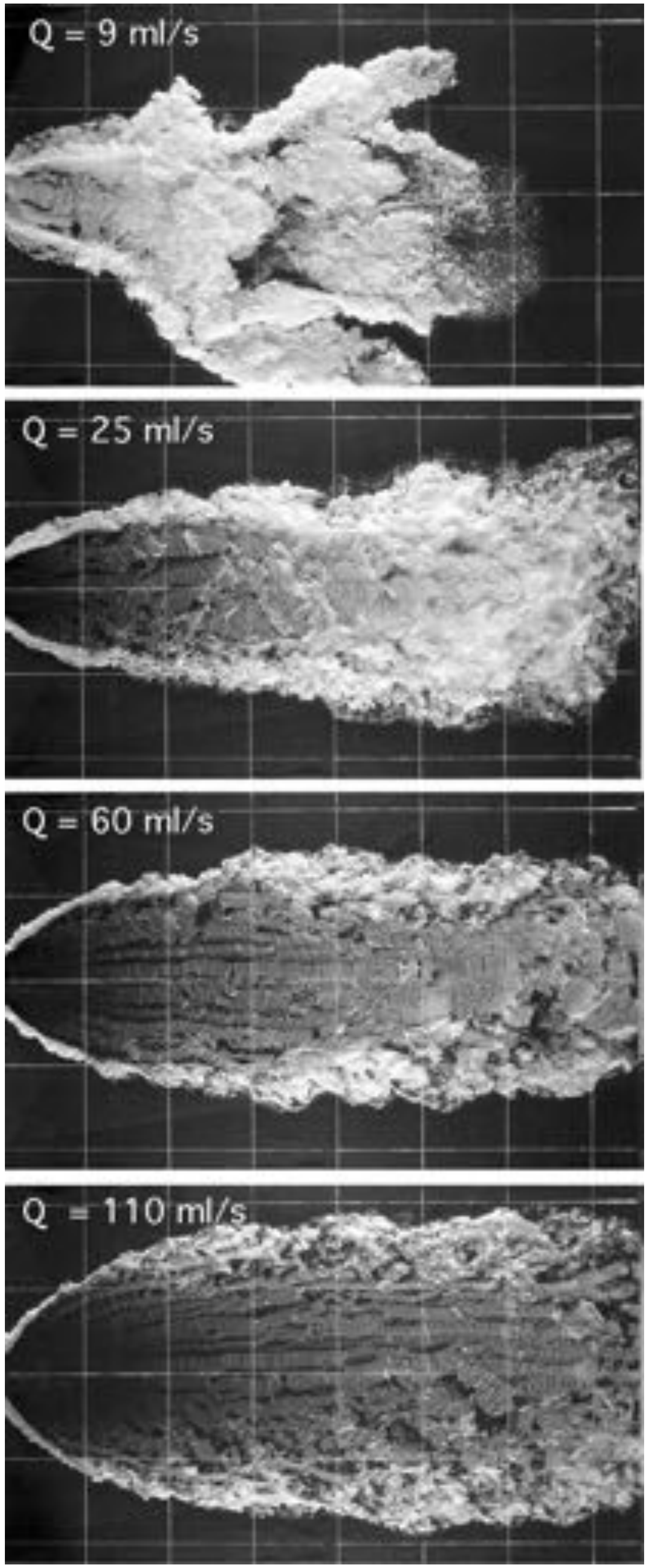

Cordonnier et al., 2015; Dietterich et al., 2017

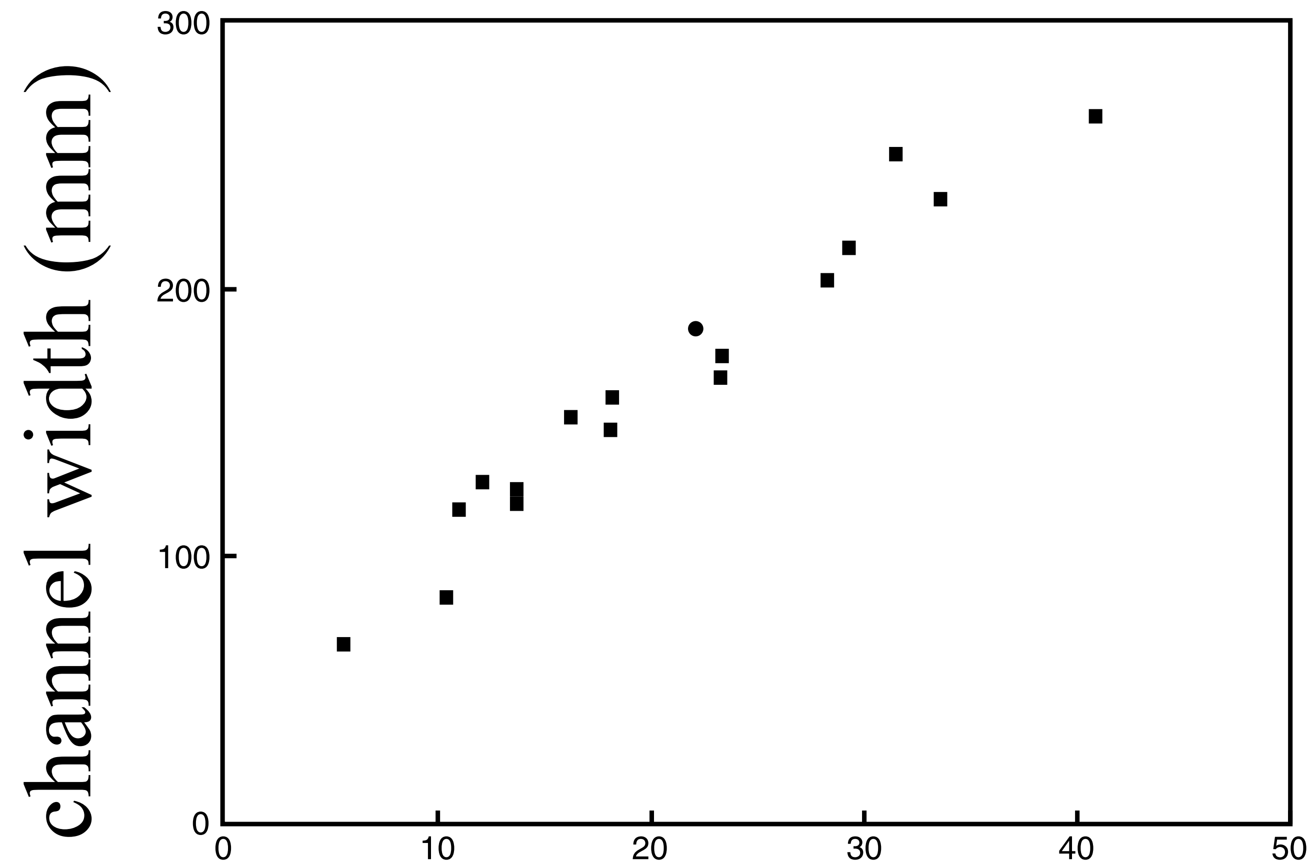
# Analog models



**Kerr et al., 2006**

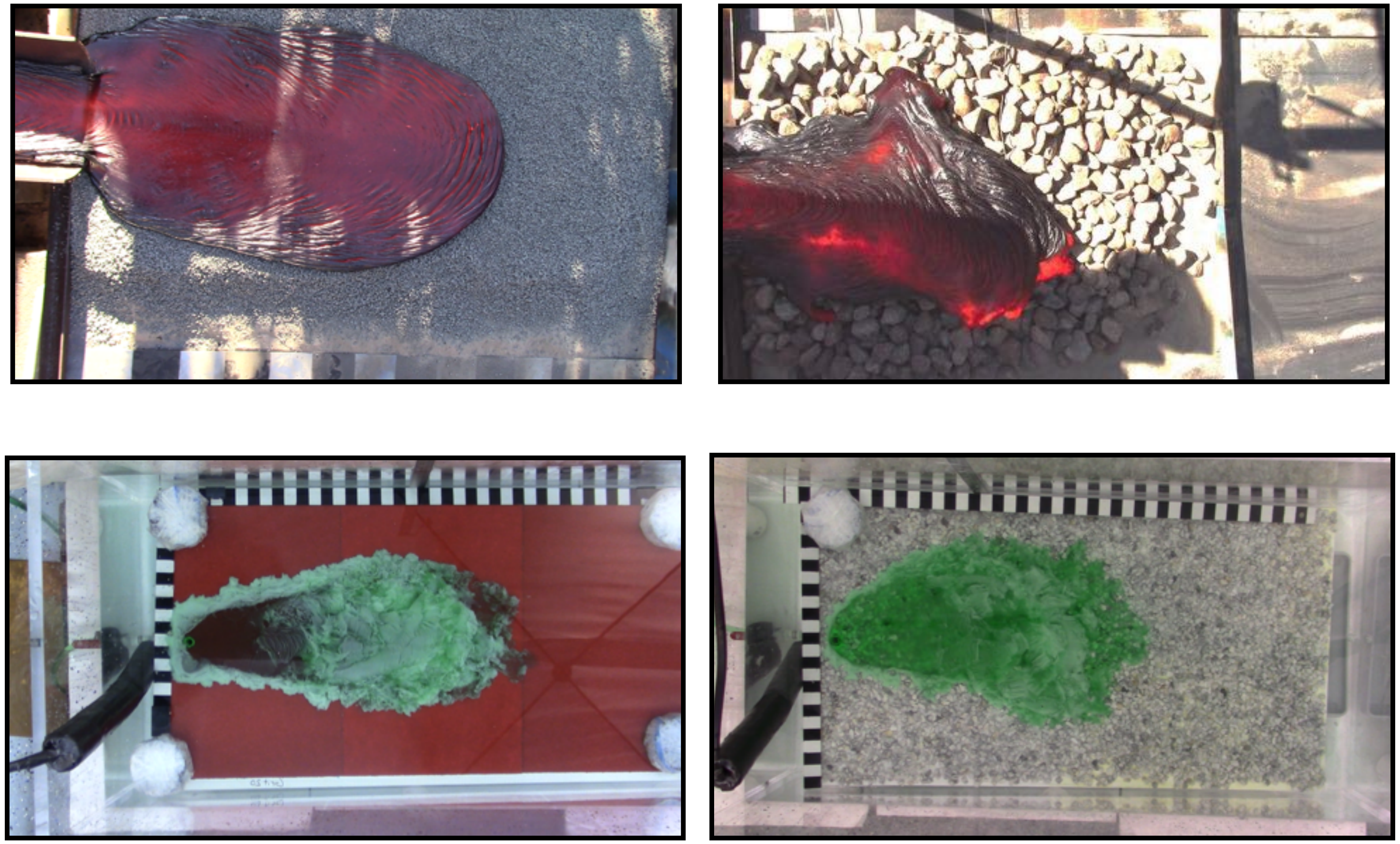


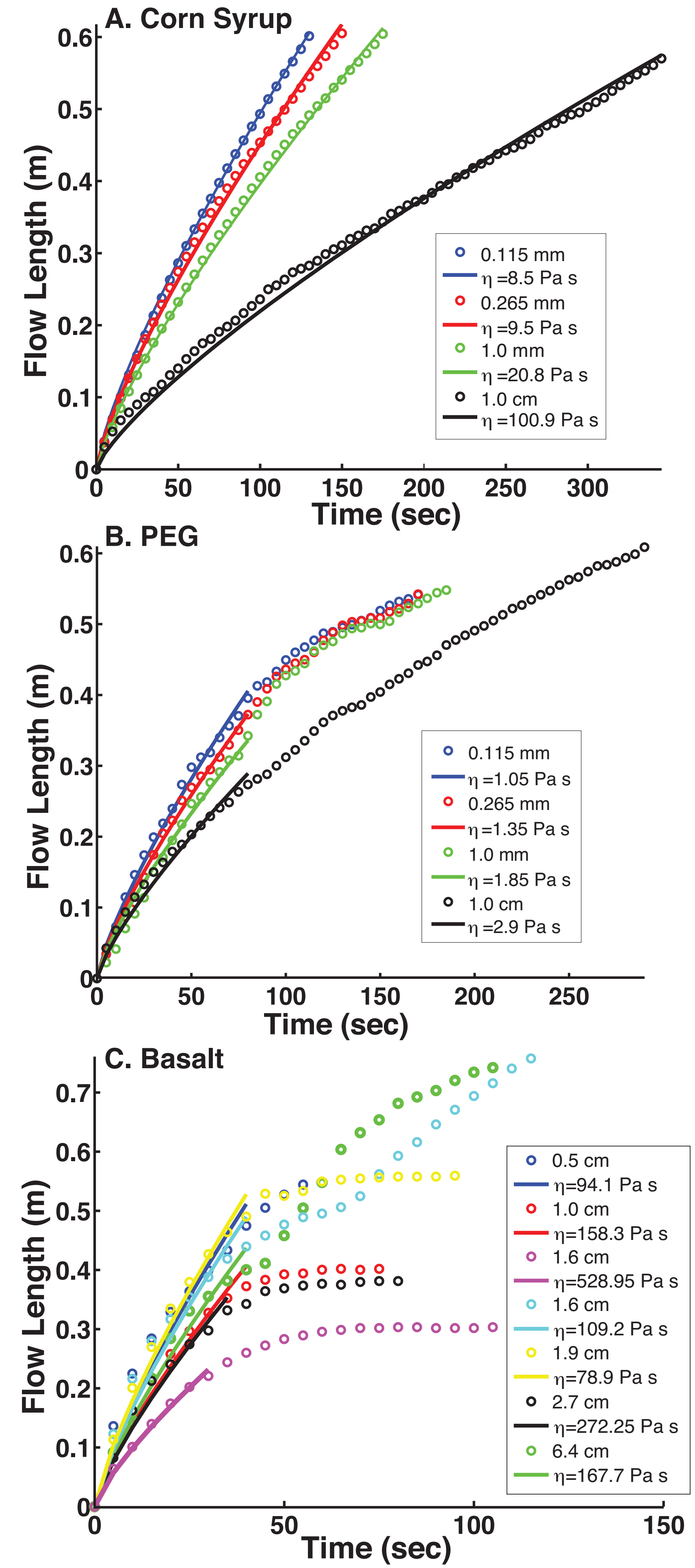

$$w = 2\left[\frac{\left(g\Delta\rho\right)^2 Q^7 \eta^4 \cos^9\theta}{\sigma_c^6 \kappa^3 \sin^7\theta}\right]^{1/13}$$

Kerr et al., 2006

# Impact of bed roughness

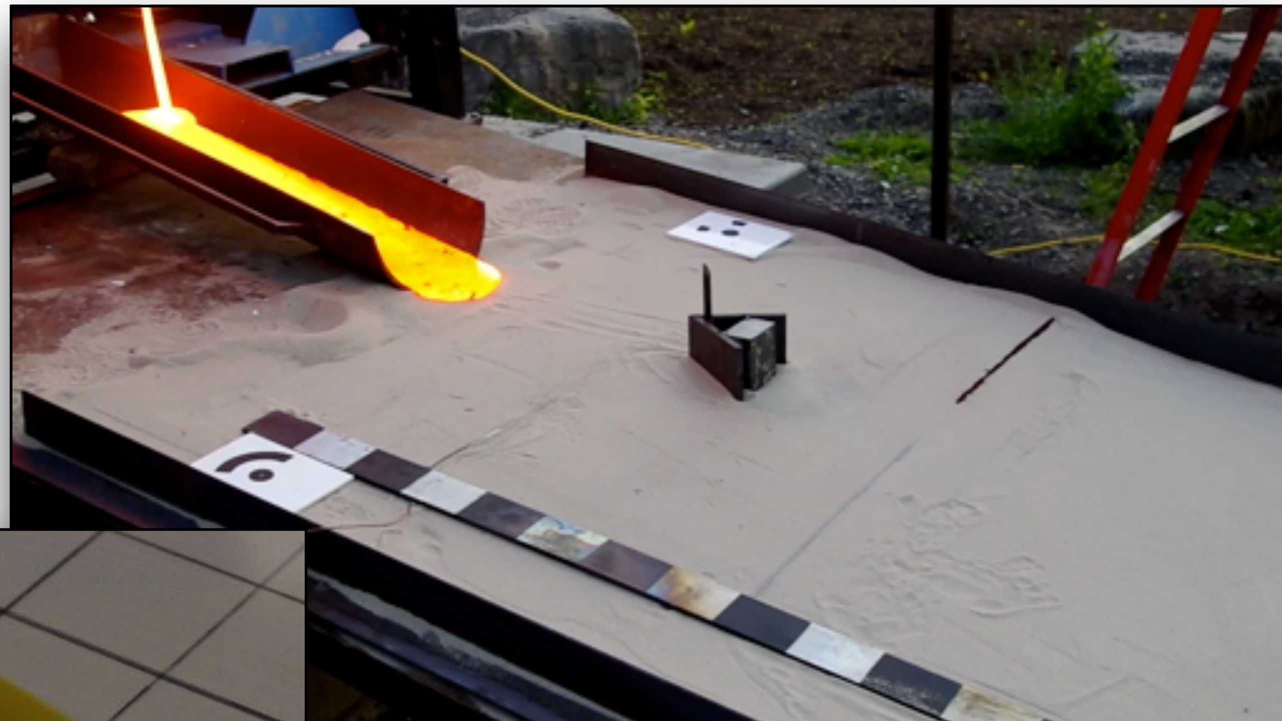


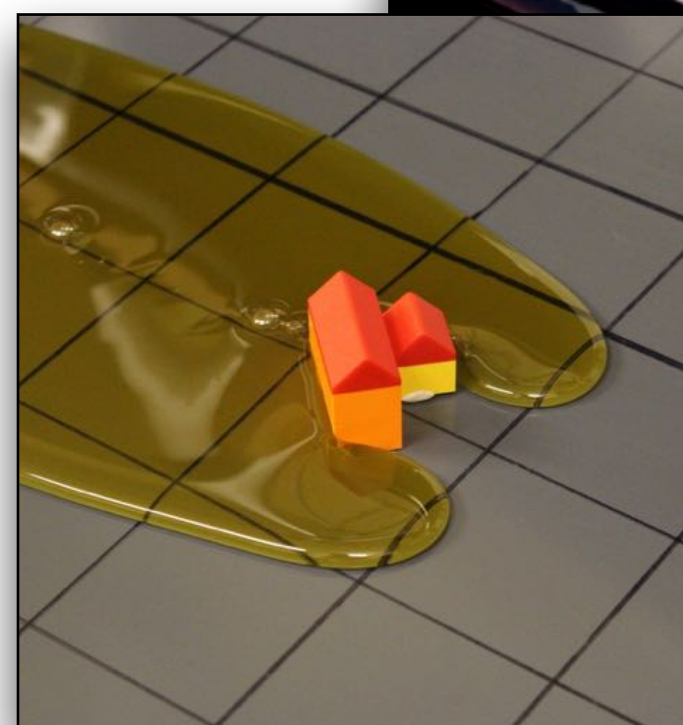
New parameterization of bed roughness as an additional viscosity term

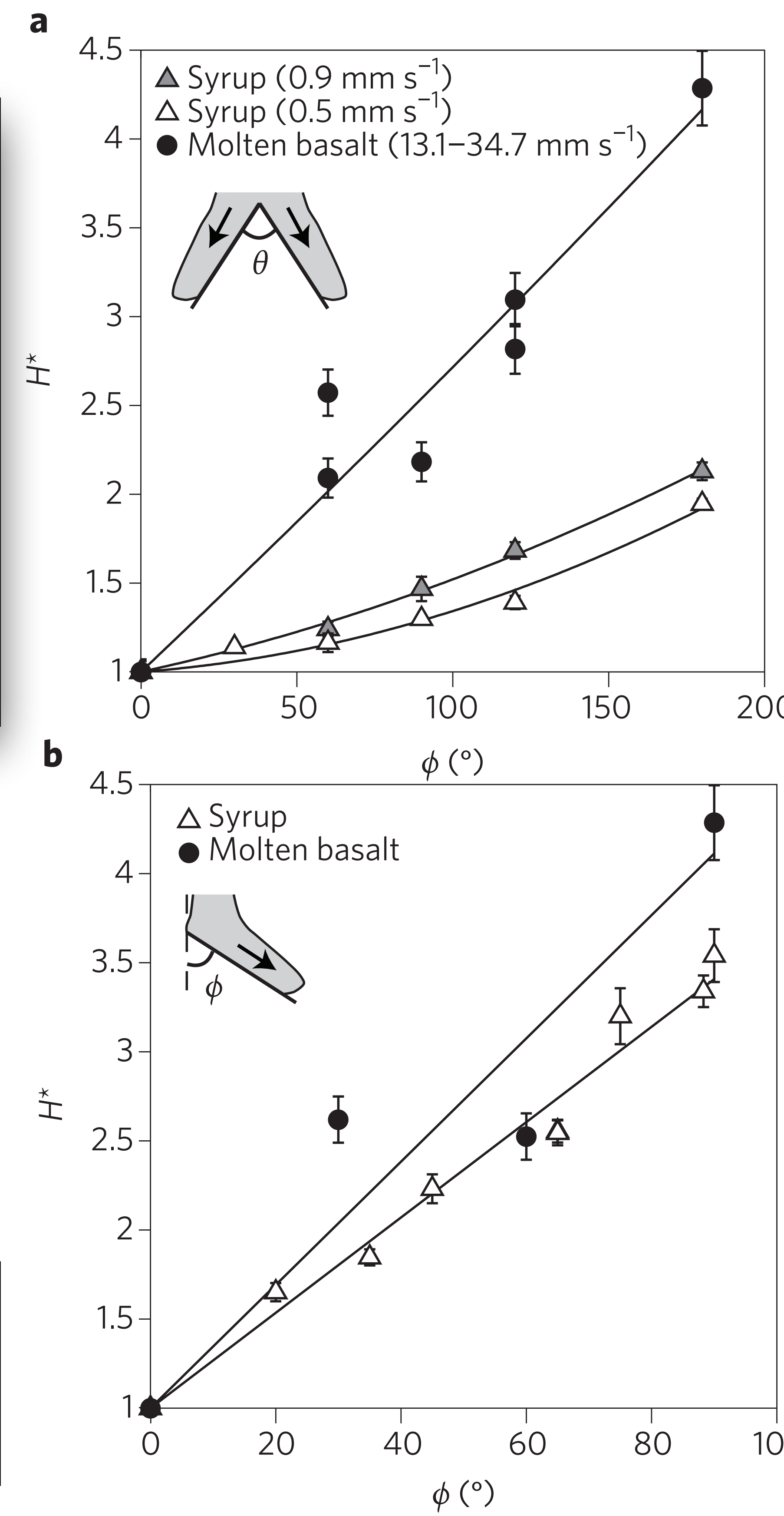



Rumpf and Lev., 2018

# Interaction with Obstacles








New designs for flow diversion and deceleration

Dietterich et al., 2015

# Impact of Episodic Effusion

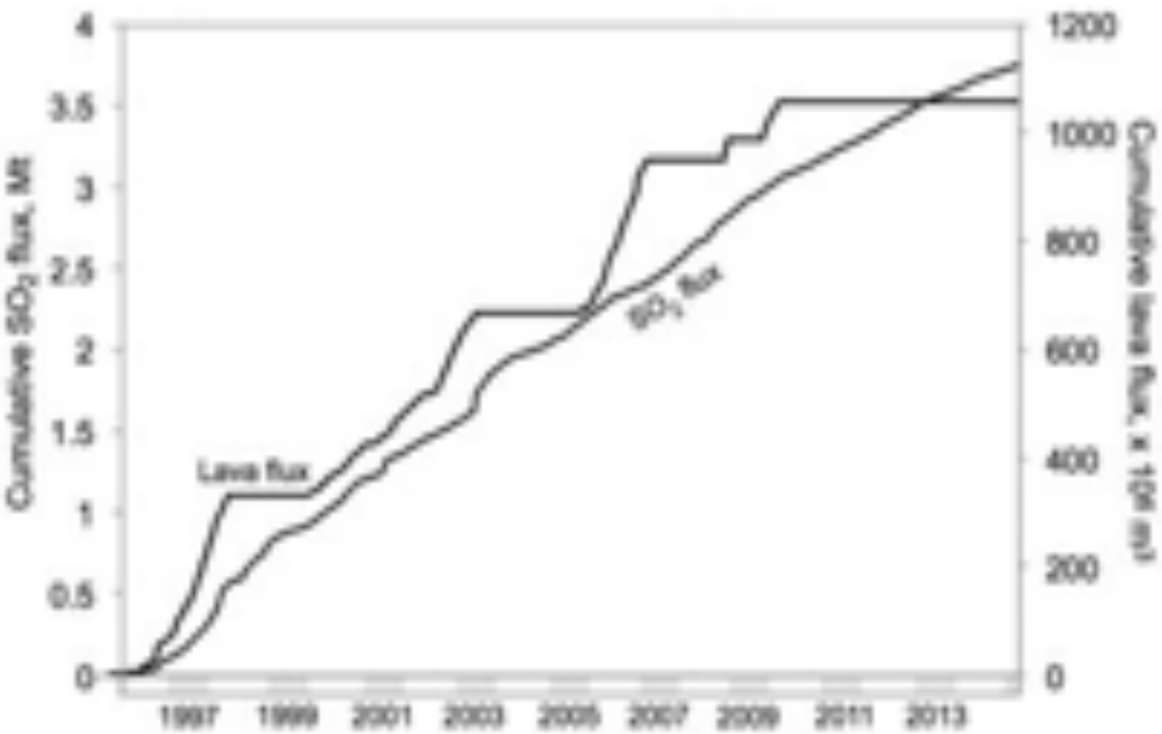



**Figure 1:** Volumetric flux of $SO_2$ and lava at Soufriere Hills Volcano, Montserrat (Christoper et al.).

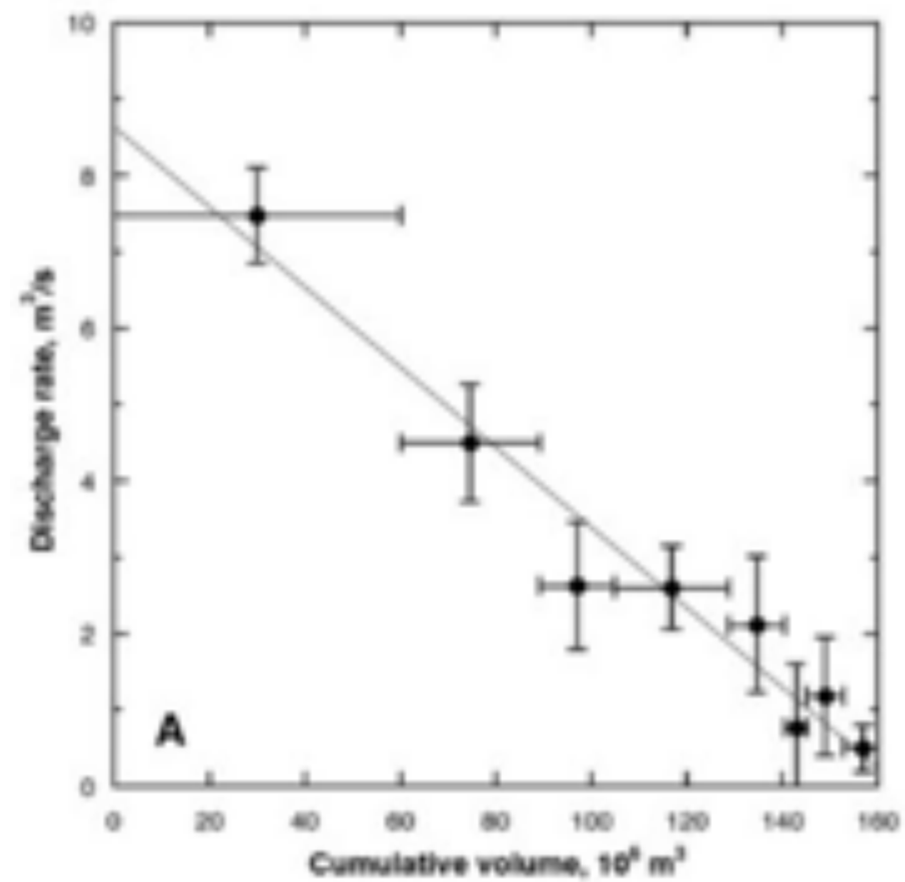
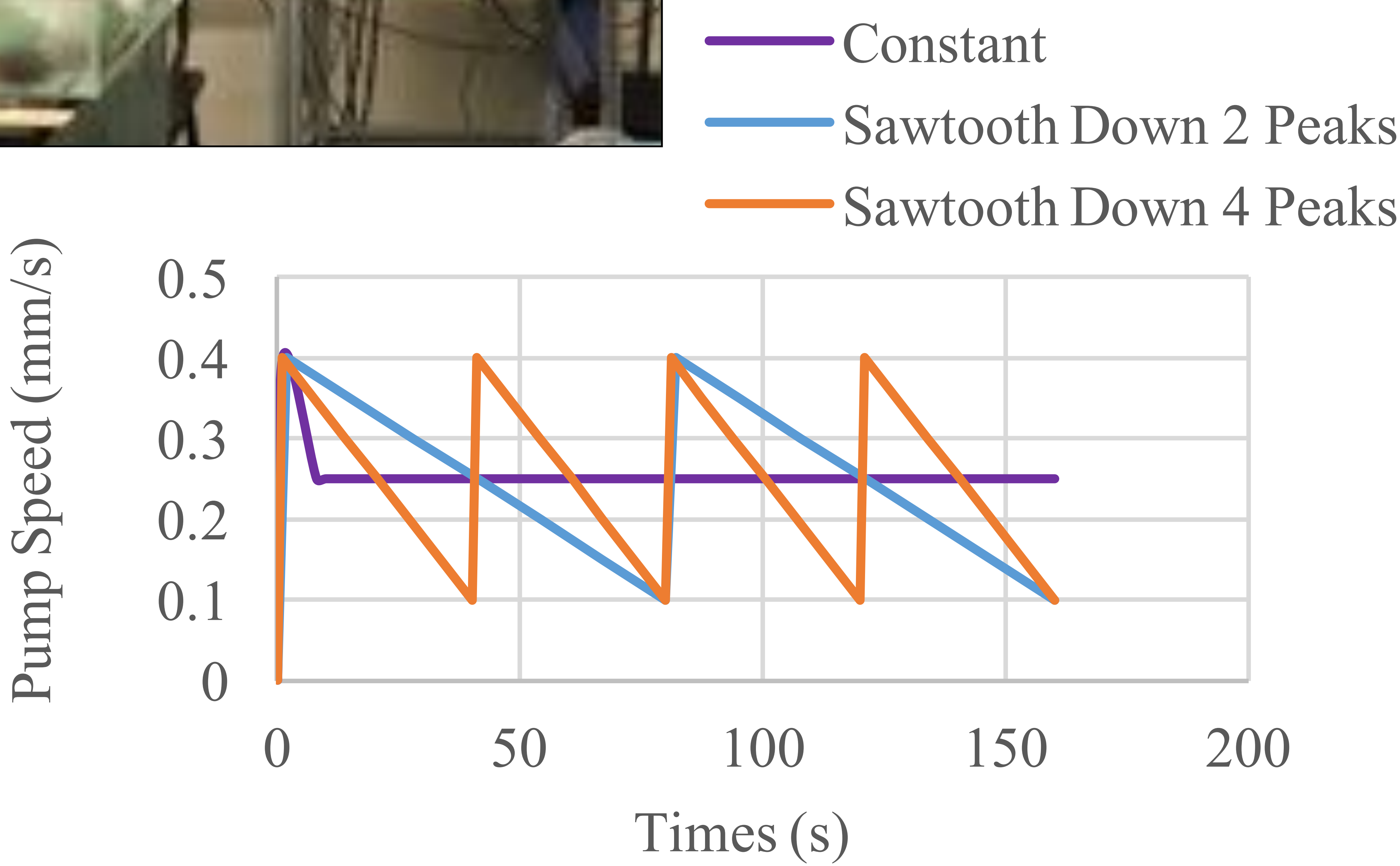


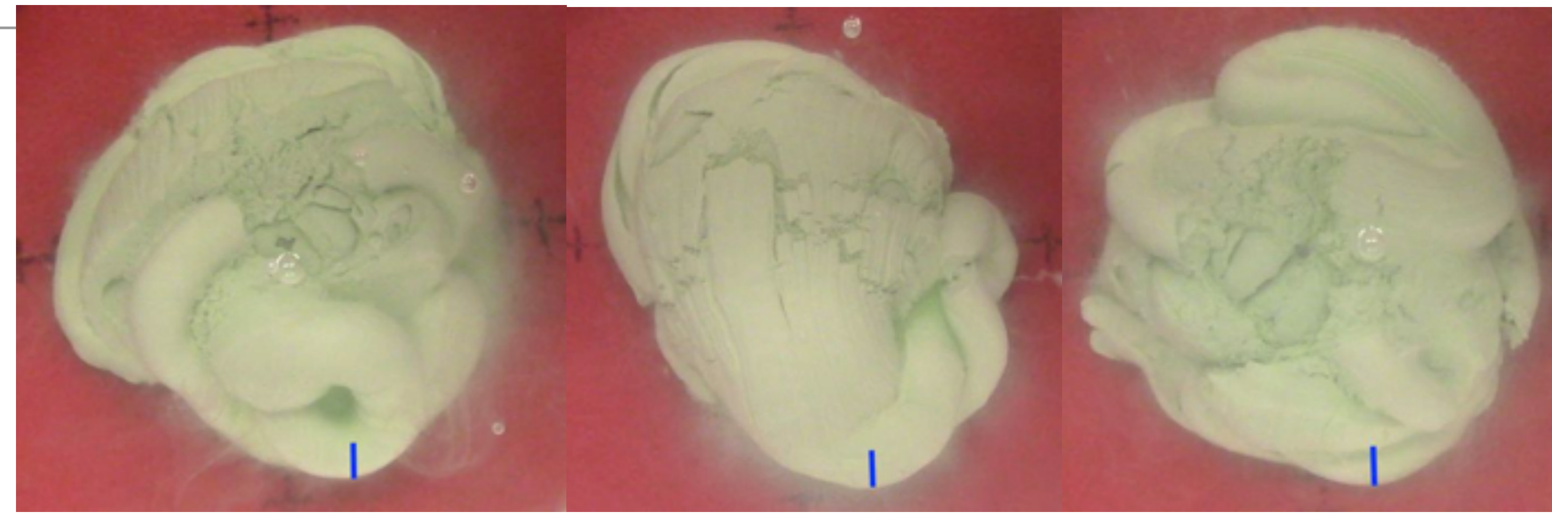

**Figure 2:** Volumetric flux of lava at Sinabung Volcano, Indonesia with respect to cumulative lava extruded (Nakada, S., et al.).



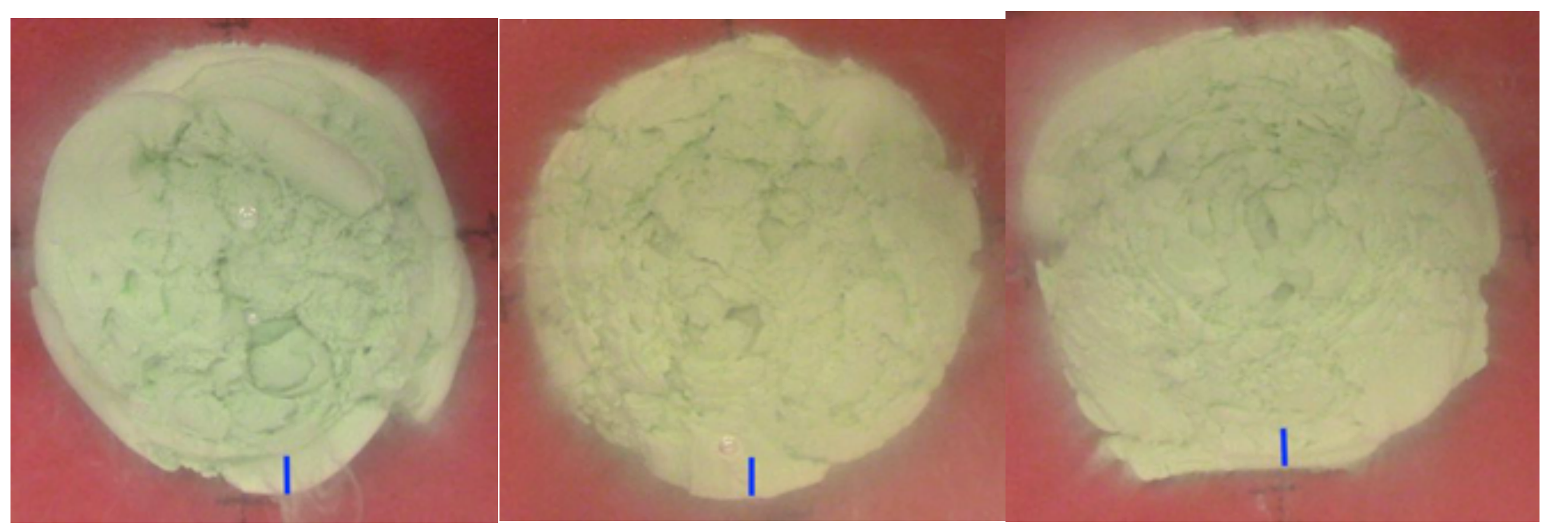
Constant
Sawtooth Down 2 Peaks
Sawtooth Down 4 Peaks
Pump Speed (mm/s)
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
200
Times (s)

# Pulsing — Impact on morphology

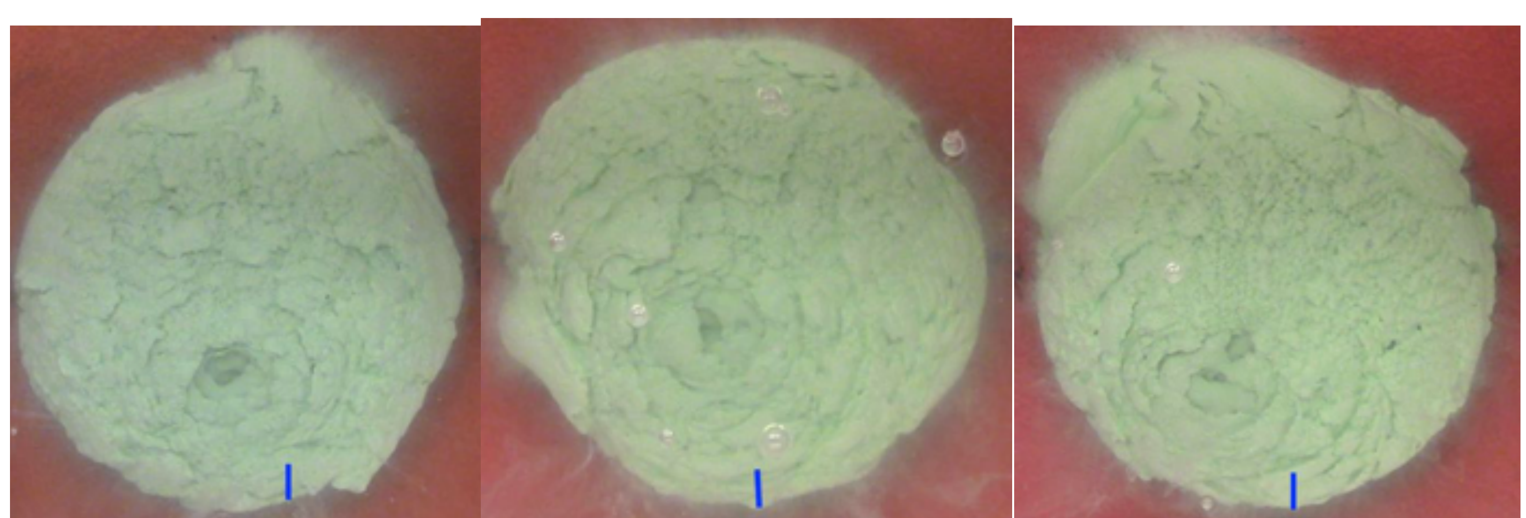
**Constant**

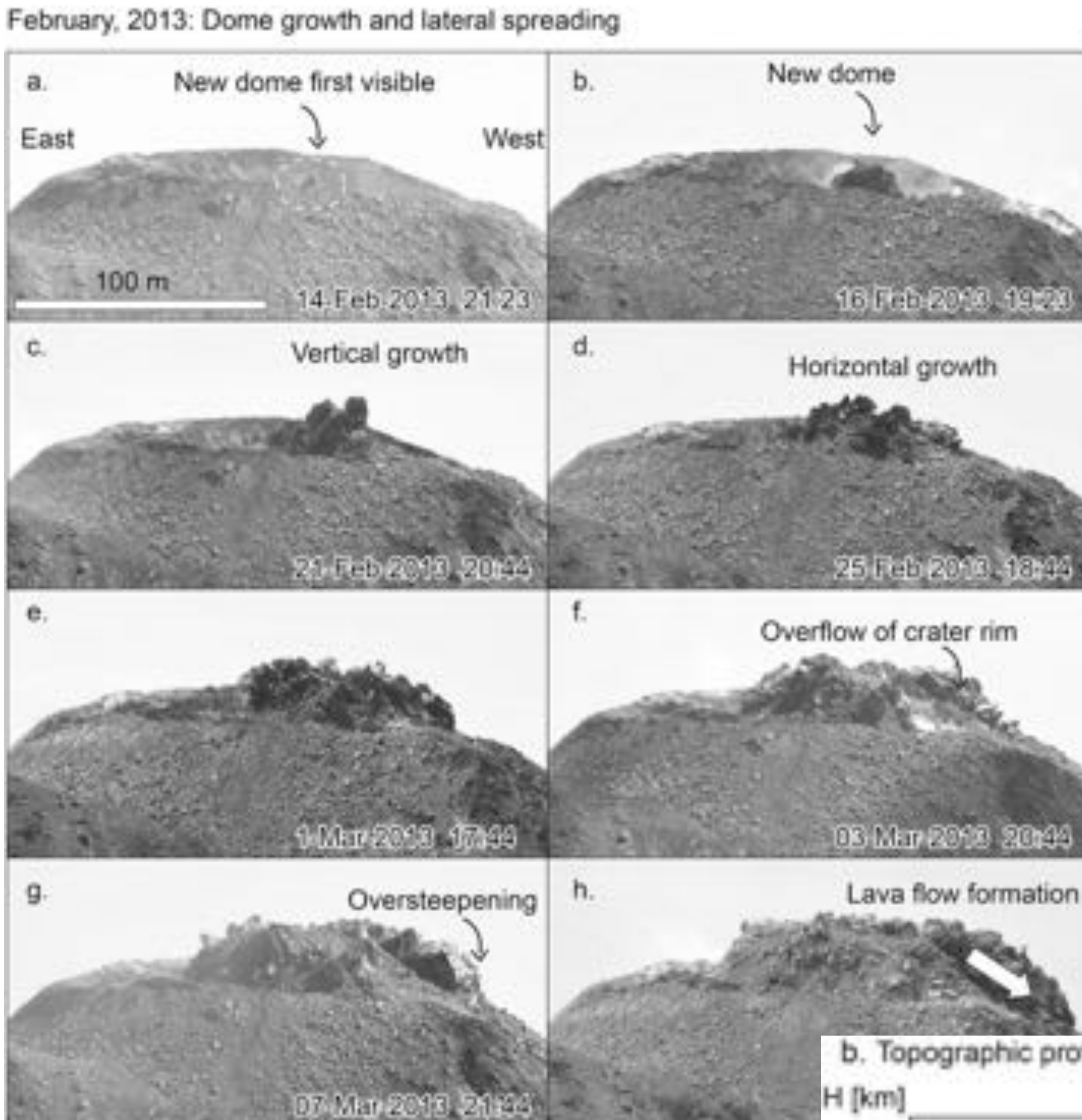


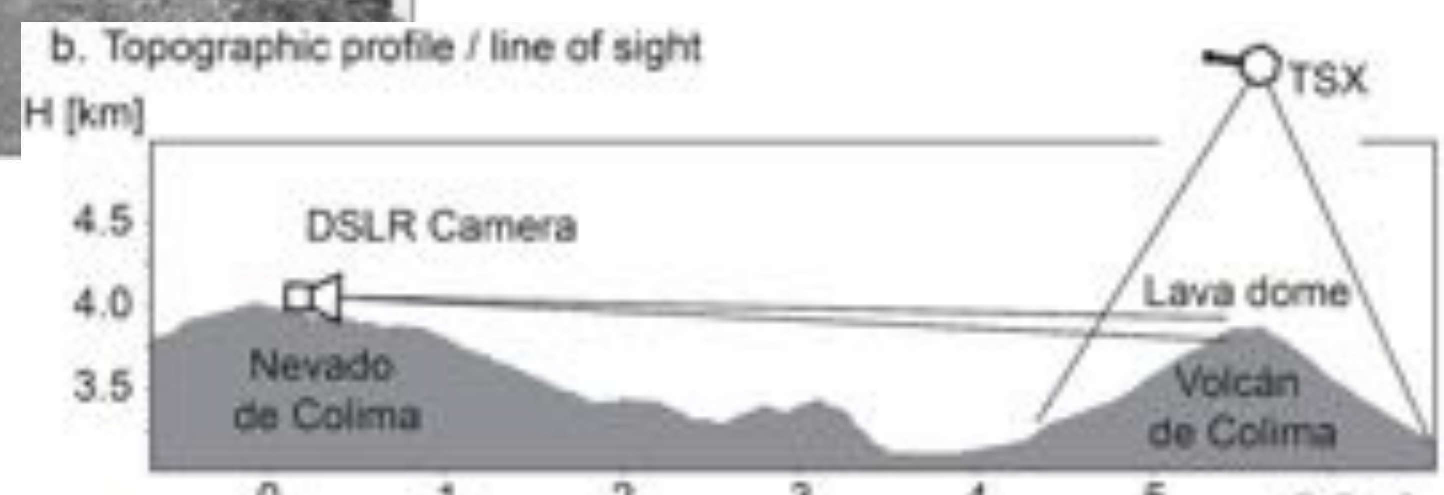
**2-peaks**



**4-peaks**

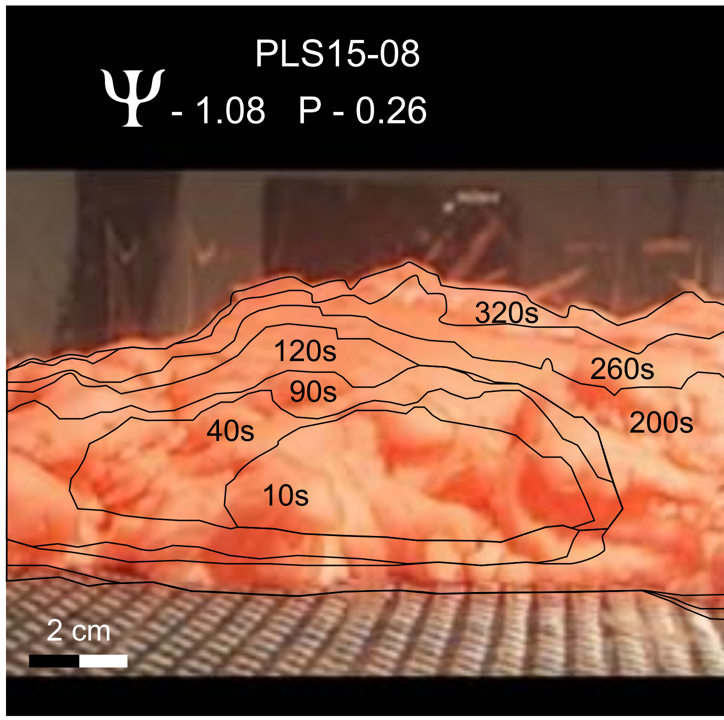


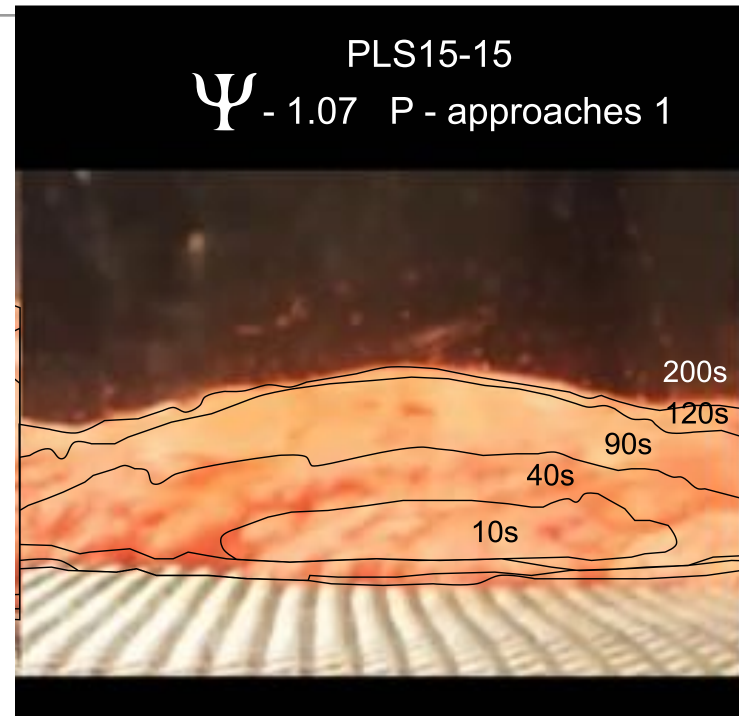


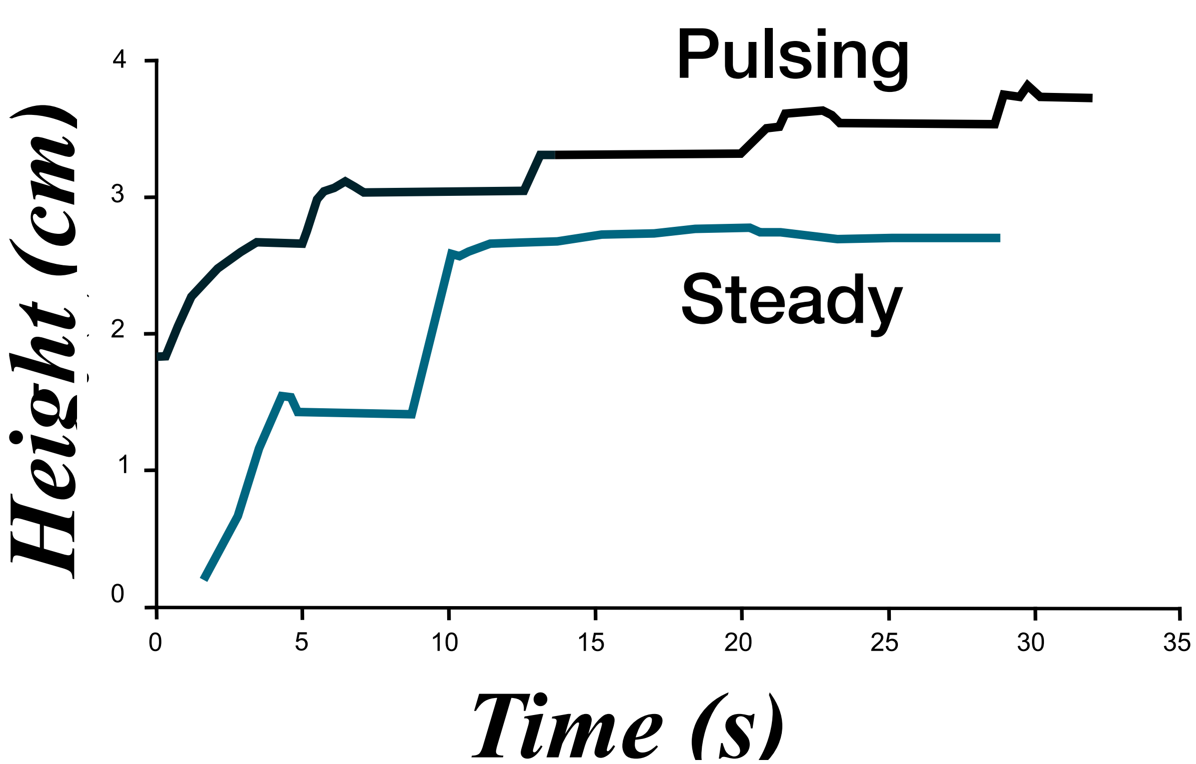



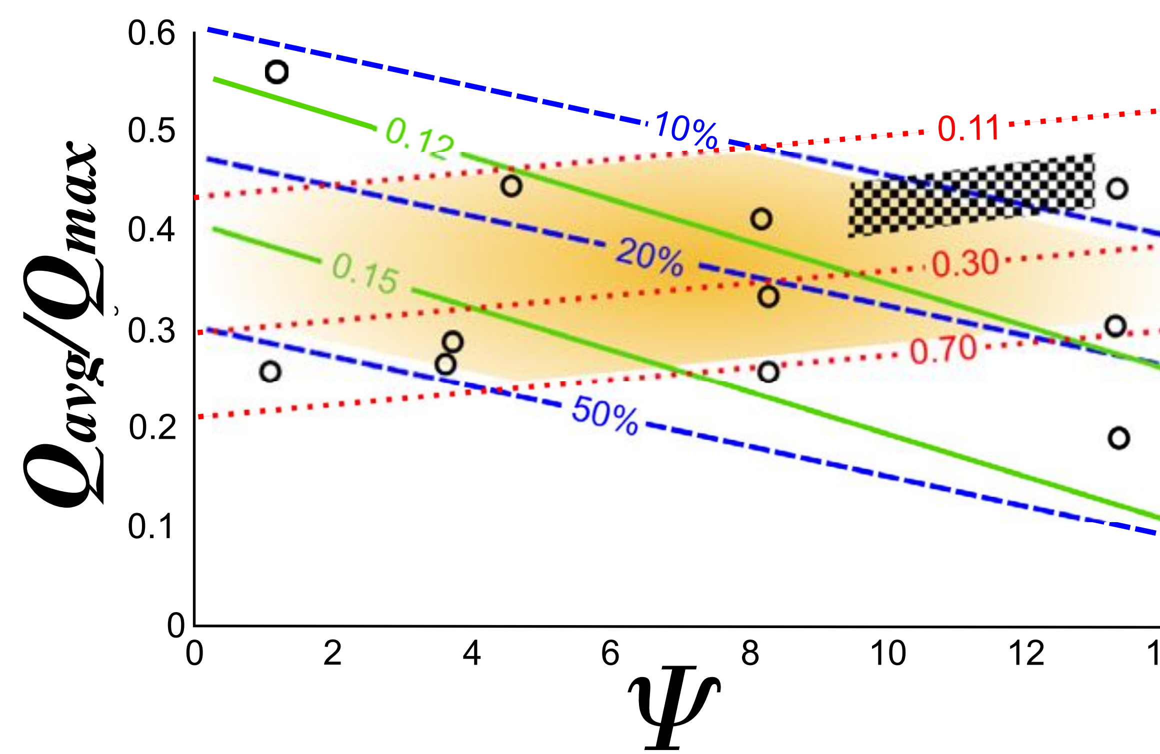

Walter et al., 2019

# Pulsing — Impact on final flow dimensions



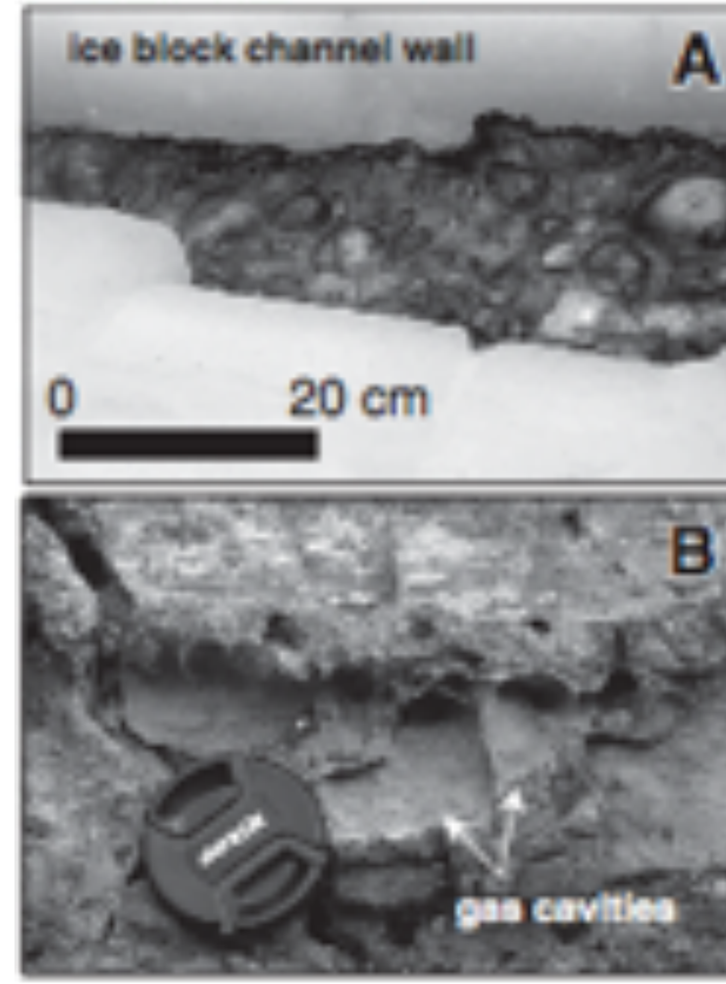



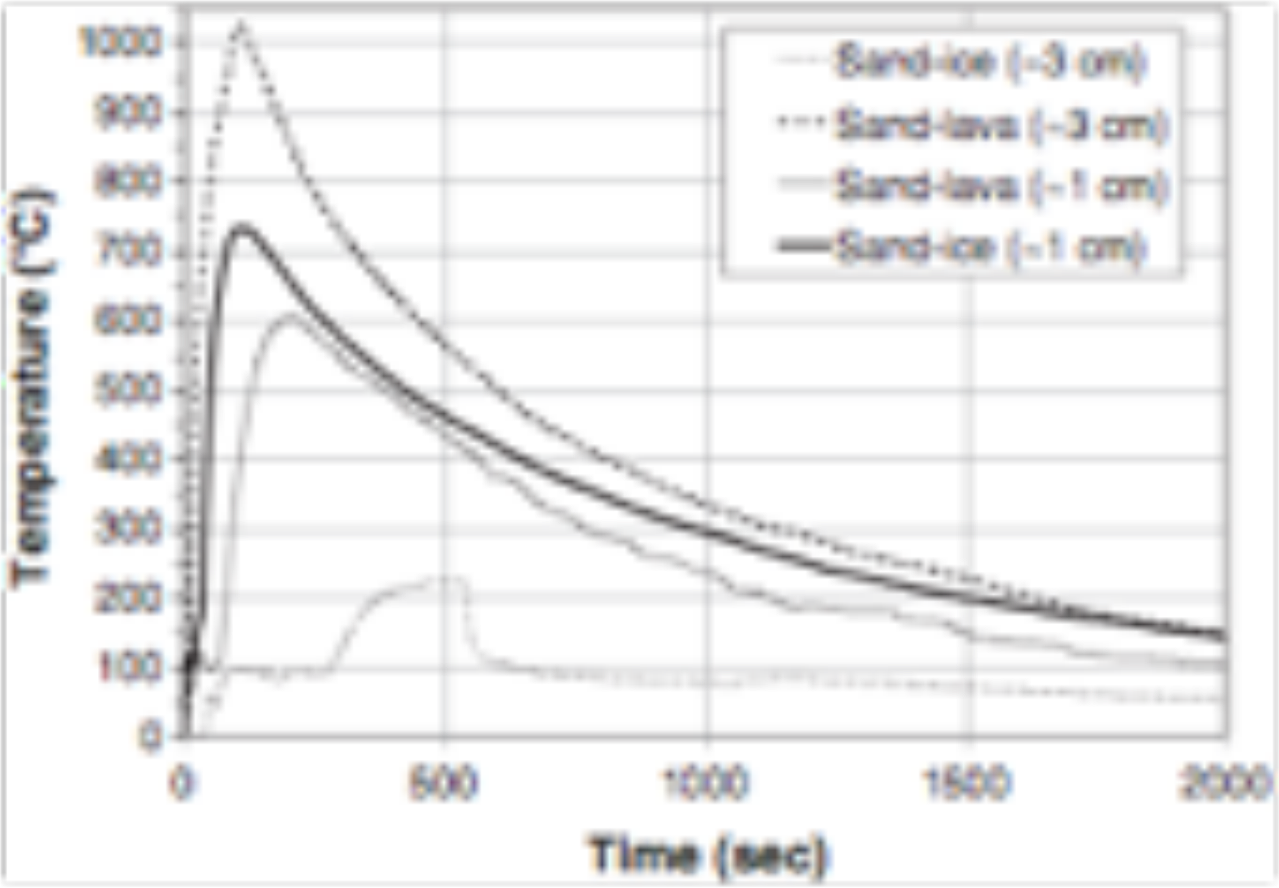




Rader et al., 2018

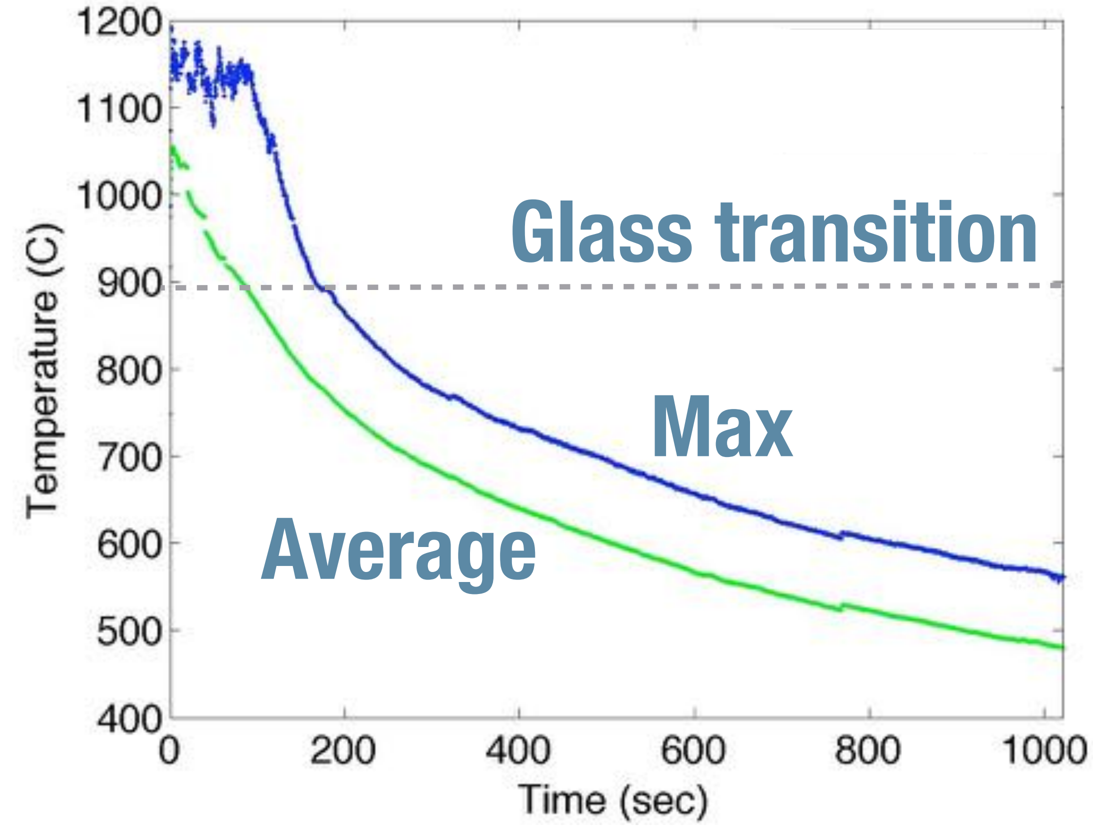

Lava-Ice interaction
Etna 2017

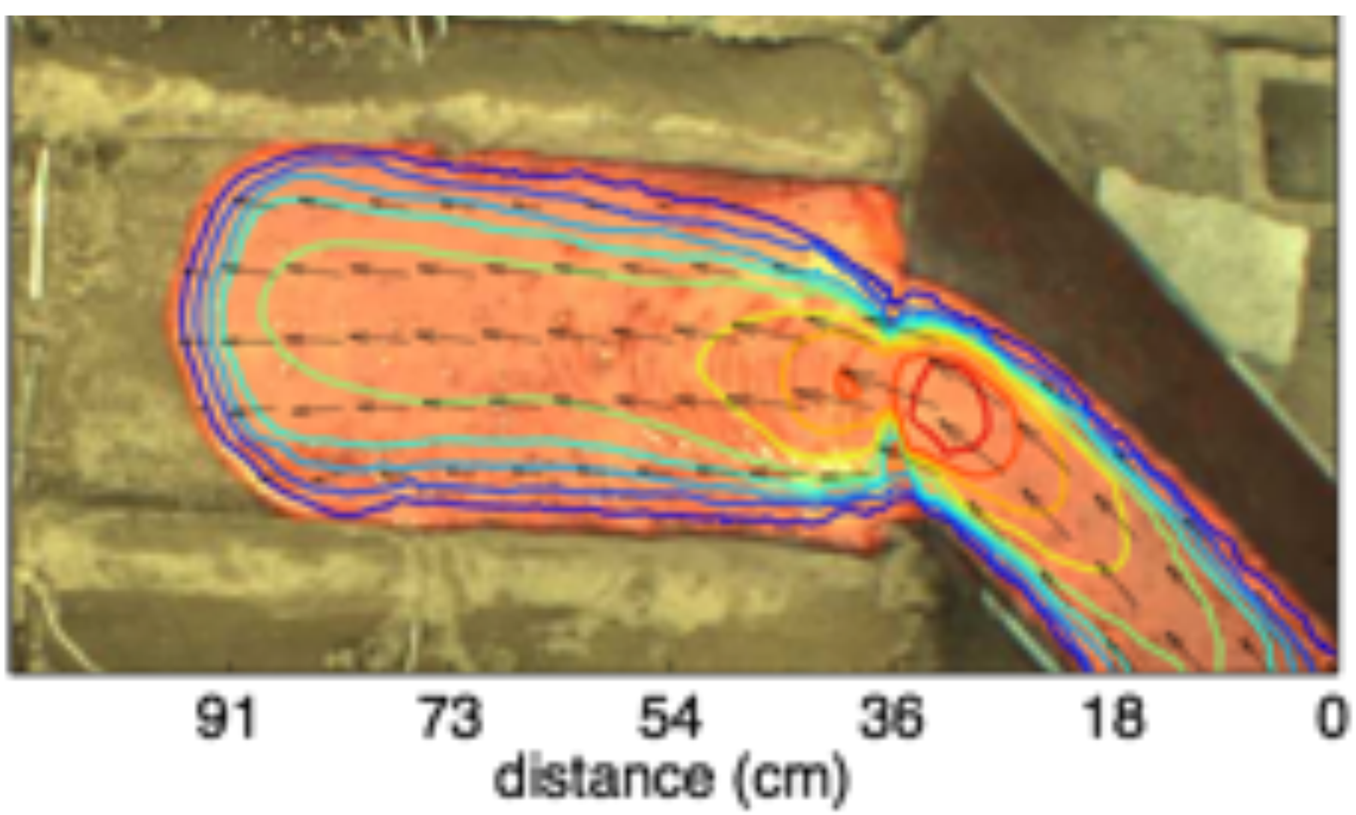
# Interaction with Snow and Ice

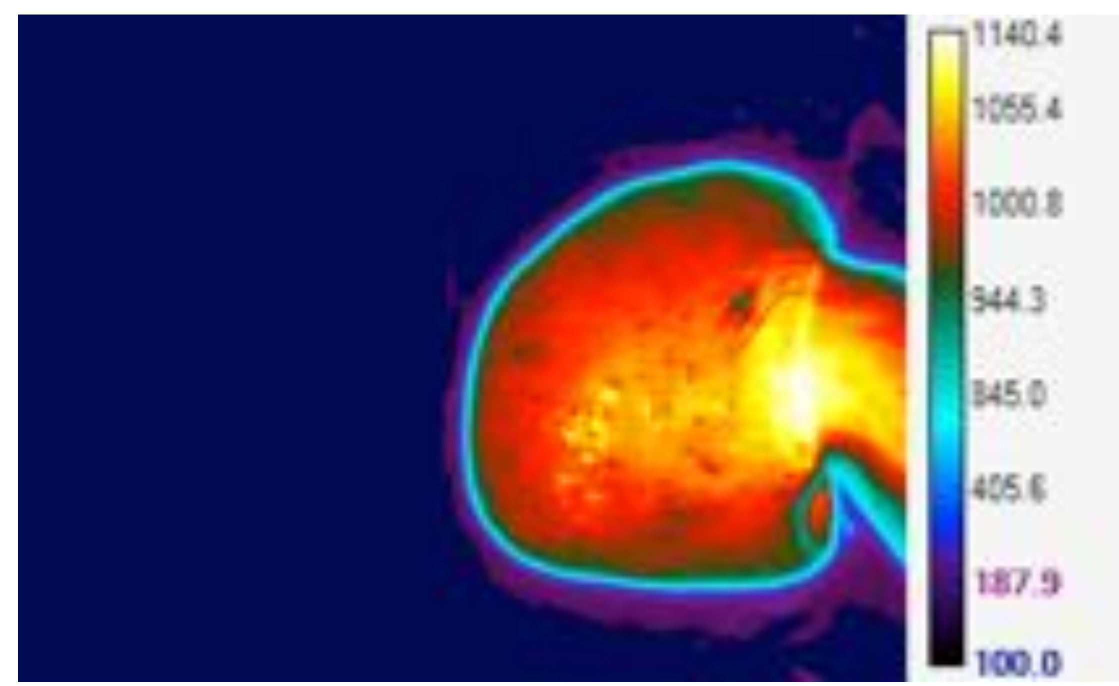

ice block channel wall
A
0
20 cm
B
gas cavities




Edwards et al., 2013



# Interaction with Water

# What do we still need to learn about lava flows?

- 3-phase lava rheology
- Impact of flux variability
- Breakouts and inflation
- Modeling submarine and sub/supra-glacial flows
- Dome stability
- Predicting the end of effusive eruptions
- [Copied from Adam's presentation:] How can deposit characteristics be inverted to constrain eruption processes?


Thank you!