

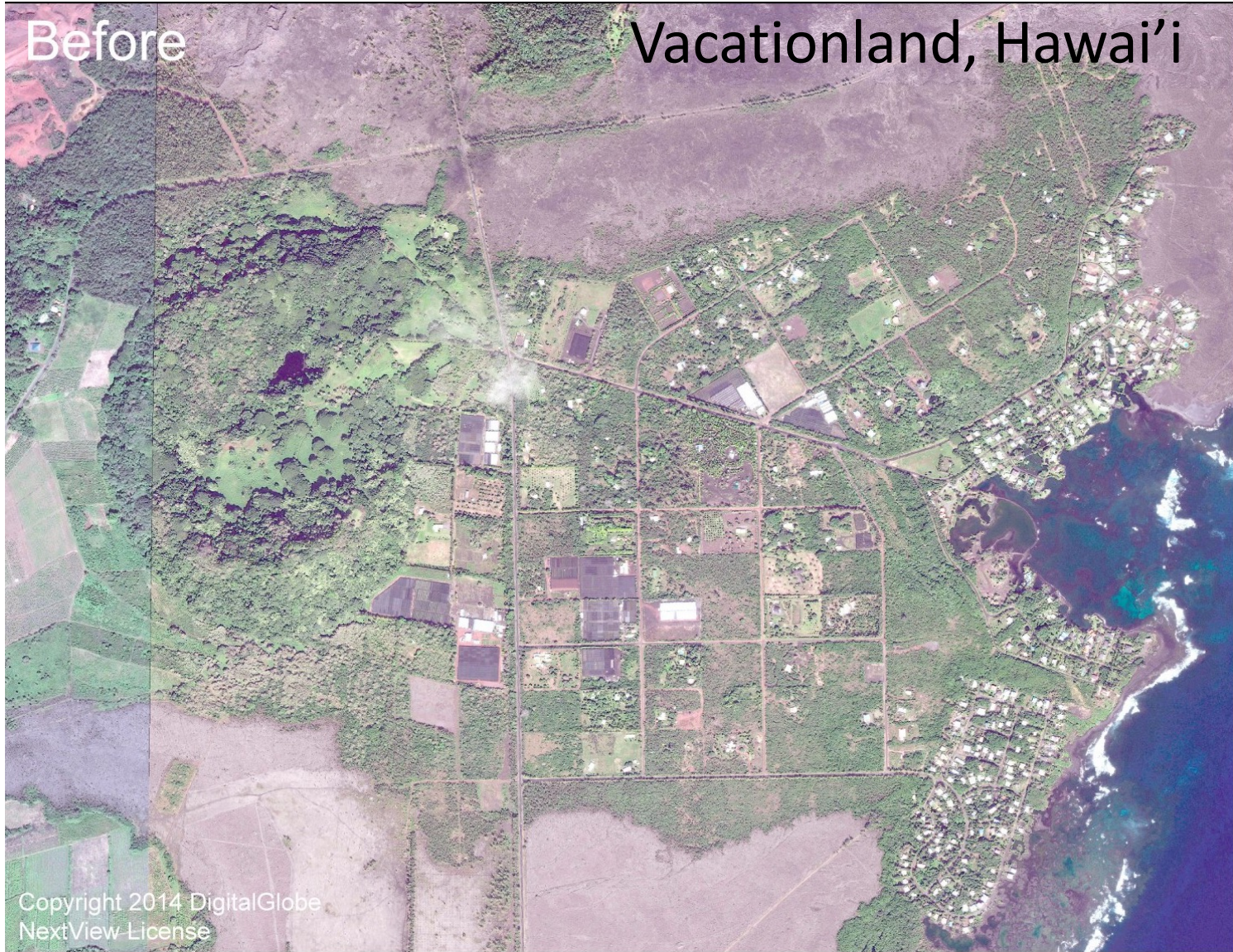


Lava flows and VICTOR

Einat Lev
Columbia University

Before

Vacationland, Hawai'i



Copyright 2014 DigitalGlobe
NextView License



After

Vacationland, Hawai'i

Image ©2018 Planet Labs, Inc., cc-by-sa 4.0

0 0.4 Miles



Before

Leilani Estates, Hawai'i

Copyright 2014 DigitalGlobe
NextView License

After

Leilani Estates, Hawai'i



Image ©2018 Planet Labs, Inc., cc-by-sa 4.0

0 0.3 Miles

Kilauea 2018 Damage to utilities



Cumbre Vieja, La Palma, Spain, 2021



Source: Overon Media

Fagradalsfjall, Iceland, 2021



Brian Emfinger/The New Yorker



Einat Lev



Fagradalsfjall 2021 Mitigation attempts

May 19, 2021



June 9th, 2021



June 23rd, 2021



Goals of modeling lava flows

Short-term forecasting

Where will this lava go?
How quickly will it get there?

Hazard assessment and planning

Where will some future lava go?
How hot / dense / fast will it be?

Deposit interpretation

What was the effusion rate?
What was this lava like?

Insight into fundamental processes

How do landscape / rheology / pulsing /
cooling influence emplacement?

How uncertain are the above assessments?

Categories of lava flow models

“Physics based” vs. “Rule based”

“Deterministic”

where, when and how

“Probabilistic” / “Stochastic”

Where, when, and how likely

Any deterministic model can be run in a probabilistic framework given sufficient computing power

Complexity of physics considered and numerics

Topography + vent only
(DOWNFLOW, MULTIFLOW)

Cellular automata / lobes
(MAGFLOW, MOLASSES,
MrLavaLoba, Q_LavHa)

Depth-averaged (1d or 2d)
FlowGo, VolcFlow, IMEX_Lava)

Fully 3D models (OpenFOAM,
FLUENT, COMSOL, Flow3D)

Where?

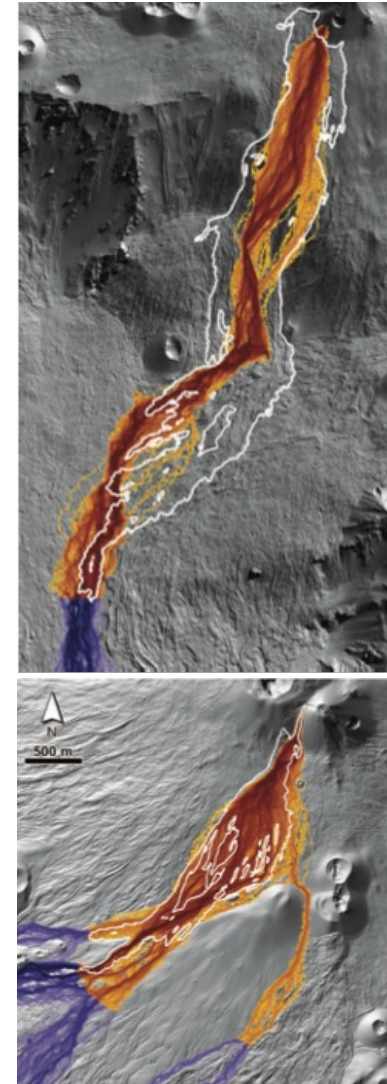
How quickly?

DOWNFLOW

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

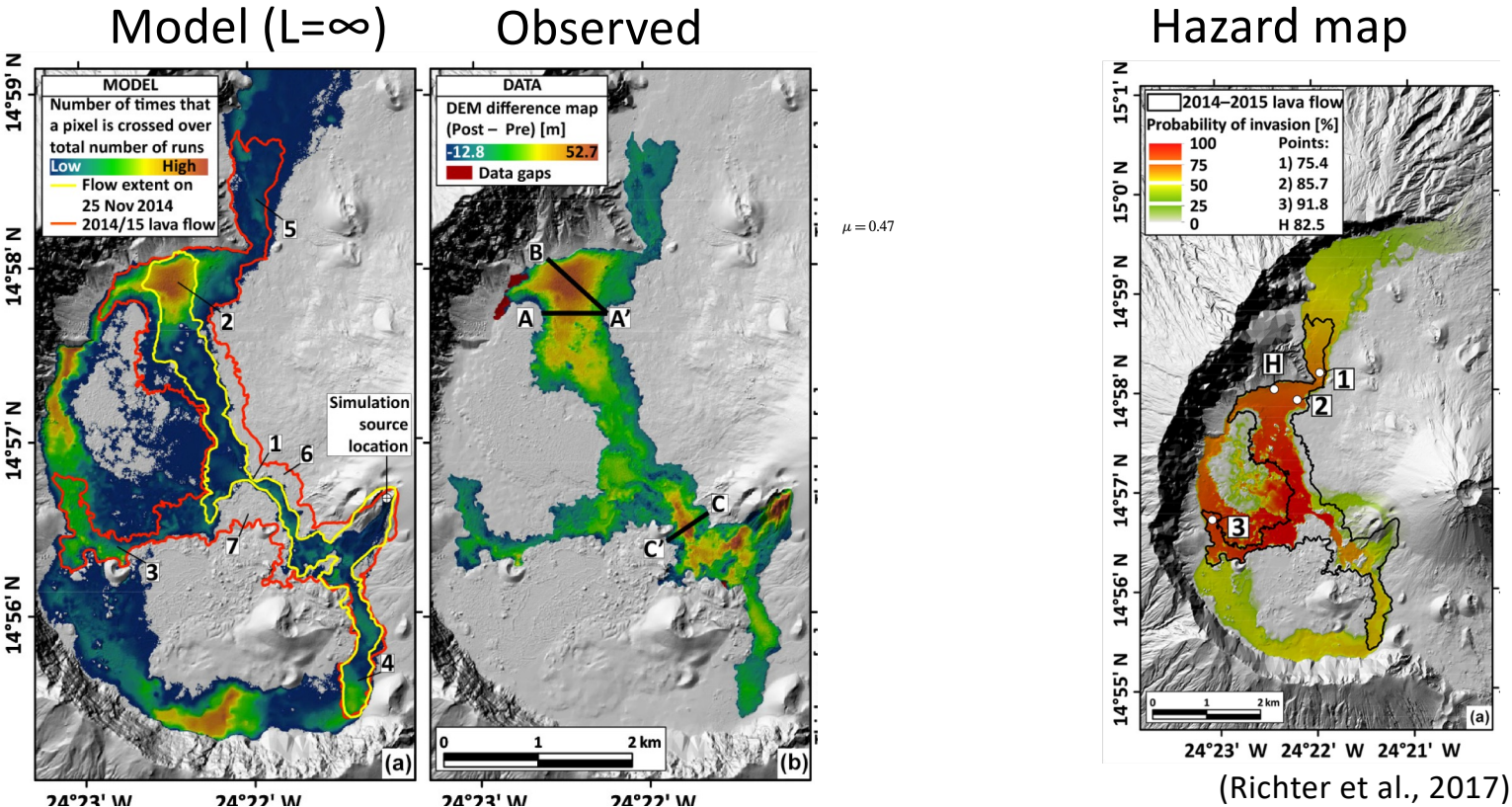
Favalli et al., 2005, 2009, 2011

Etna 2006

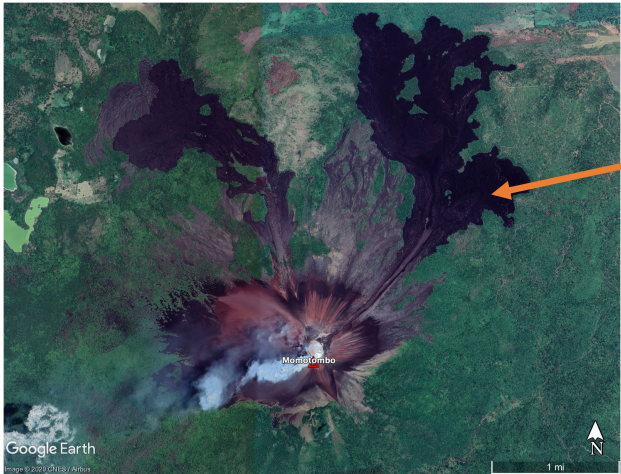


DOWNFLOW

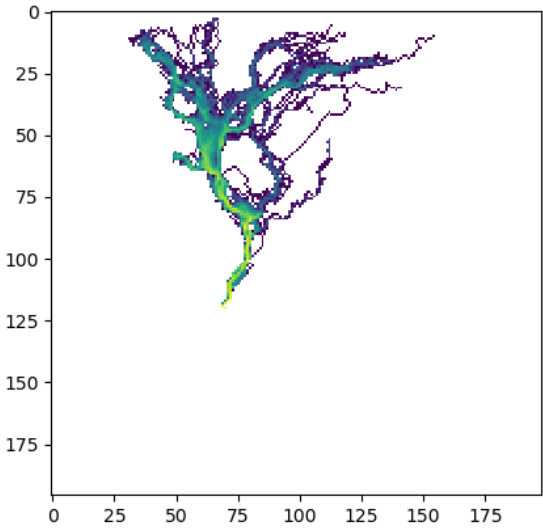
Test case: 2014–2015 eruption of Fogo volcano



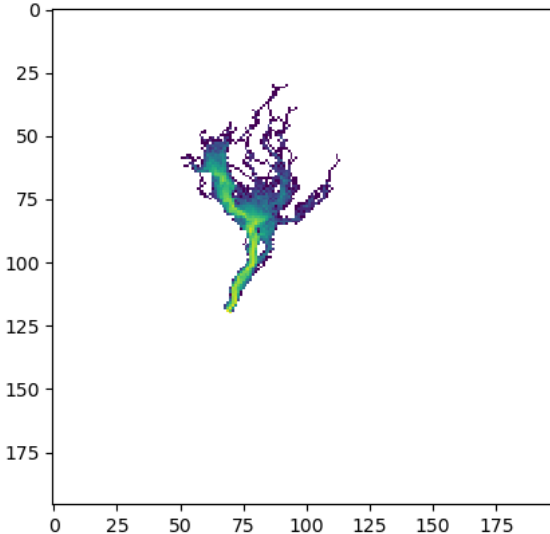
DOWNFLOW on VICTOR



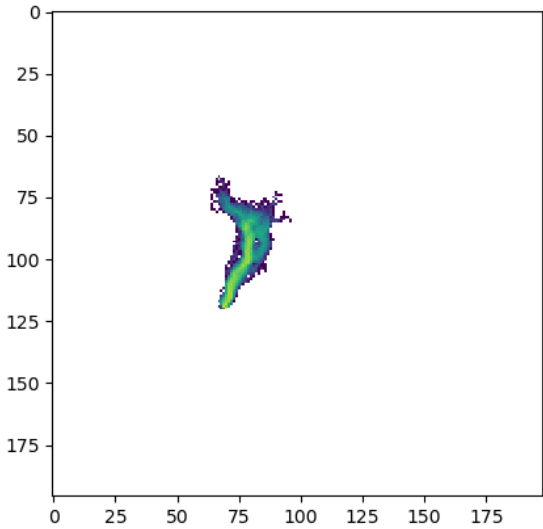
Momotombo, Nicaragua
2015-2016 eruption



dh = 2 m

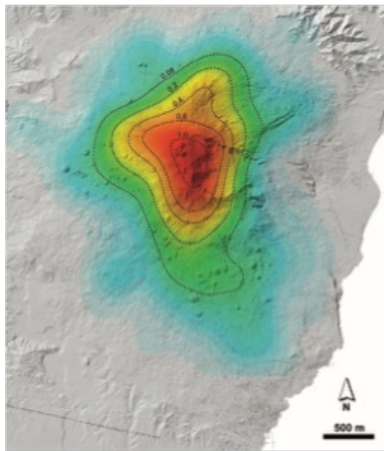


dh = 5 m



dh = 10 m

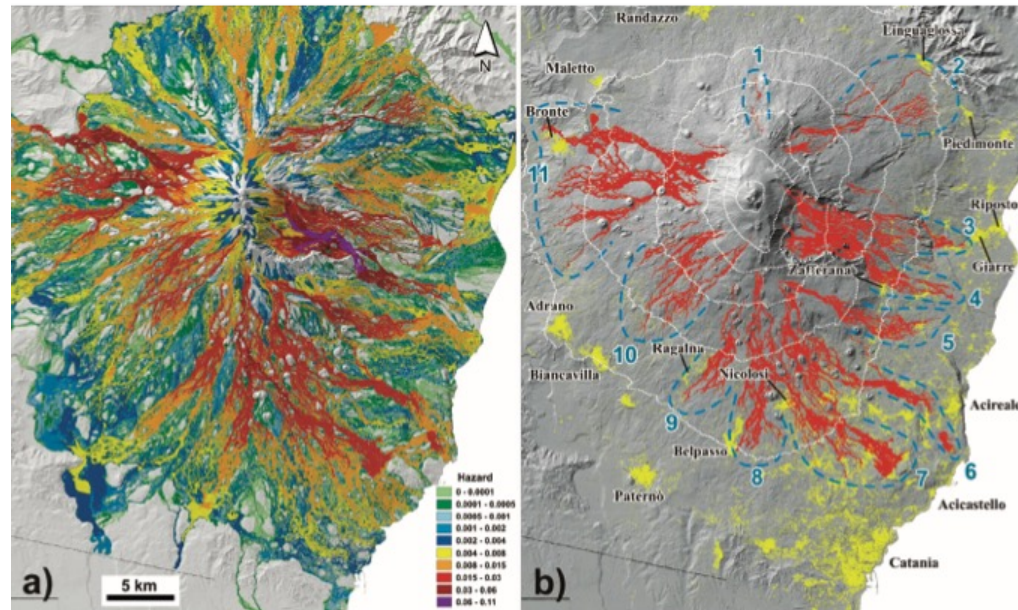
DOWNFLOW-> Hazard map



Vent opening density function

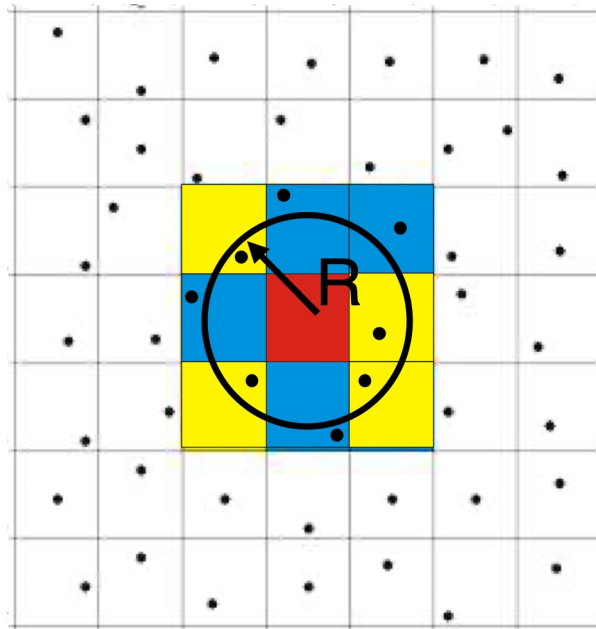
$$P(x,y) = \iint P_{\text{DOWNFLOW}}(x,y; x',y') \cdot P_L(h,L) \cdot p_v(x',y') dx' dy' \quad (2)$$

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

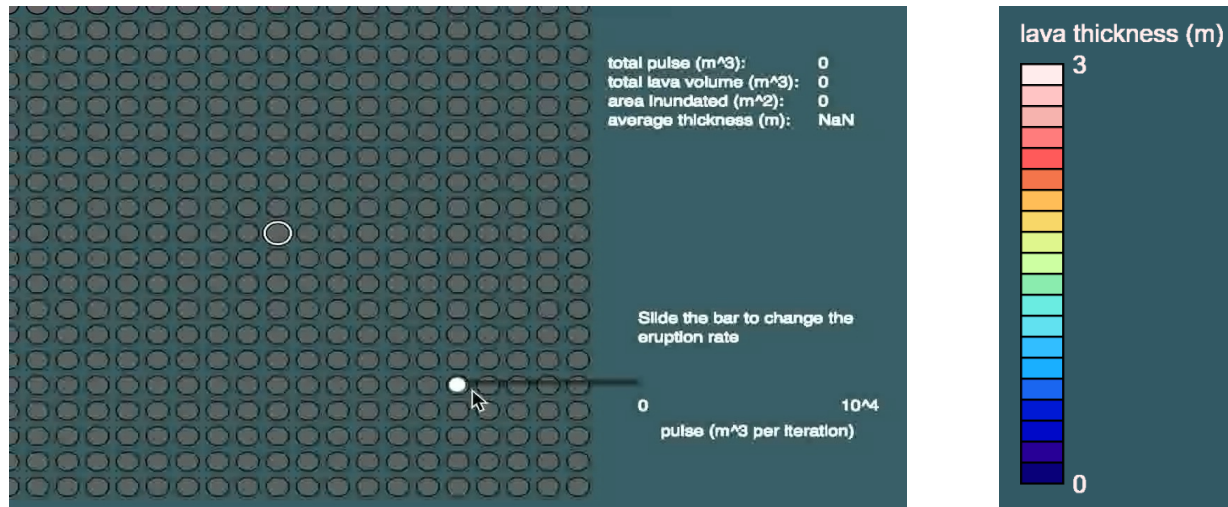


Cellular Automata models

- Popular in volcanology for simplicity and speed
- Rules for transferring lava between cells, based on probability, slope, temperature, etc



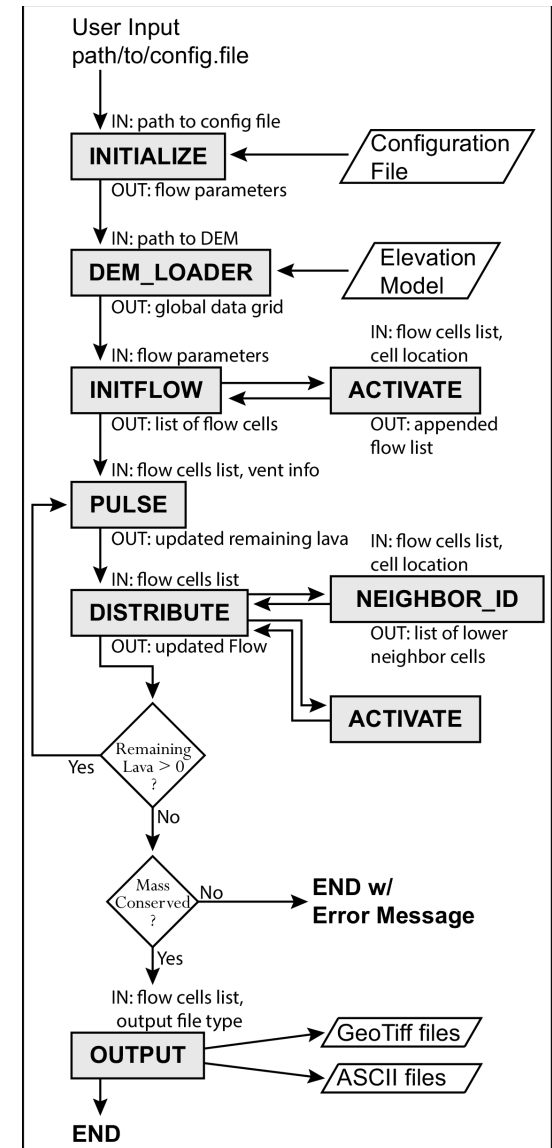
MOLASSES



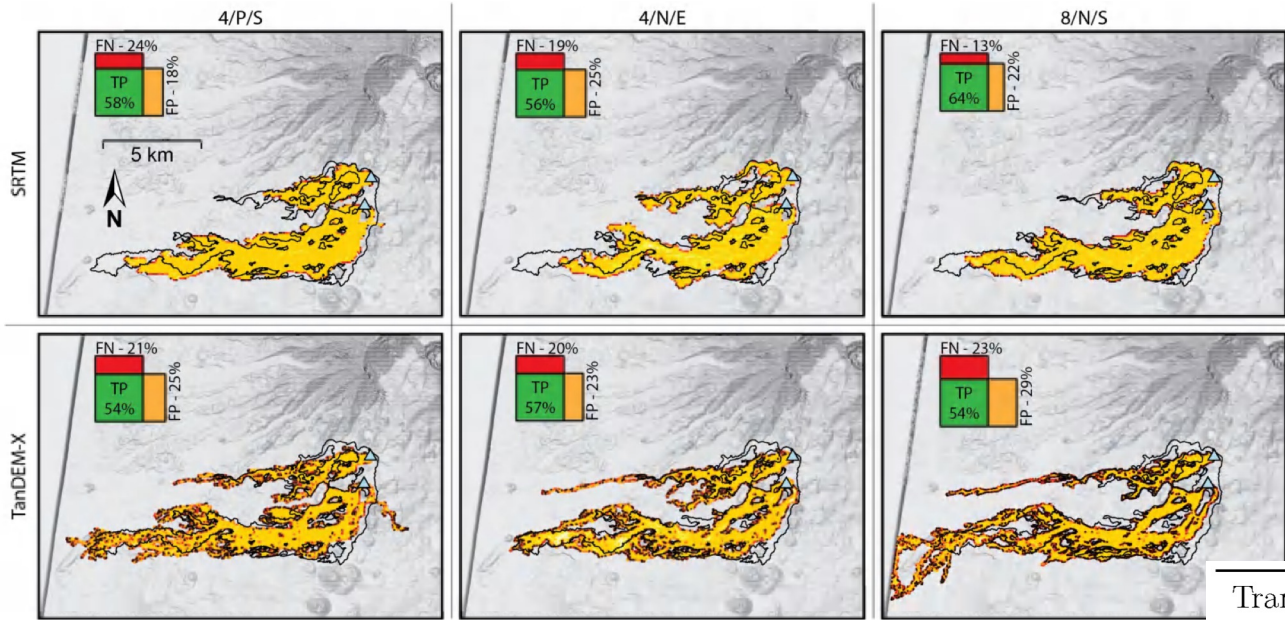
http://www.cas.usf.edu/~cconnor/lava_sandbox2.html

Inputs for MOLASSES include:

- A digital elevation model (DEM) of the region.
- Vent location
- Total erupted volume
- Pulse volume
- Average final flow thickness



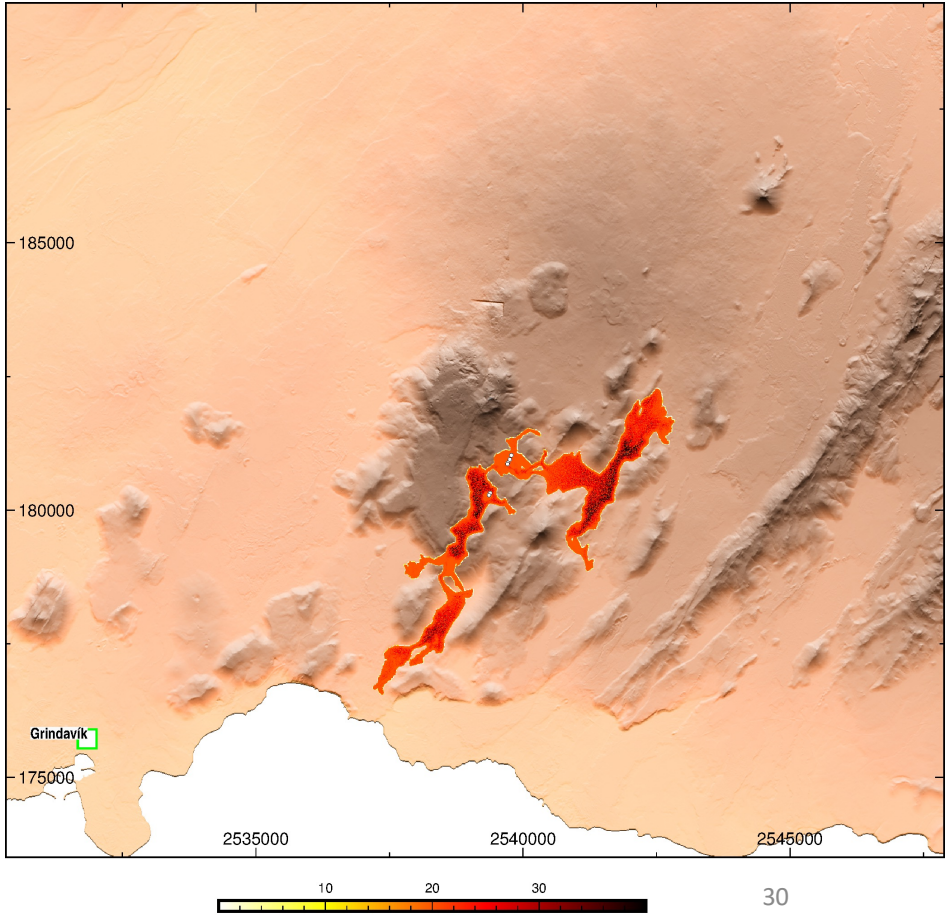
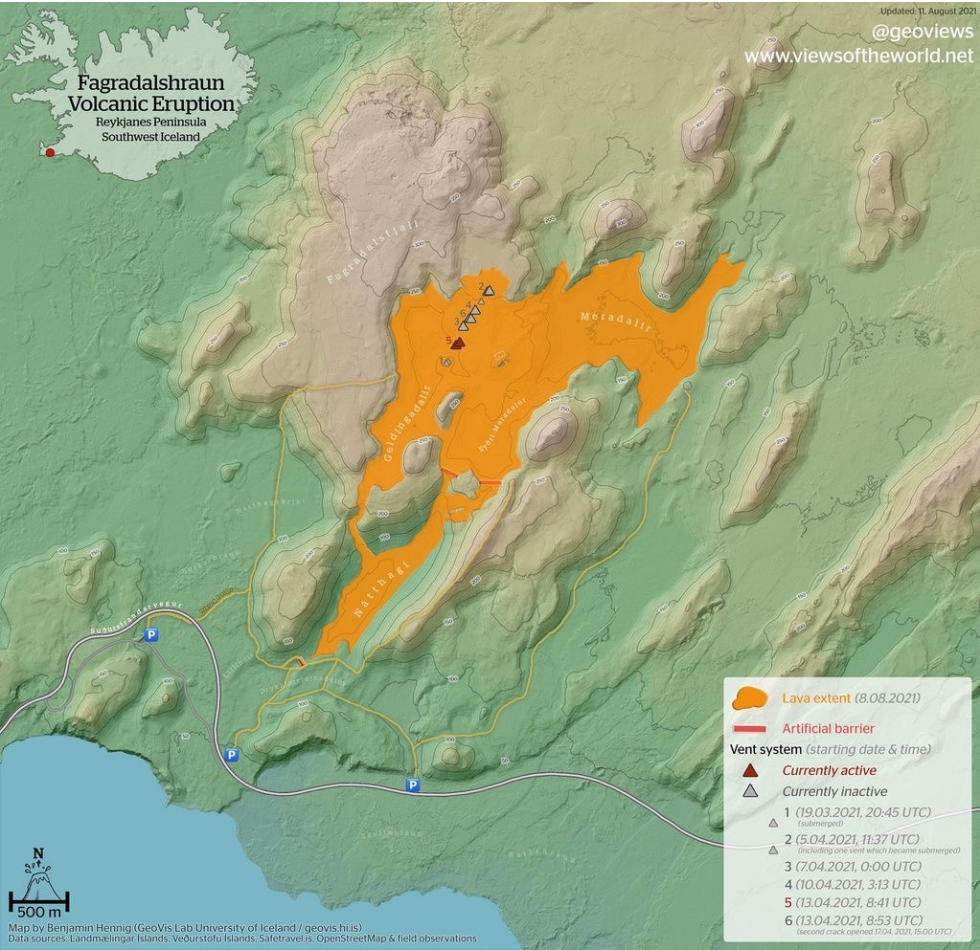
MOLASSES test case – Tolbachik 2012-2013



$$\text{Model Sensitivity} = \frac{|Lava \cap Sim|}{|Lava|}$$

Transition Function	SRTM DEM		TanDEM-X DEM	
	Jaccard	Sensitivity	Jaccard	Sensitivity
4/P/S	56.7%	76.4%	53.0%	72.4%
8/P/S	61.1	80.8	46.8	67.2
4/N/S	57.2	77.5	44.0	64.0
8/N/S	63.1	82.8	46.7	67.4
4/P/E	51.2	71.5	54.2	73.4
8/P/E	58.8	78.2	56.3	76.0
4/N/E	54.5	74.5	55.7	73.7
8/N/E	59.6	78.8	56.2	75.3

MOLASSES for Fagradalsfjall



Activity: Try using MOLASSES on VICTOR

- Login to VICTOR
- Open a Terminal window, type `victor setup` and choose 10 for MOLASSES
- Once a MOLASSES folder appears in your home directory, go to it, and double-click `molasses.ipynb`
- Run through the steps in the notebook until you get a map of flow coverage
- Open the map in a new tab, download it, and put in the group Padlet

Q-LAVHA

- QGIS plugin
- Dispersal probability:

$$P_i = \frac{\Delta h_i}{\sum_{j=1}^8 \Delta h_j}, \quad i = 1, 2, 3, \dots, 8 \quad \text{Or:} \quad P_i^2 = \frac{(\Delta h_i)^2}{\sum_{j=1}^8 (\Delta h_j)^2}, \quad i = 1, 2, \dots, 8$$

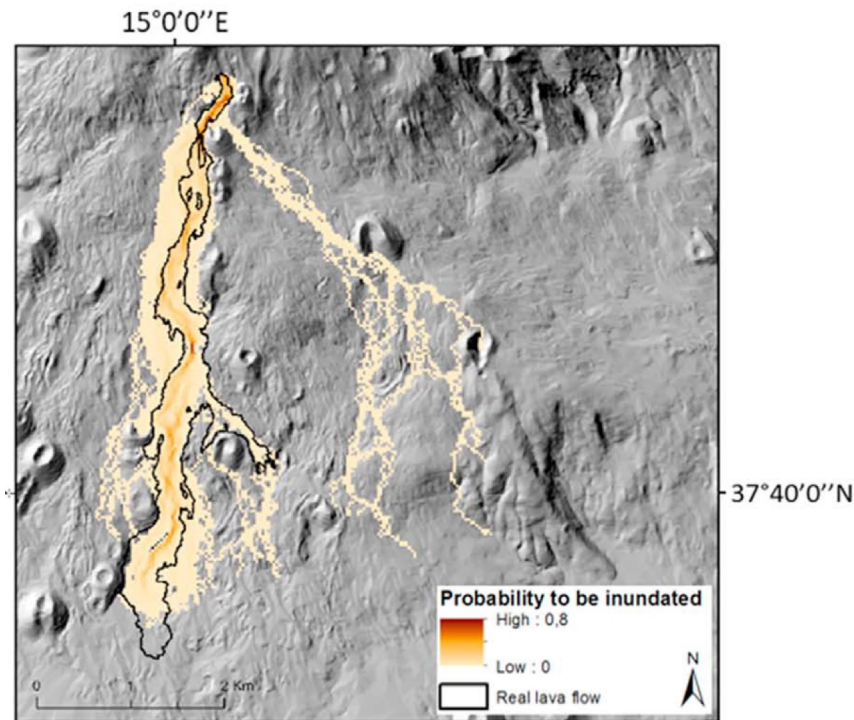
- Mechanism to overcome small pits
- Reduced probability with distance from vent ('cooling'):

$$\varphi(x, \mu, \sigma) = 1 - \frac{1}{2} \left(1 + \operatorname{erf} \left(\frac{x - \mu}{\sqrt{2\sigma^2}} \right) \right)$$

- Flow length limit is set as input, or can be calculated through cooling (using the FlowGo model)

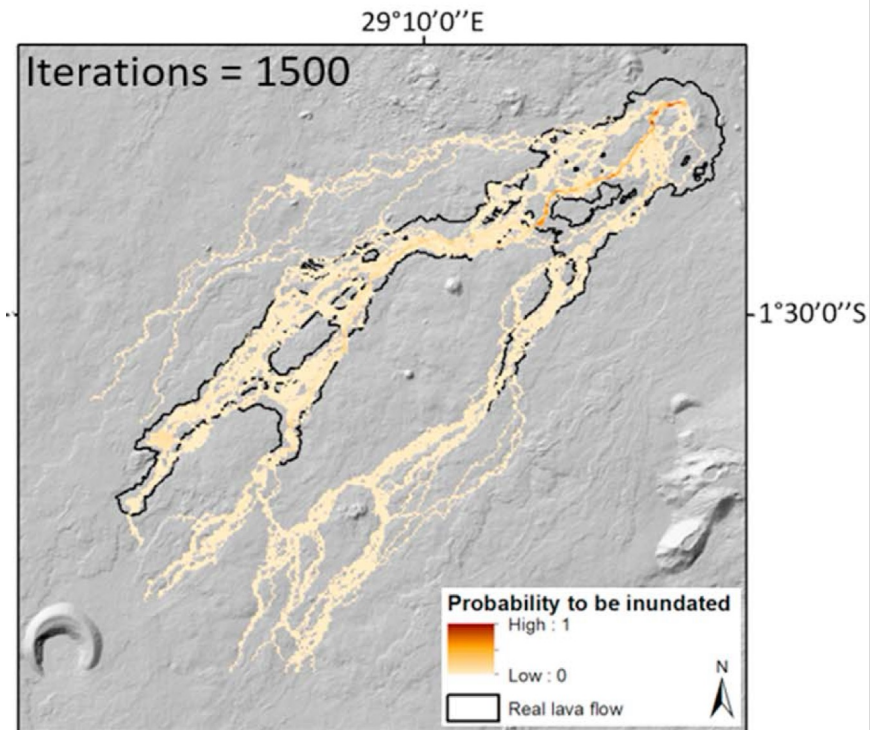
If $(h_0 + H_c) - h_i \geq 0$ then $\Delta h_i = (h_0 + H_c) - h_i$
If $(h_0 + H_c) - h_i < 0$ then $\Delta h_i = 0$
If all $\Delta h_i = 0$ then
If $(h_0 + H_p) - h_i \geq 0$ then $\Delta h_i = (h_0 + H_p) - h_i$
If $(h_0 + H_p) - h_i < 0$ then $\Delta h_i = 0$

Q-LAVHA test cases



$FI_{true\ positive} = 0.33; FI_{false\ positive} = 0.63; FI_{false\ negative} = 0.04$

Etna 2001



Nyiragongo 2006

To install the Q-LavHA plugin for your profile:

- Go to VICTOR's graphical desktop
- Open QGIS
- In "Plugins", choose "manage plugins". Select "install from zip file"
- Choose the zip file from ~/shared/Models/Q-LavHA/

MrLavaLoba

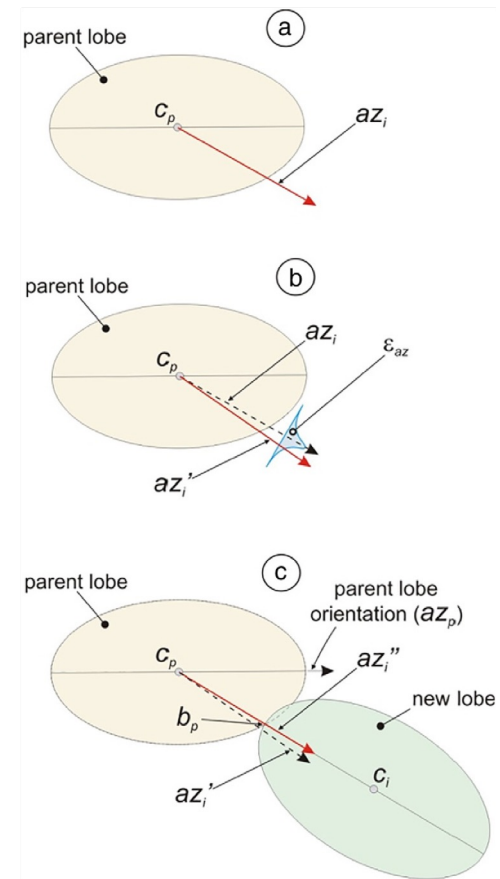
1. Set the first lobe on the vent

2. Iteratively every step:

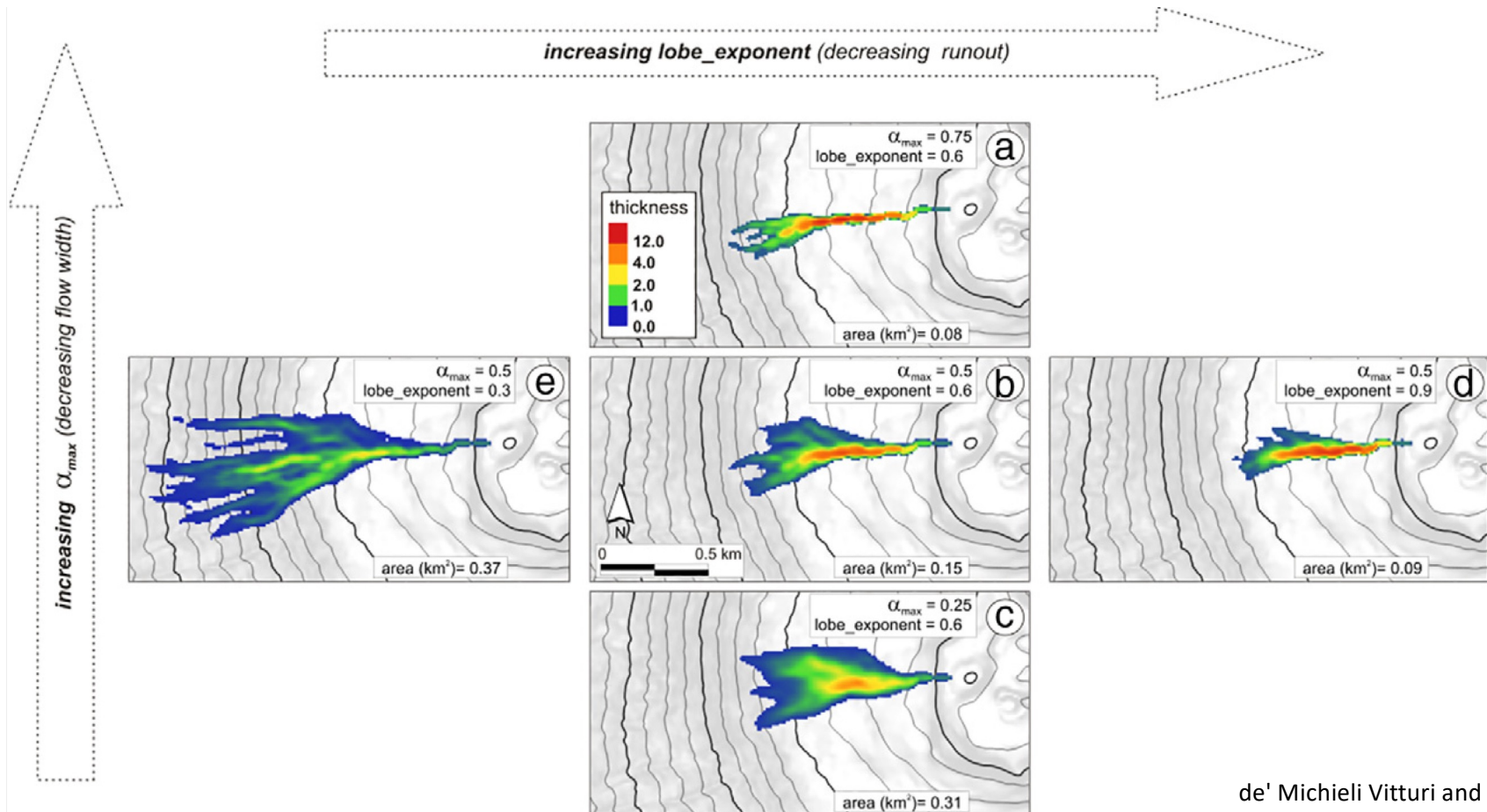
2a) Determine which lobes bud new ones based on the "lobe exponent" ε ($\varepsilon=0$: only youngest lobe buds new ones. $\varepsilon=1$: all existing lobes have the same probability to be the parent)

2b) Determine the point to bud the next lobe:

- STEP 1. Set preliminary direction to lowest point on the parent lobe perimeter
- STEP 2. Perturb that direction to reflect local slopes distribution
- STEP 3. Add an inertial perturbation based on parent lobe direction, to obtain lobe azimuth

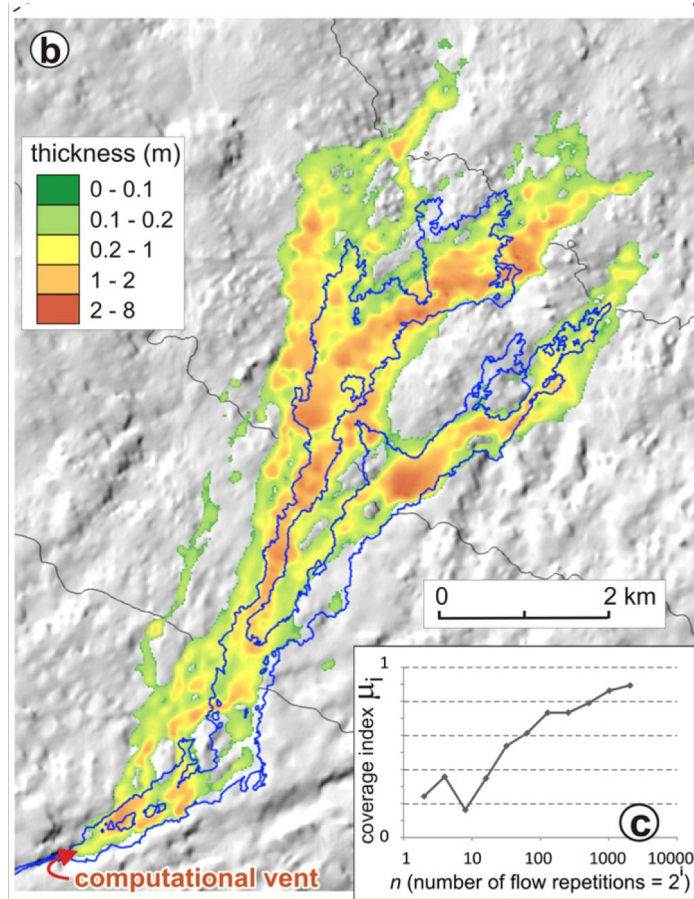


MrLavaLoba sensitivity to parameters

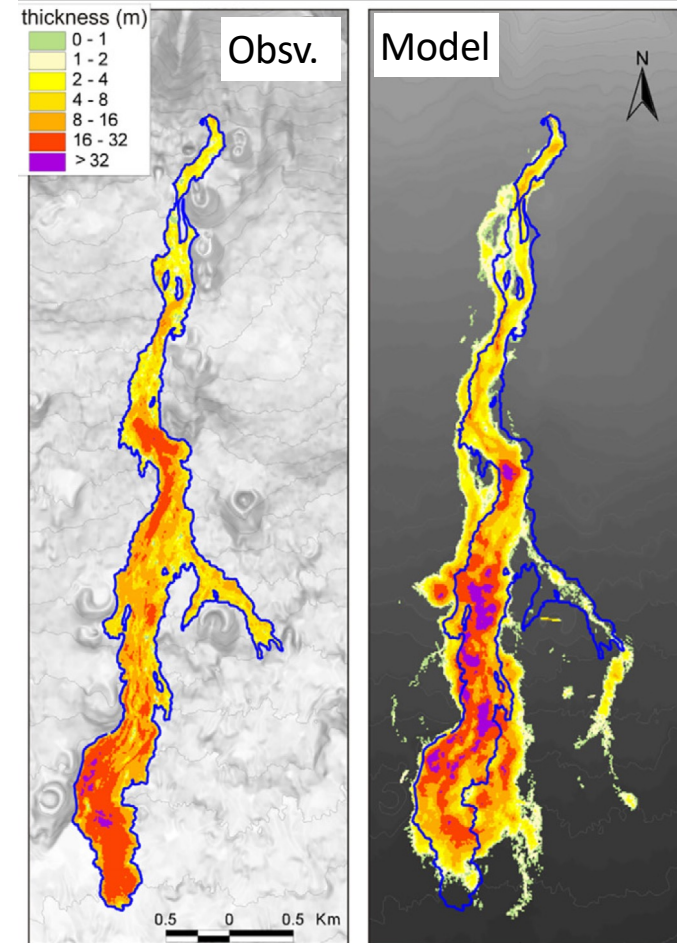


MrLavaLoba test cases

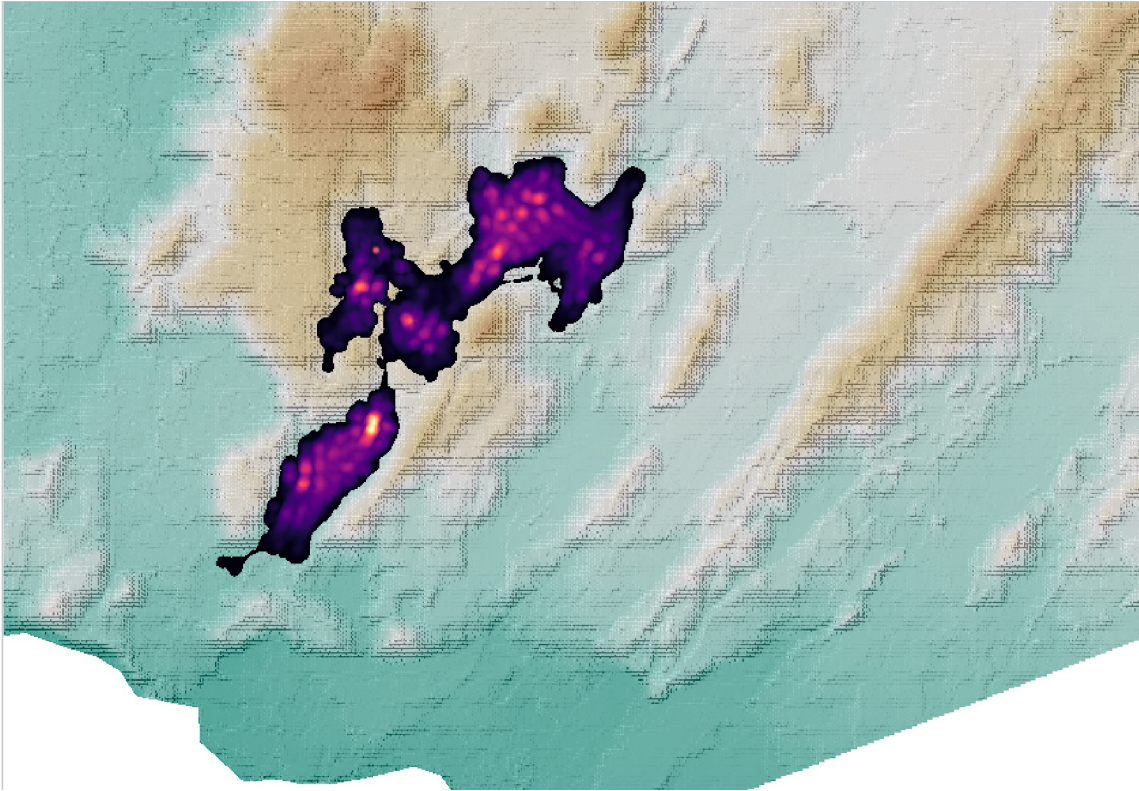
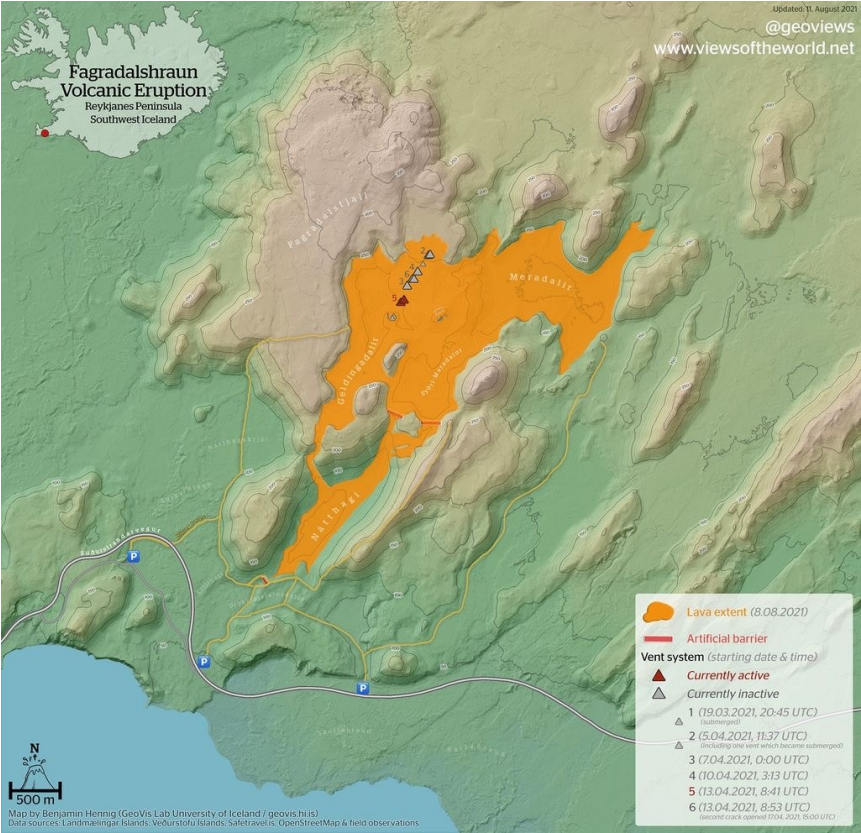
Kilauea 2014-2015



Etna 2001



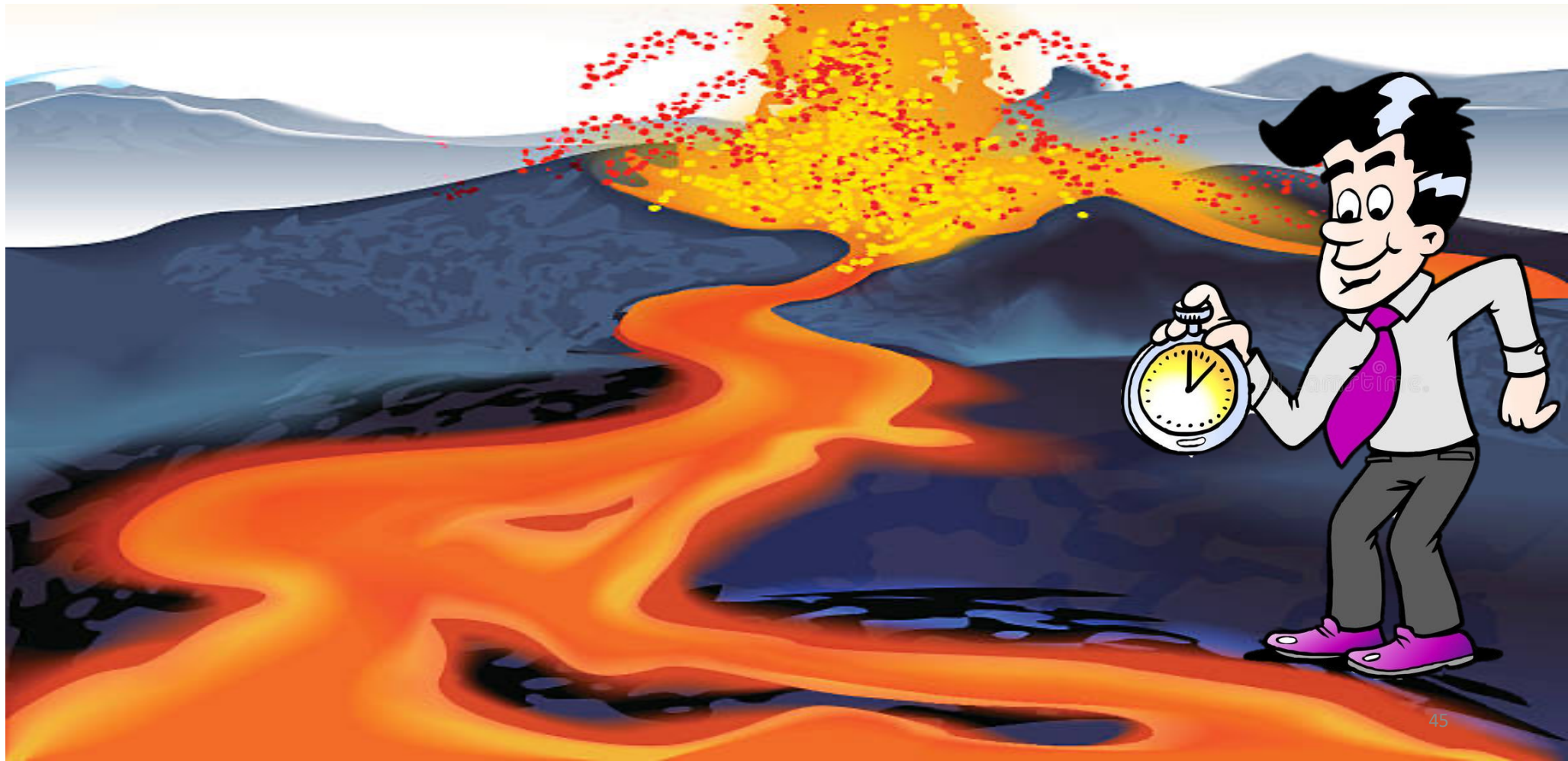
MrLavaLoba for Fagradalsfjall



Activity: MrLavaLoba on VICTOR

1. Login to VICTOR if not there yet
2. In a Terminal window, type `victor setup` and choose 9 for MrLavaLoba
3. Once a `mr_lava_loba` folder appears in your home directory, go to it, and double-click `mr_lava_loba.ipynb`
4. Run through the steps in the notebook until you get a map of flow coverage
5. Open the map in a new tab, download it, and put in the group Padlet

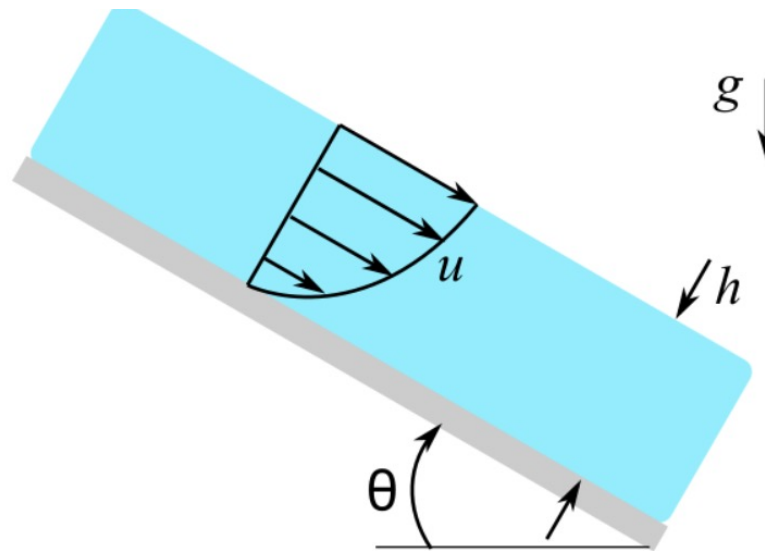
How quickly will the lava travel?



Need to know: Rheology!

Jeffreys equation
(Newtonian fluid):

$$Velocity_{max} = \frac{\text{density} \times g \times \text{depth}^2 \times \sin(\text{slope})}{3 \times \text{bulk viscosity}}$$



Need to know: Rheology!

Jeffreys equation
(Newtonian fluid): $Velocity_{max} = \frac{density \times g \times depth^2 \times \sin(slope)}{3 \times bulk\ viscosity}$

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

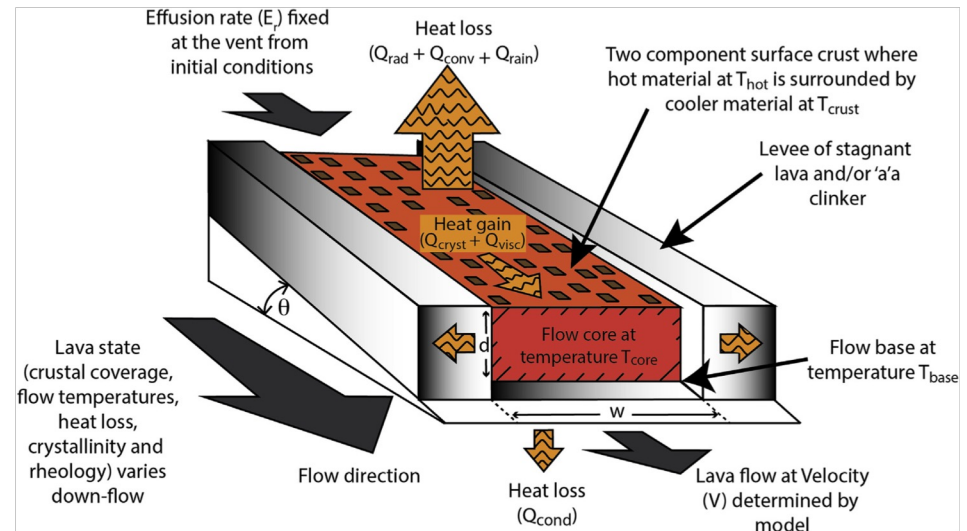
Herschel-Bulkley fluid: $\bar{u} = \frac{H^2 \rho g \sin \beta}{3K} \left(\frac{3n}{H^3(n+1)} \left(\frac{\rho g \sin \beta}{K} \right)^{\frac{1-n}{n}} \right) \times \left(H(H-h_c)^{\frac{n+1}{n}} - \frac{n}{2n+1} (H-h_c)^{\frac{2n+1}{n}} \right)$.

Depth-averaged physics-based models

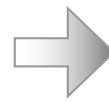
- **pyFlowGo (1D)** (Rowland and Harris, Chevrel)
- **VolcFlow** (Kelfoun)
- **IMEX-Lava** (Biagioli, di Mitcheli Vituri)
- **Flow2d** (Hyman, Dietterich 2023)

FlowGO / pyFlowGo

- 1D along-track deterministic, physics-based model
- Original in Excel, now in Python, free on GitHub

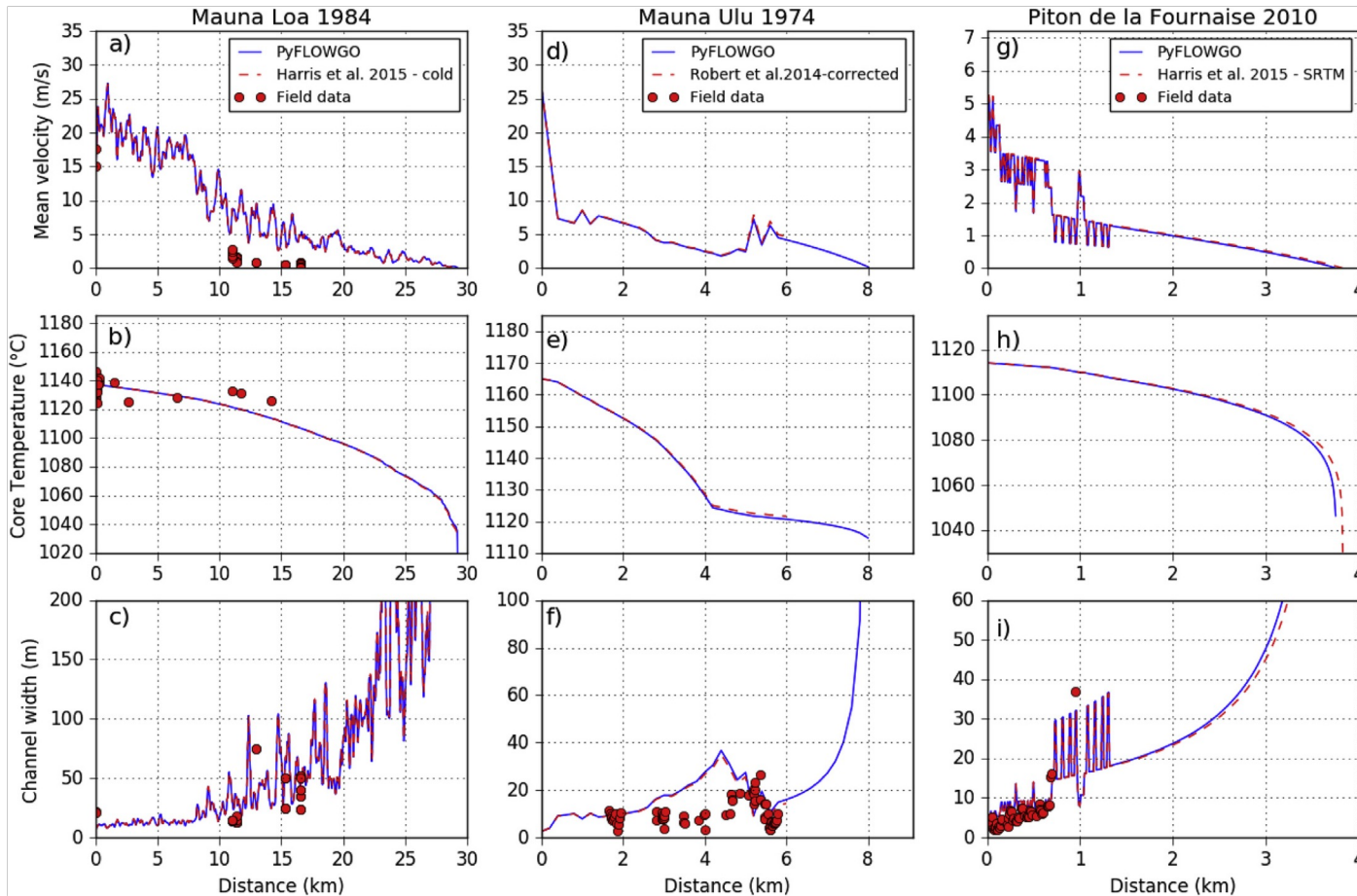


- **Input: Slopes along track**
- **Initial: channel width and thickness, temperature, crystallinity, and composition**



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

pyFlowGo test cases



Demonstration: PyFLOWGO on VICTOR



VolcFLOW

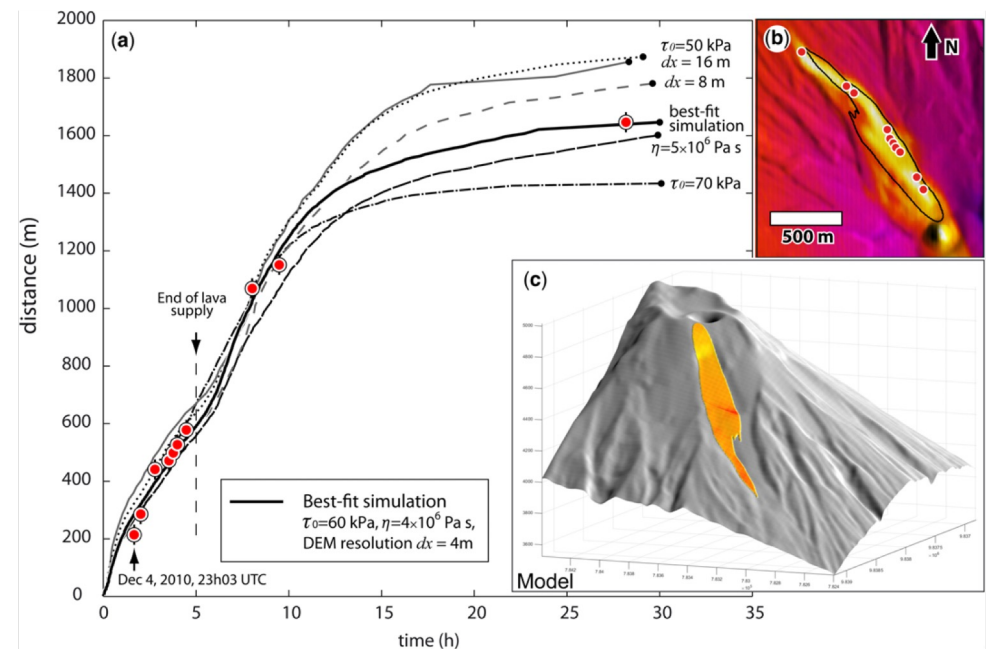
- Depth-averaged approach that solves mass (1) and momentum (2-3) conservation equations (Deterministic, Physics-based)

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

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

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

A closed MATLAB® executable!



IMEX_Lava

$$\nabla \cdot \mathbf{u} = 0, \quad (2.59a)$$

$$\frac{\partial(\rho\mathbf{u})}{\partial t} + \nabla \cdot (\rho\mathbf{u}\mathbf{u}^T) = -\nabla p + \nabla \cdot \boldsymbol{\tau} + \rho\mathbf{g} + \mathbf{f}_\Sigma, \quad (2.59b)$$

$$\partial_t \alpha + \nabla \cdot (\mathbf{u}\alpha) = 0, \quad (2.59c)$$

$$\frac{\partial(\rho c_p T)}{\partial t} + \nabla \cdot (\rho c_p T \mathbf{u}) - \bar{\chi}_\Sigma \Delta(kT) = -\frac{\epsilon \sigma_{SB} f A_{fs}}{Vol} (T^4 - T_{env}^4) - \frac{\lambda f A_{fs}}{Vol} (T - T_{env}), \quad (2.59d)$$

IMEX-Lava: Test case Pico de Fogo

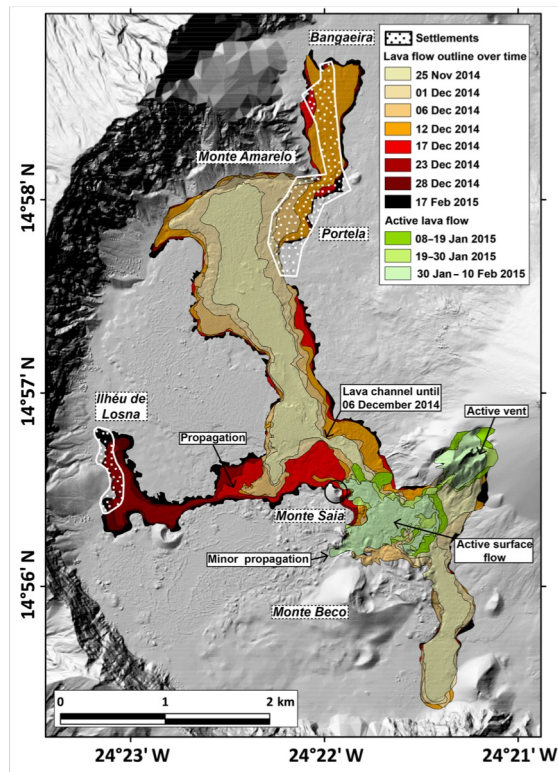
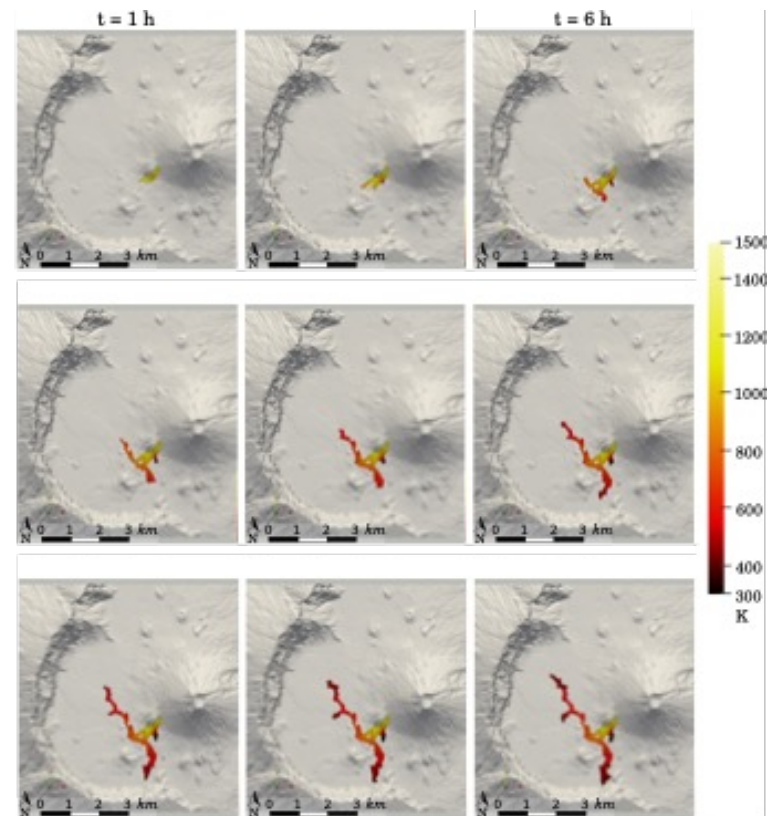
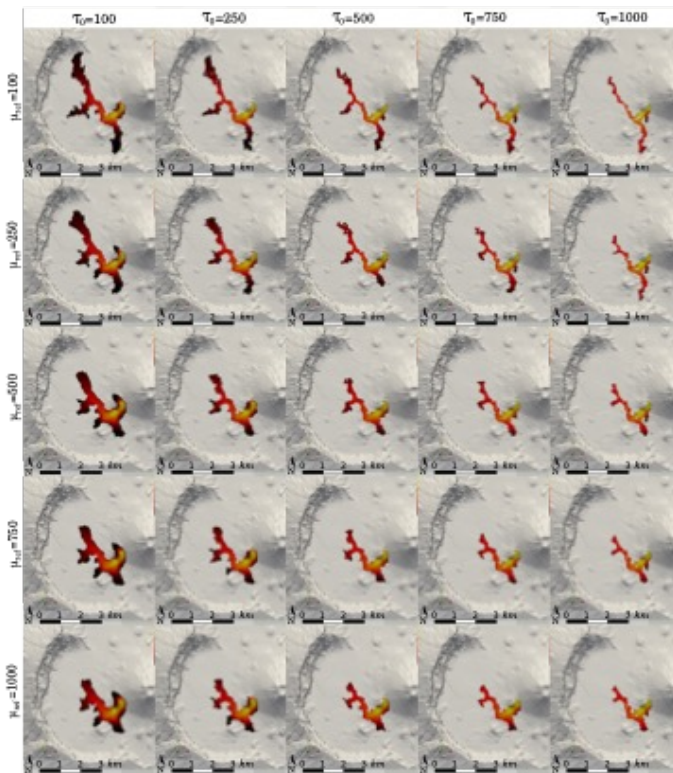


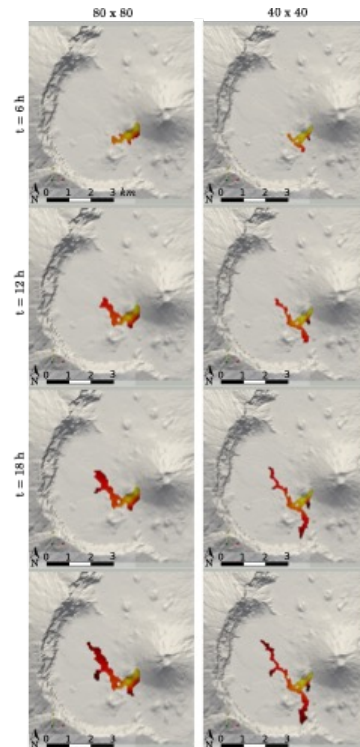
Figure 7. Lava flow outline over time from TerraSAR-X coherence maps (cf. Appendices C and D).



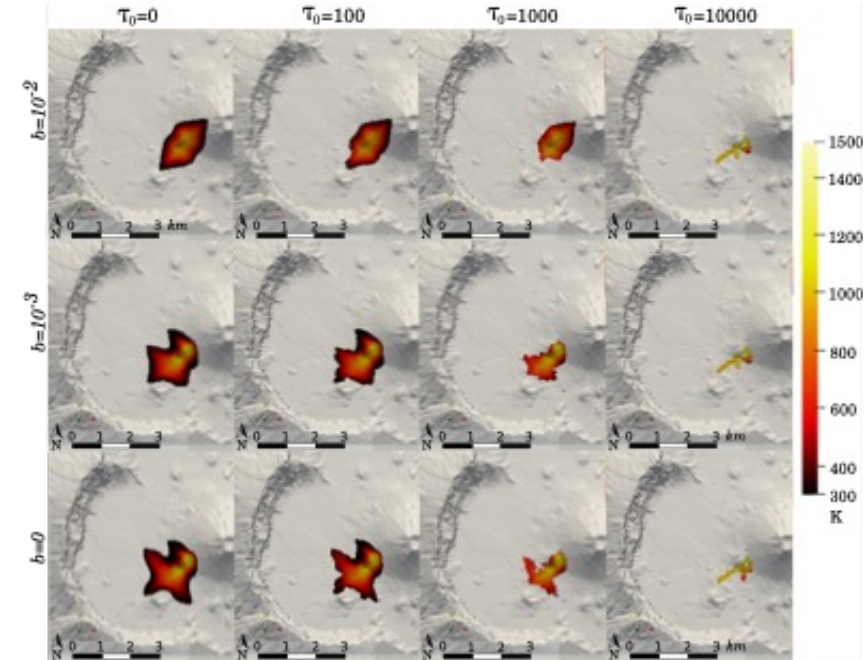
IMEX-Lava: Sensitivity to parameters



Yield stress, ref. viscosity

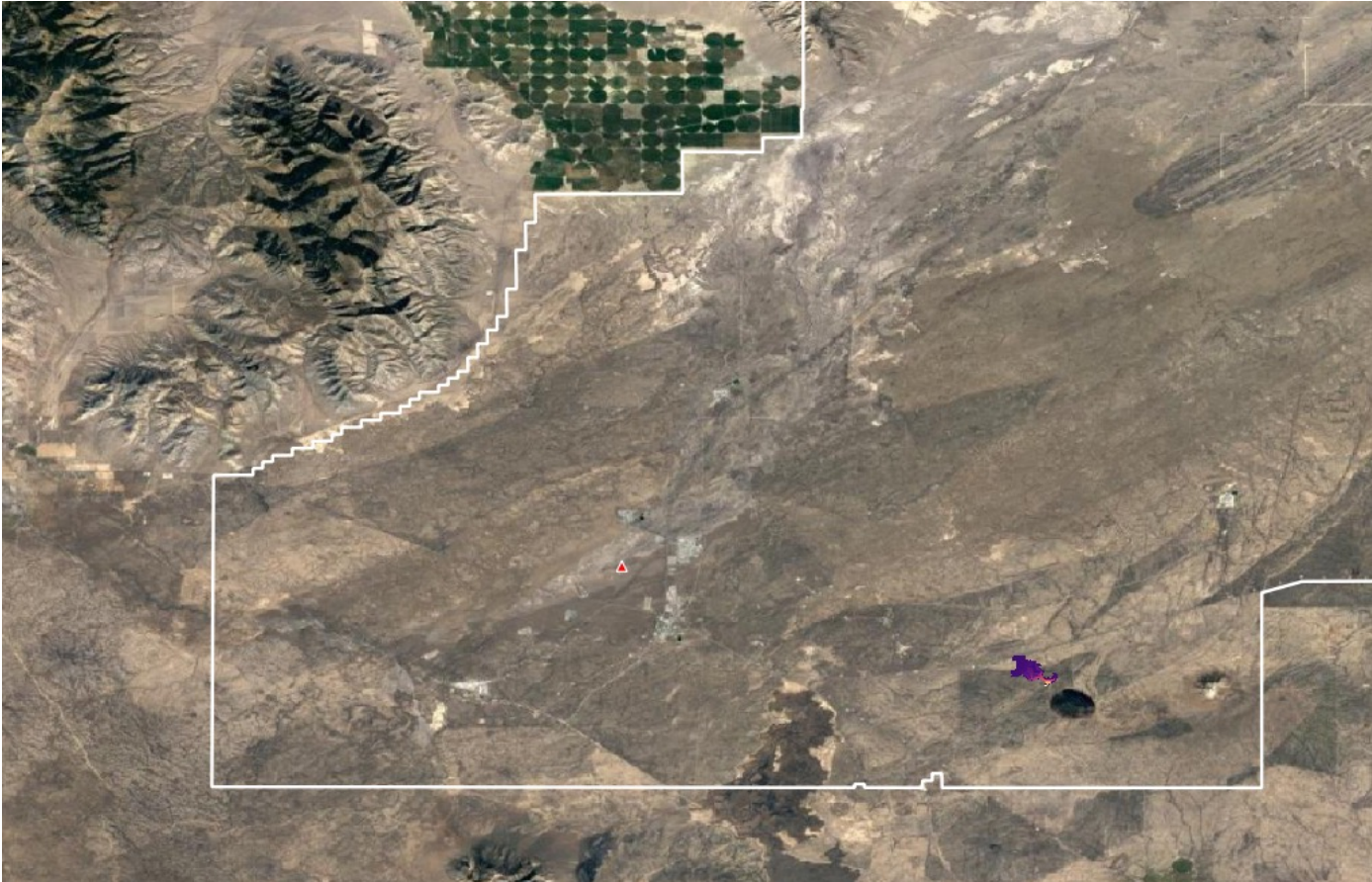


Grid size



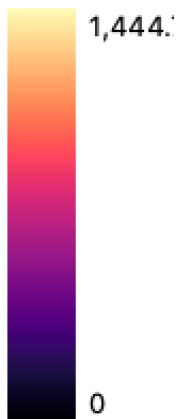
Yield stress, T-dep of viscosity

IMEX-Lava for INL



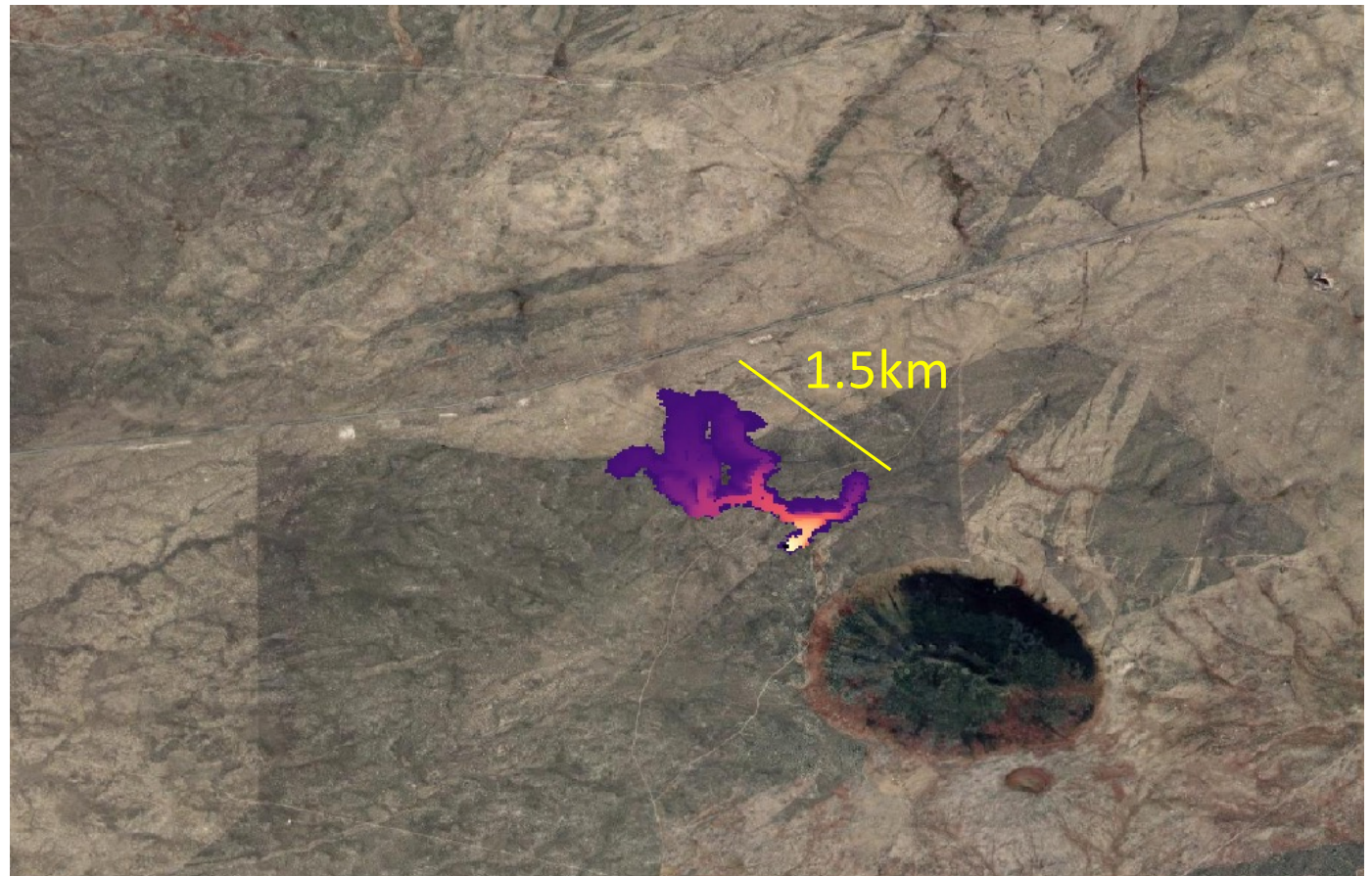
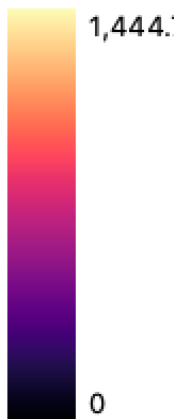
IMEX-Lava for INL

- One day



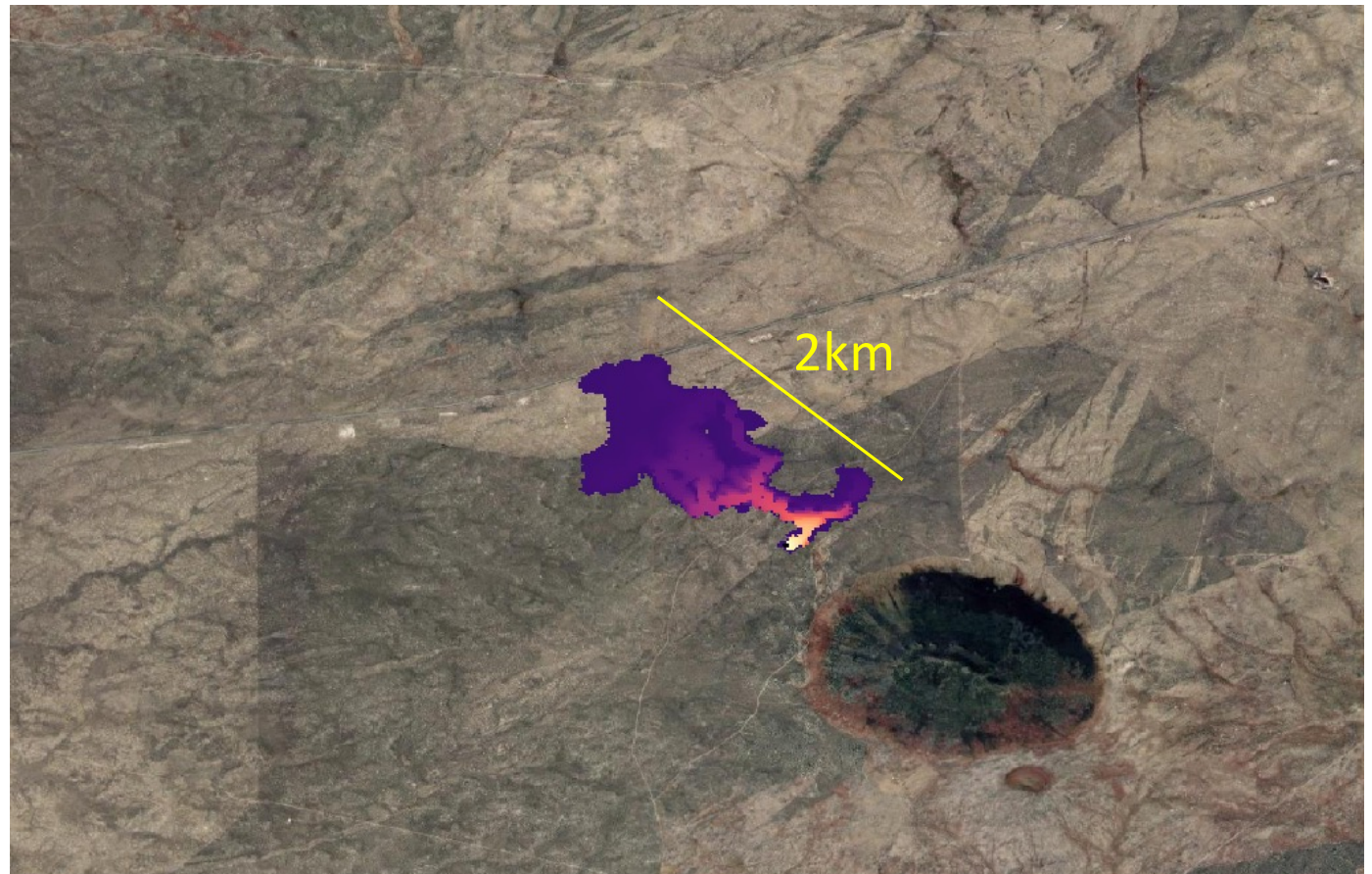
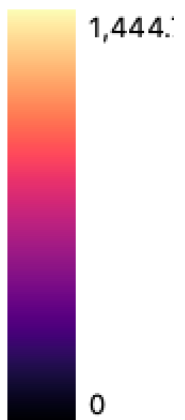
IMEX-Lava for INL

- One week



IMEX-Lava for INL

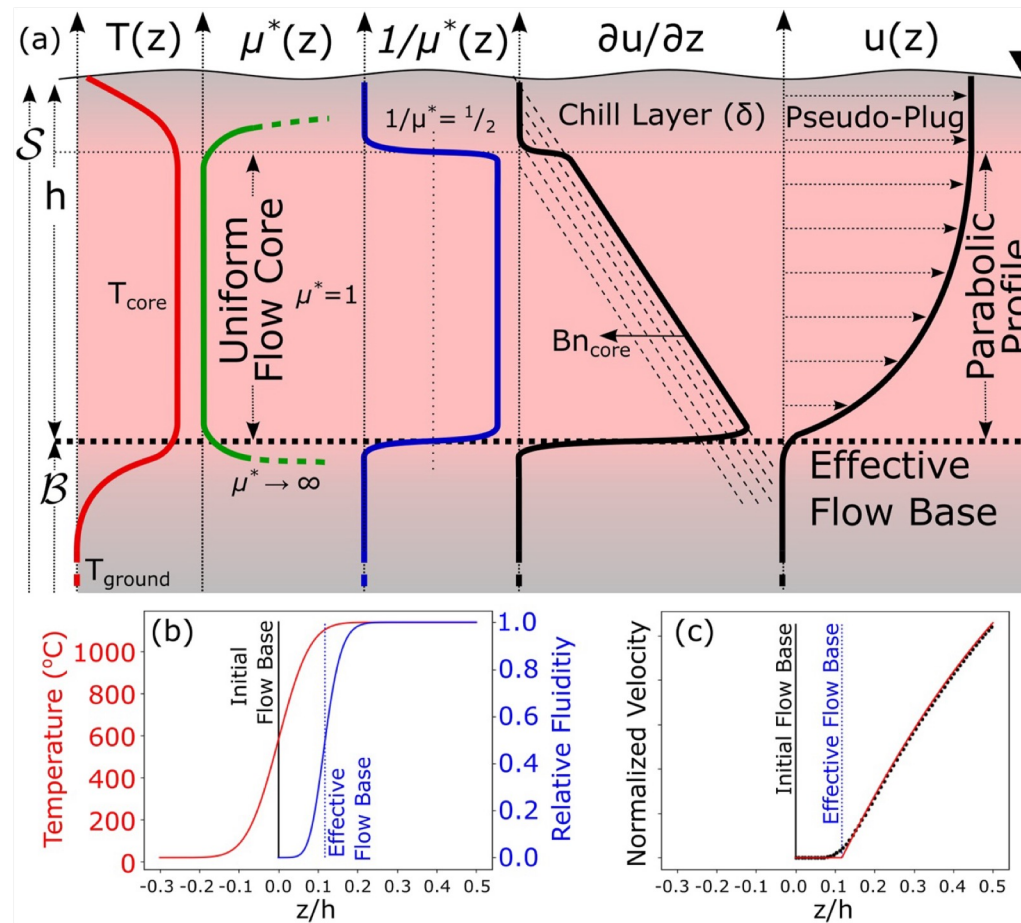
- Two weeks



At home: Try IMEX_LAVA on VICTOR

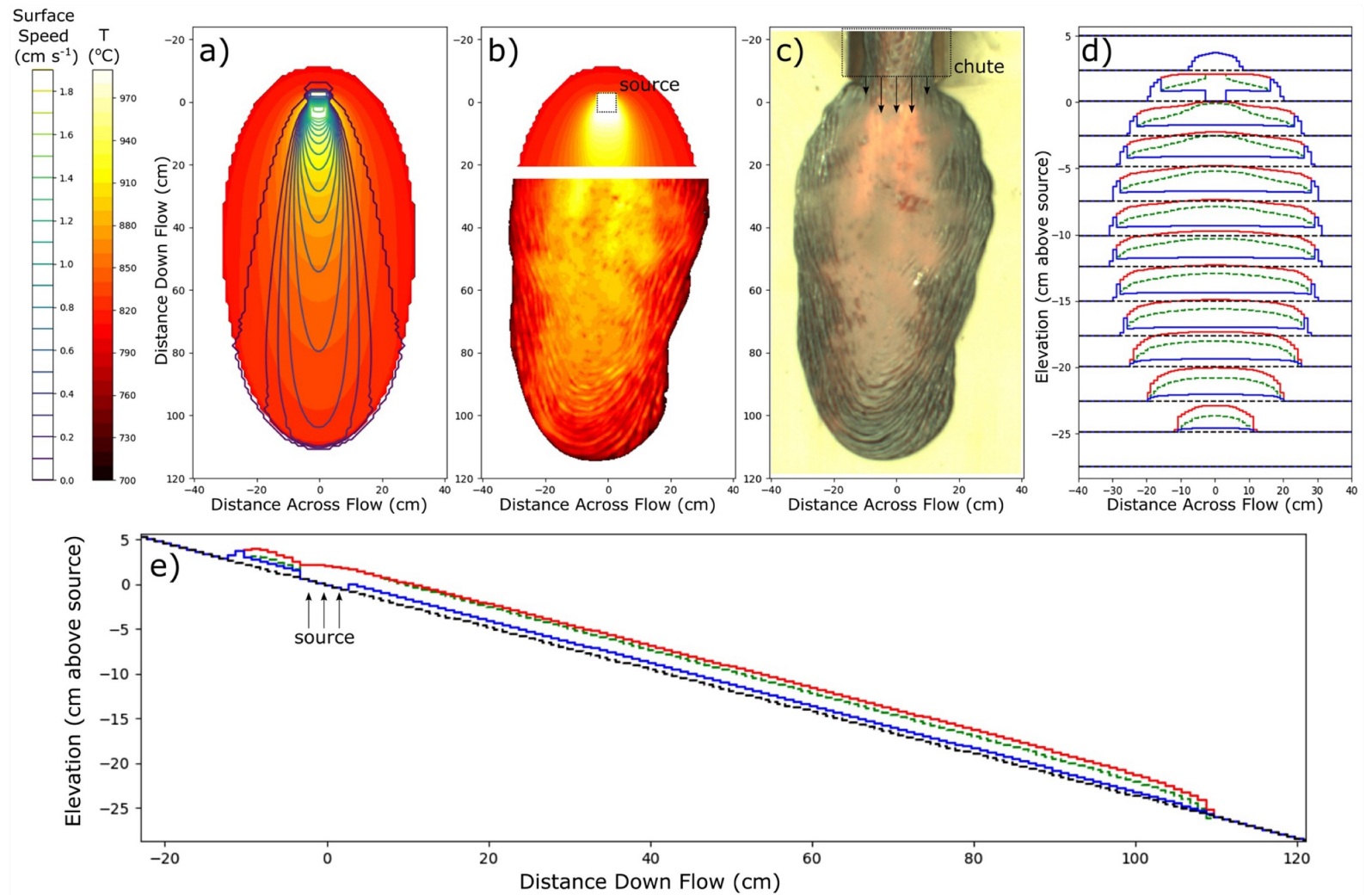
1. Login to VICTOR if not there yet
2. In a Terminal window, type `victor setup` and choose 5 for IMEX-Lava
3. Once a IMEX folder appears in your home directory, go to it, and double-click `IMEX.ipynb`
4. Run through the steps in the notebook until you get a map of flow coverage

Lava2D



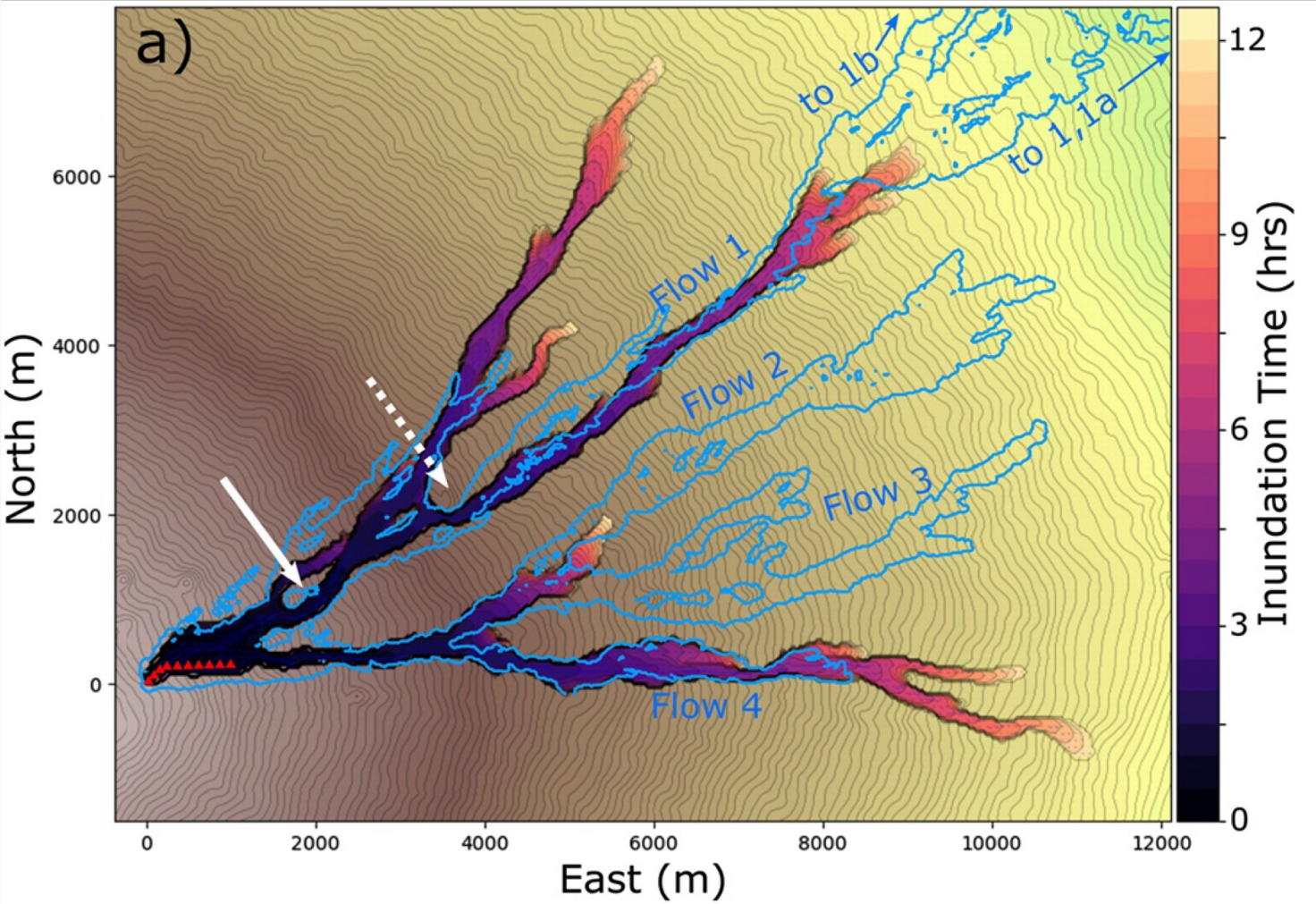
“Although some models use realistic cooling, they are generally too slow to be used in emergencies. Most previous lava flow models have instead estimated this cooling by assuming that temperature within a lava flow does not vary significantly with depth; however, this assumption is not realistic. Real lavas are much cooler at the surface and base than in their cores.” (Hyman et al, 2022)

Lava2D



Hyman et al., 2022

Lava2D



At home: Try Lava2d on VICTOR

1. Login to VICTOR if not there yet
2. In a Terminal window, type `victor setup` and choose Lava2d
3. Once a Lava2d folder appears in your home directory, go to it, and double-click `lava2d.ipynb`
4. Run through the steps in the notebook until you get a map of flow coverage

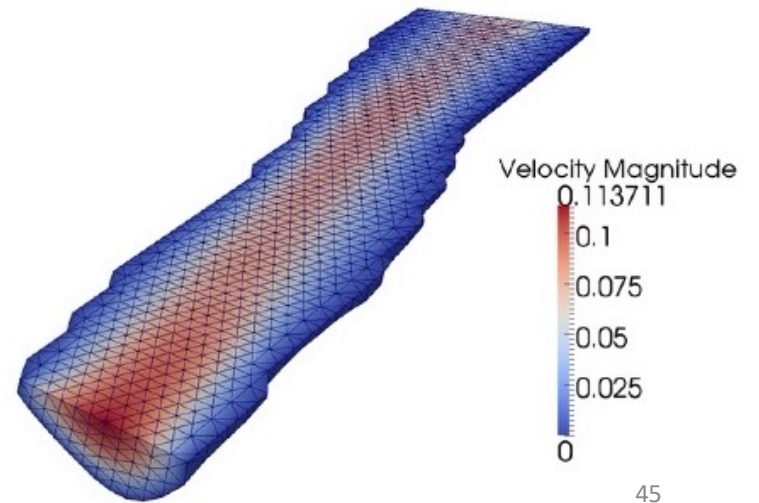
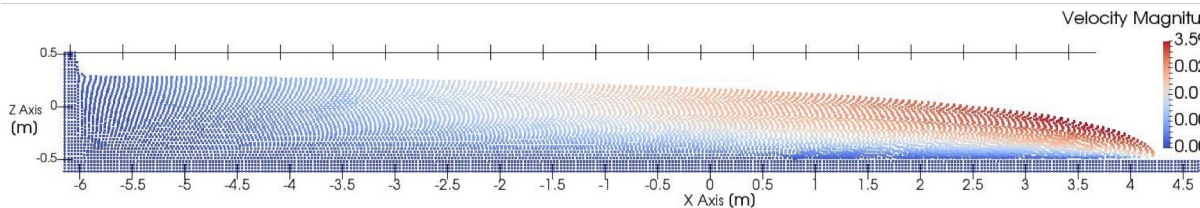
Computational Fluid Dynamics (CFD) models

Finite Element: FLUENT, COMSOL, ELMER, GetFEM...

Finite volume: Flow3D, OpenFOAM...

SMAC: LavaSIM

SPH: GPUSPH



Model assessment frameworks

Benchmarking

Comparing the performance of models when simulating a specific case with a known solution

Model intercomparison

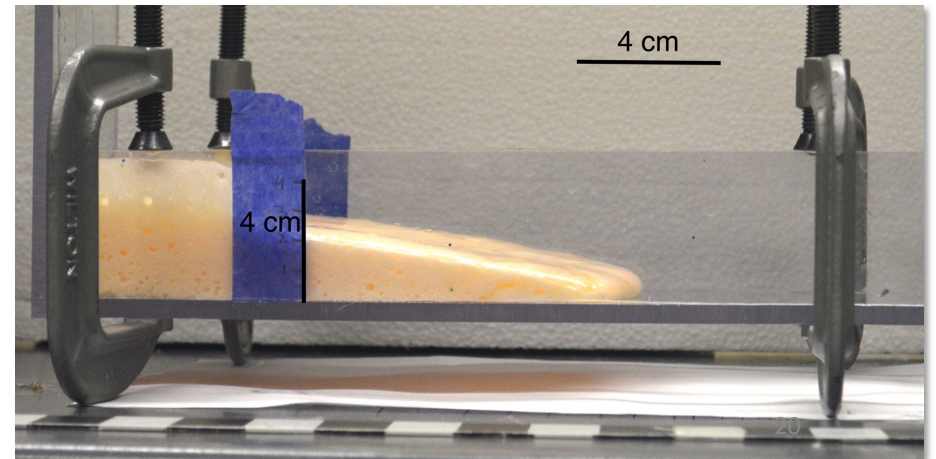
Comparing the performance of models to each other when the solution is not known

Benchmarking

Analytical solution

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

Experiments

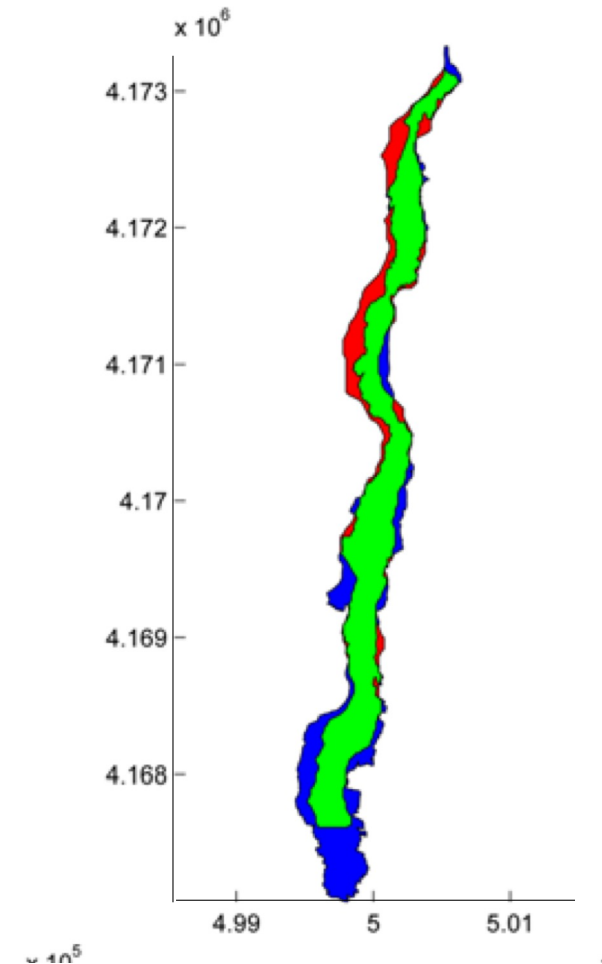
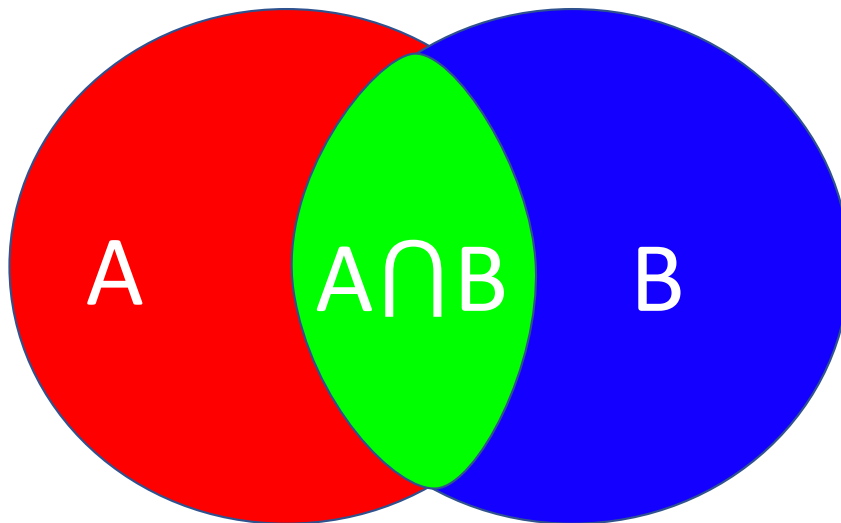


Cordonnier et al., 2015; Dietterich et al., 2017; Birnbaum et al., 2021

Comparing with natural flow examples

Jaccard similarity index (J_s):

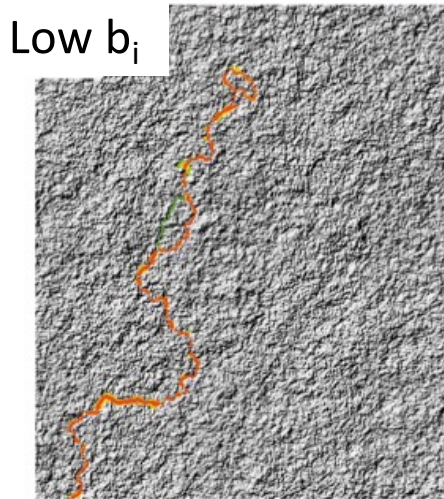
$$J_s(A, B) = \frac{|A \cap B|}{|A \cup B|}$$



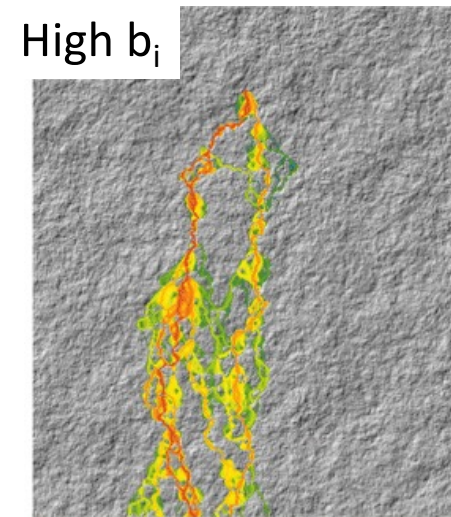
Comparing with natural flow examples

Flow branching index:

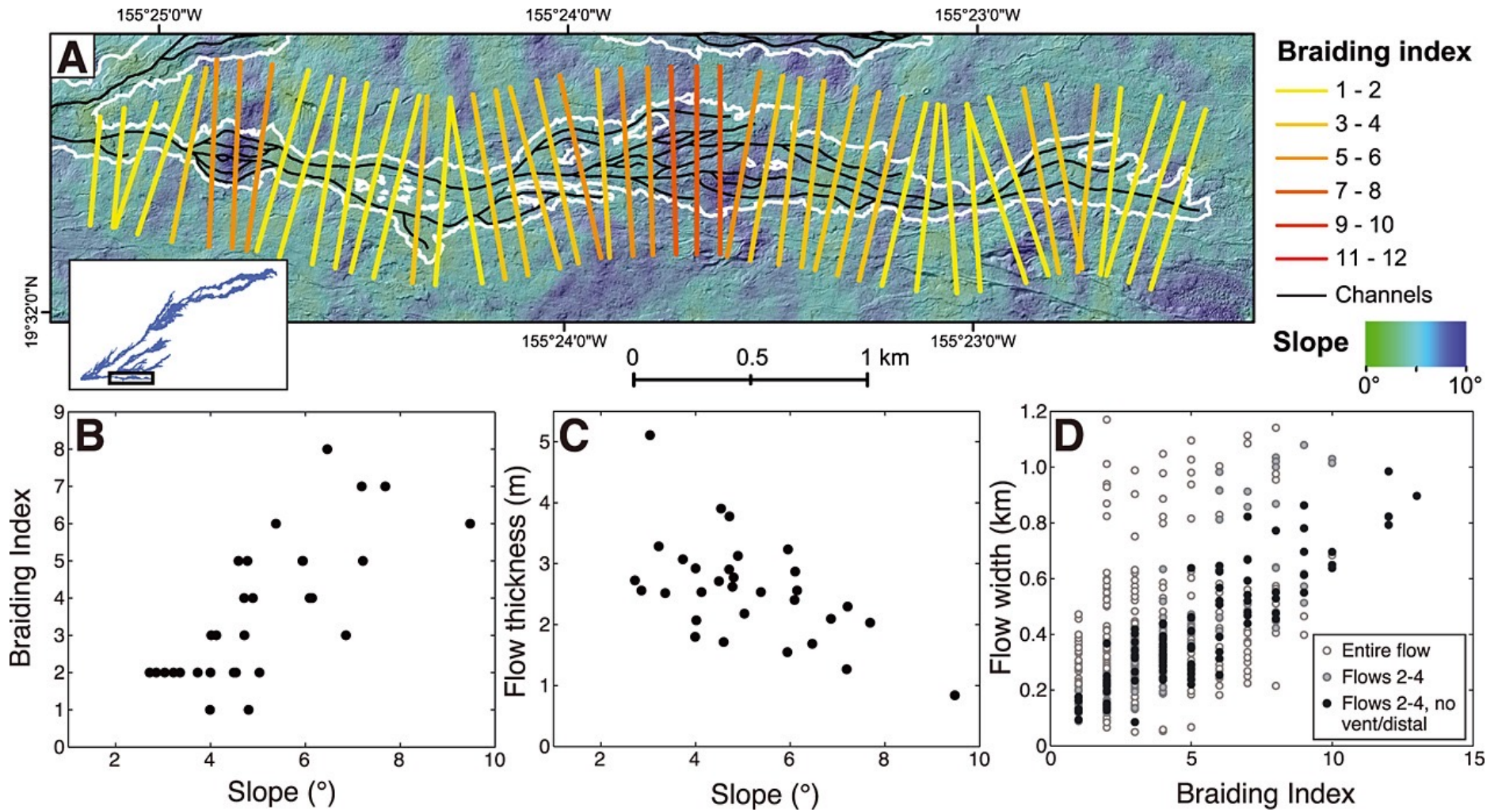
- The sum of all internal and external (perimeter) boundary contour lengths P_i of the flow, divided by the maximum horizontal distance L_{max} of the vent to the farthest flow lobe



$$b_i = \frac{1}{L_{max}} \sum_{i=1}^{N+1} P_i$$

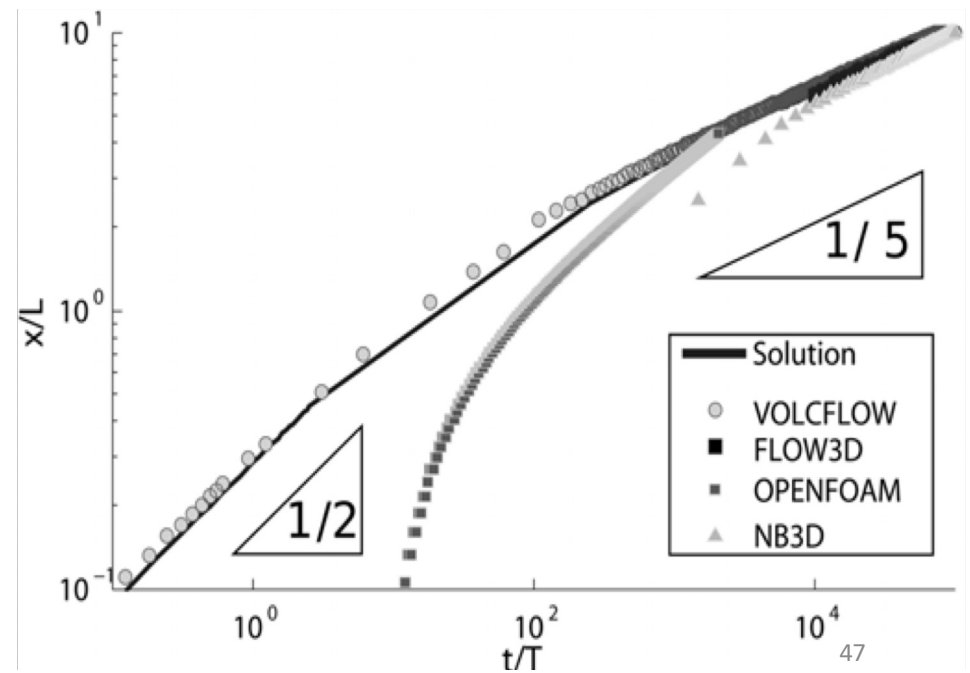
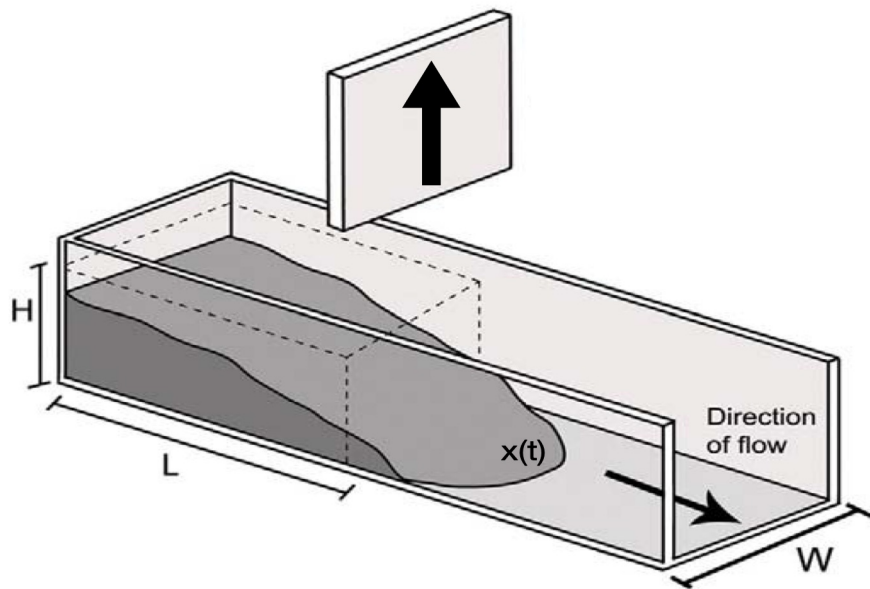


Richardson and Karlstrom, 2019

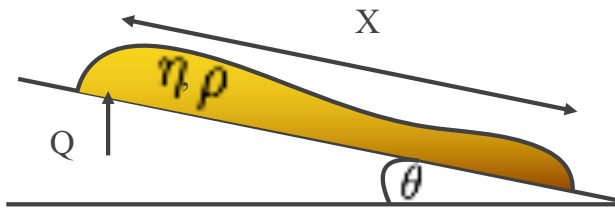


A hierarchy of Benchmarks

BM1 – Dam break

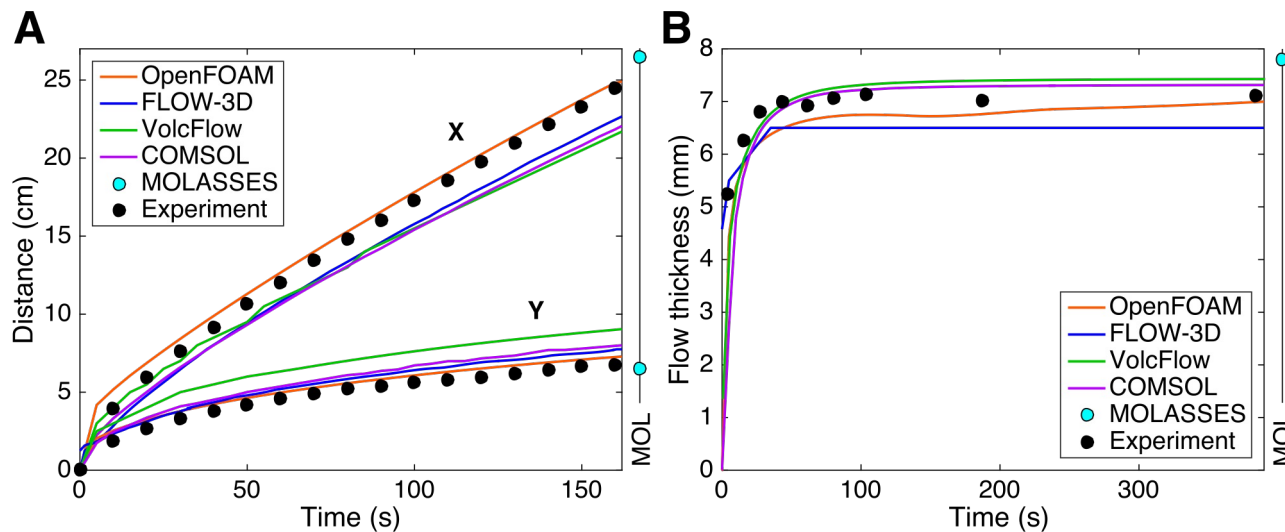


BM2 – Point source on an inclined plane



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

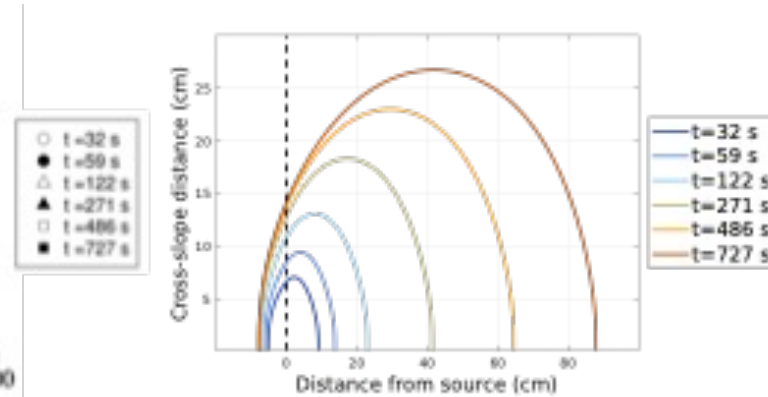
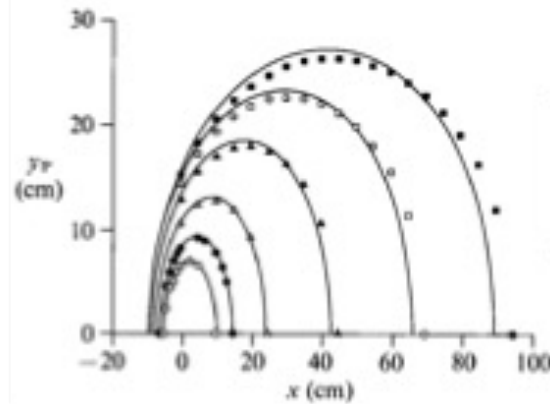
Lister, 1992



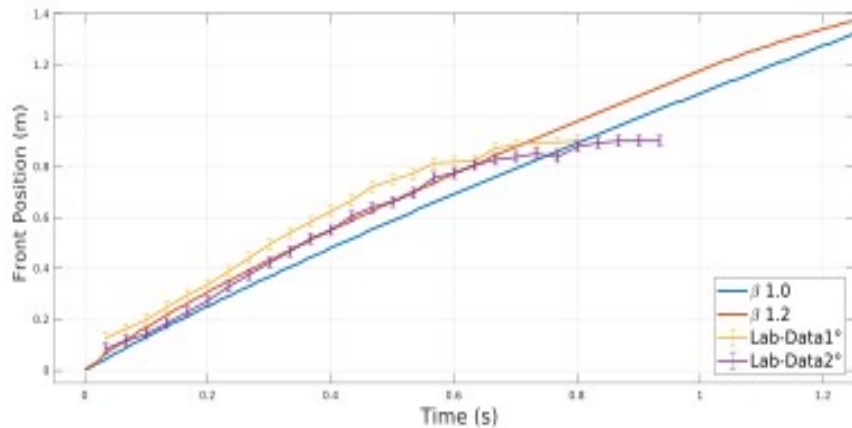
Cordonnier et al., 2015; Dietterich et al., 2017

IMEX_Lava

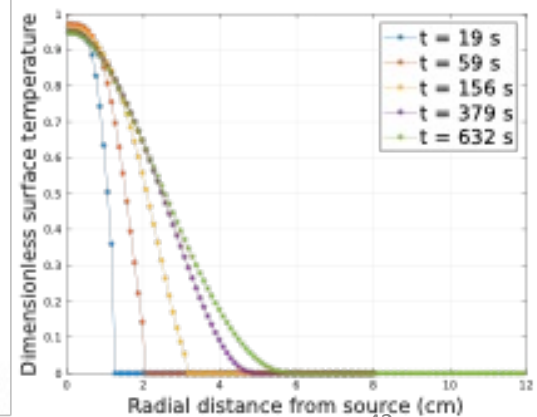
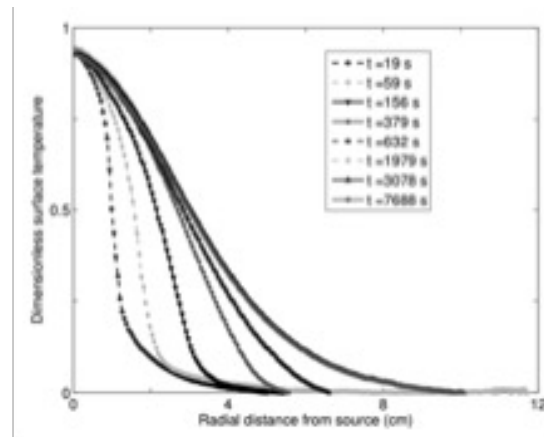
BM2: Point source, inclined plane



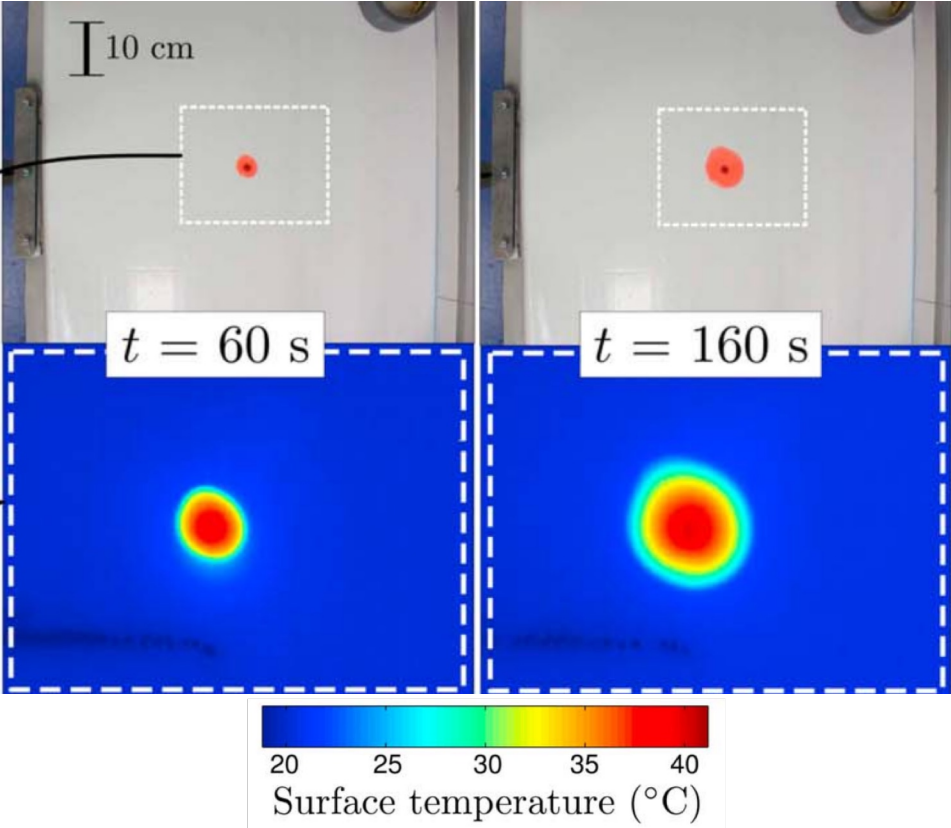
BM1. Dam break with oil



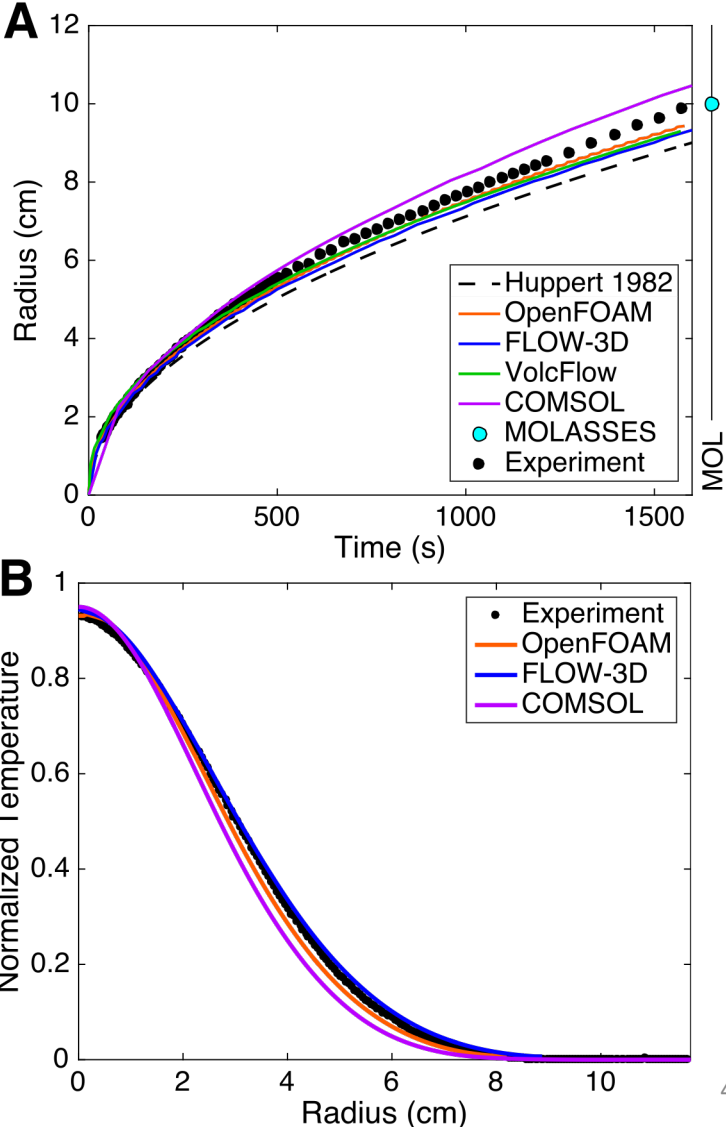
BM3. Axisymmetric cooling and spreading



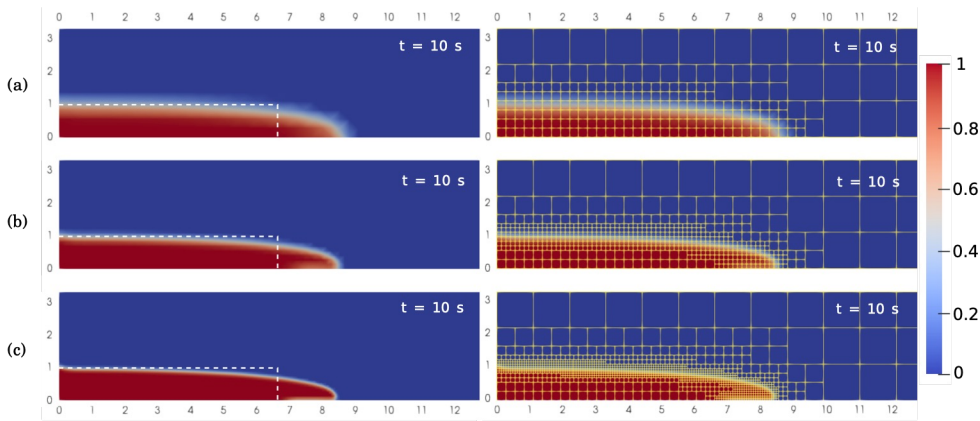
BM3 – Spreading, temperature



Garel et al., 2012

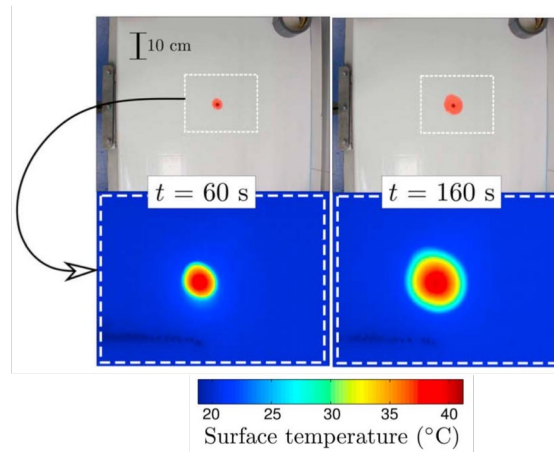


interThermalRadConvFOAM (aka LavaFOAM) benchmarking

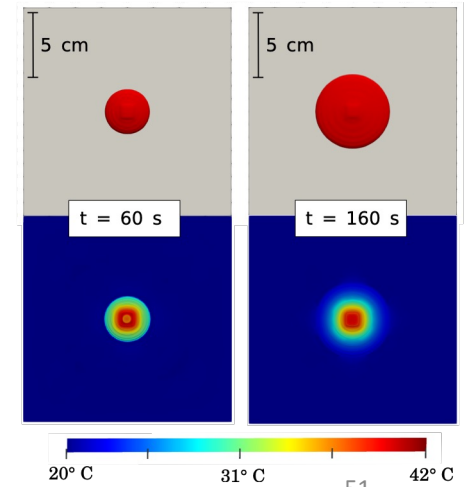


BM1. Dam break

BM2. Spreading+Cooling

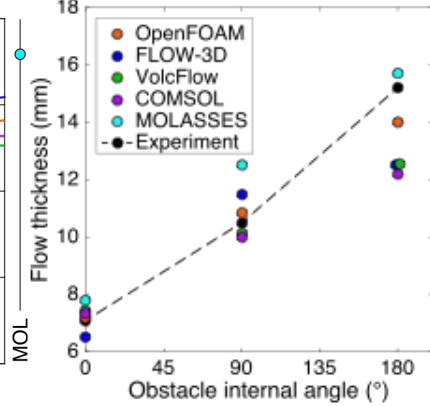
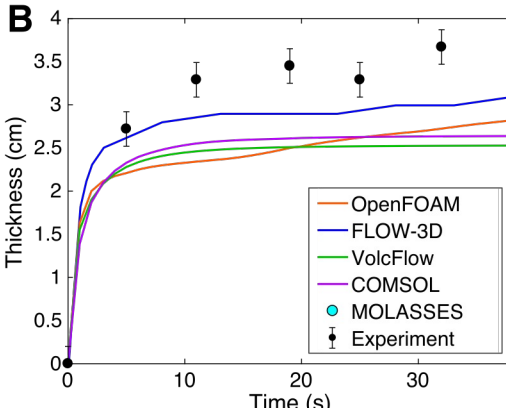
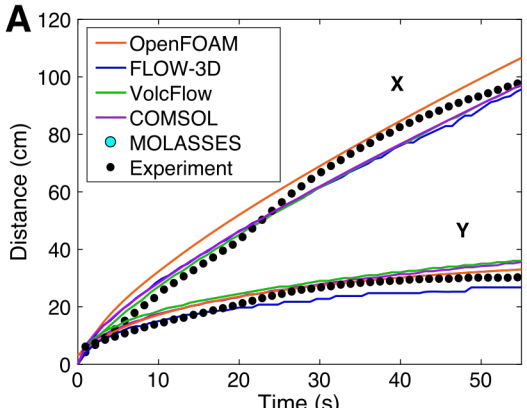
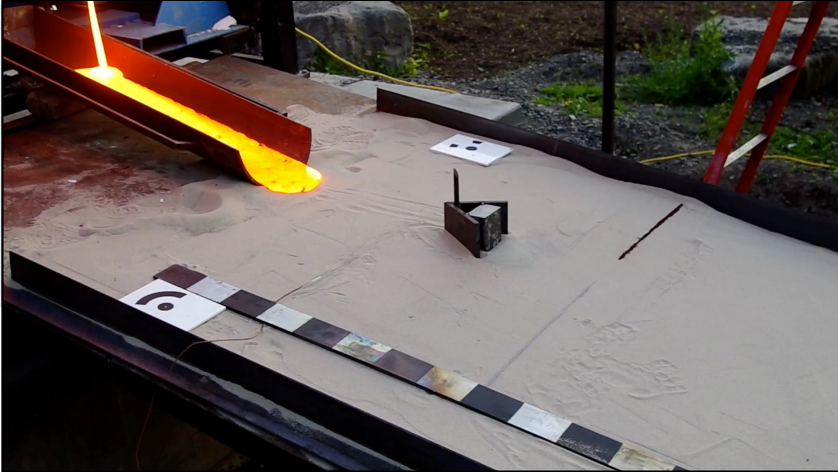
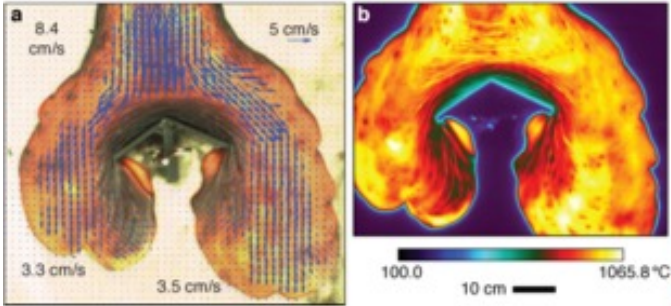


(a) Picture taken from Garel et al. [91].



(b) Results of our simulation.

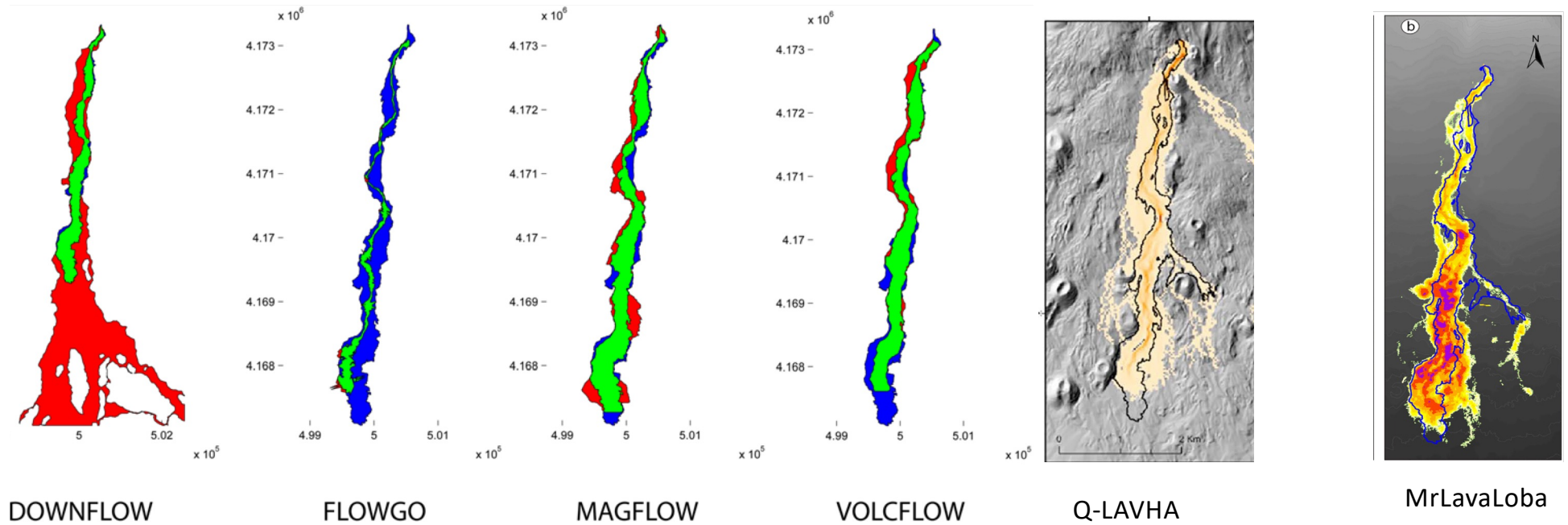
BM4 — Basalt lab experiment



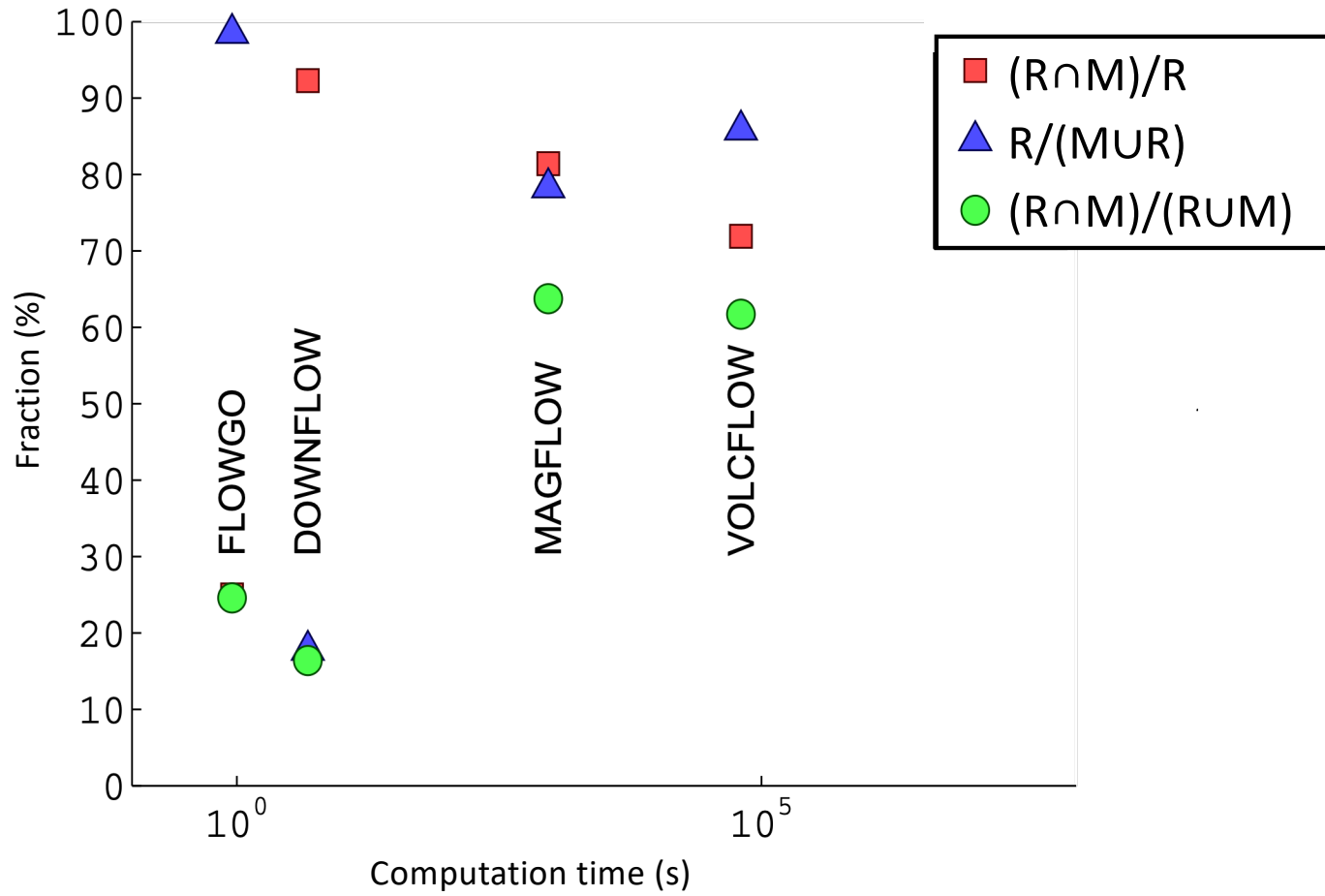
Cordonnier et al., 2015; Dietterich et al., 2017

Model inter-comparison — Inundation area

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



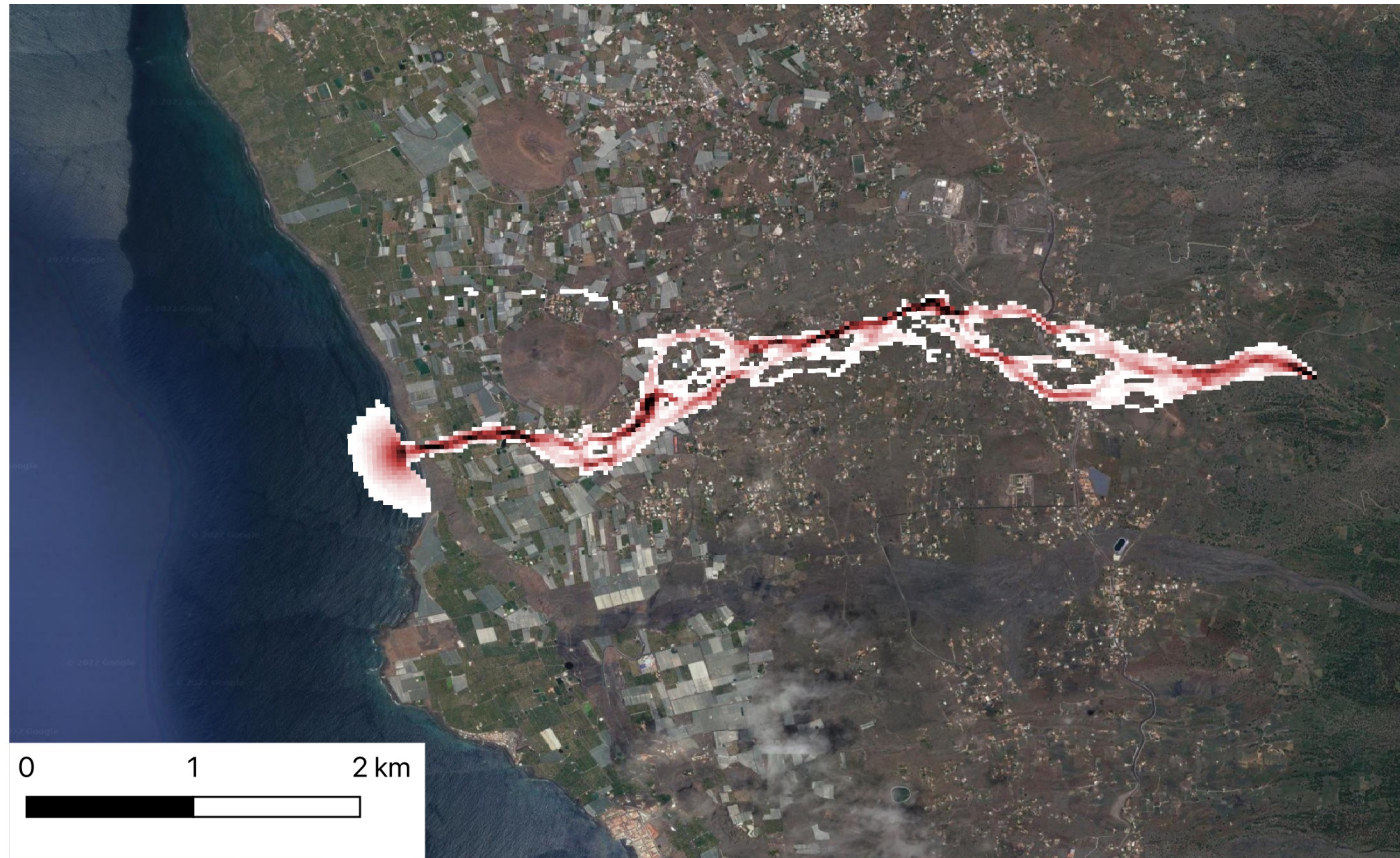
Cordonnier et al., 2015; Dietterich et al., 2017



Stochastic models match footprint

Using MOLASSES

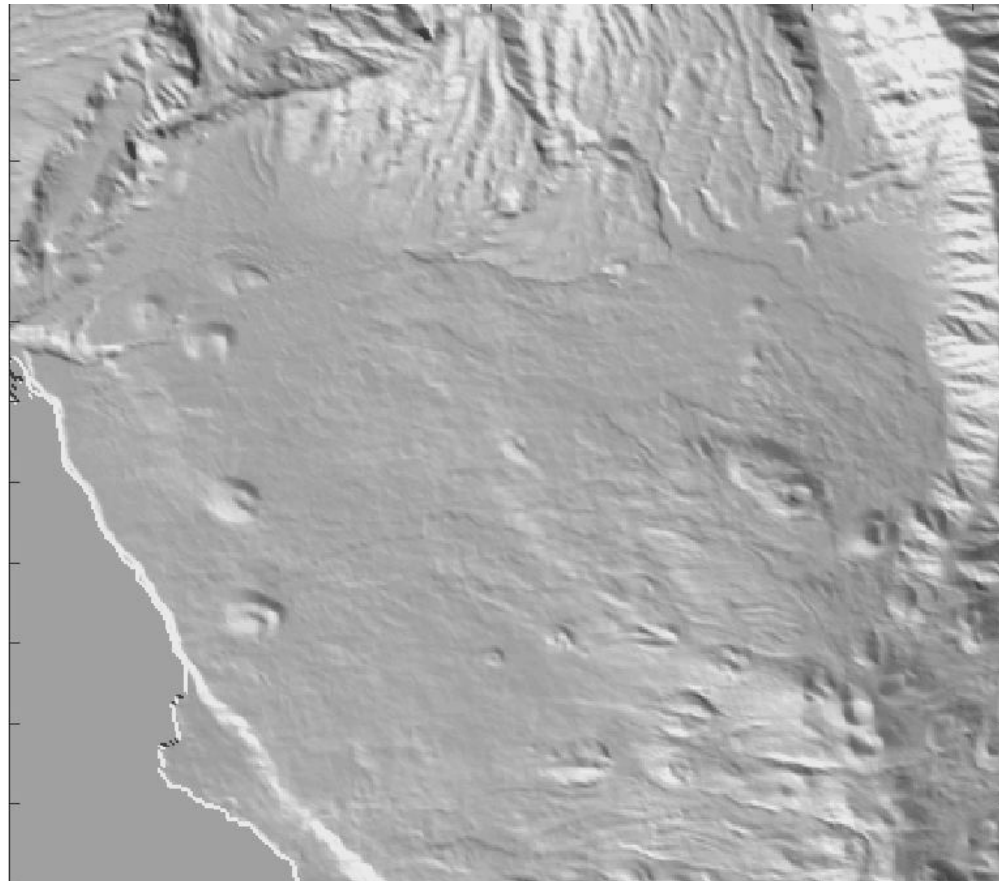
Cumbre Vieja,
2021



Physics-based models match velocities

Using VolcFlow (Kelfoun et al.)

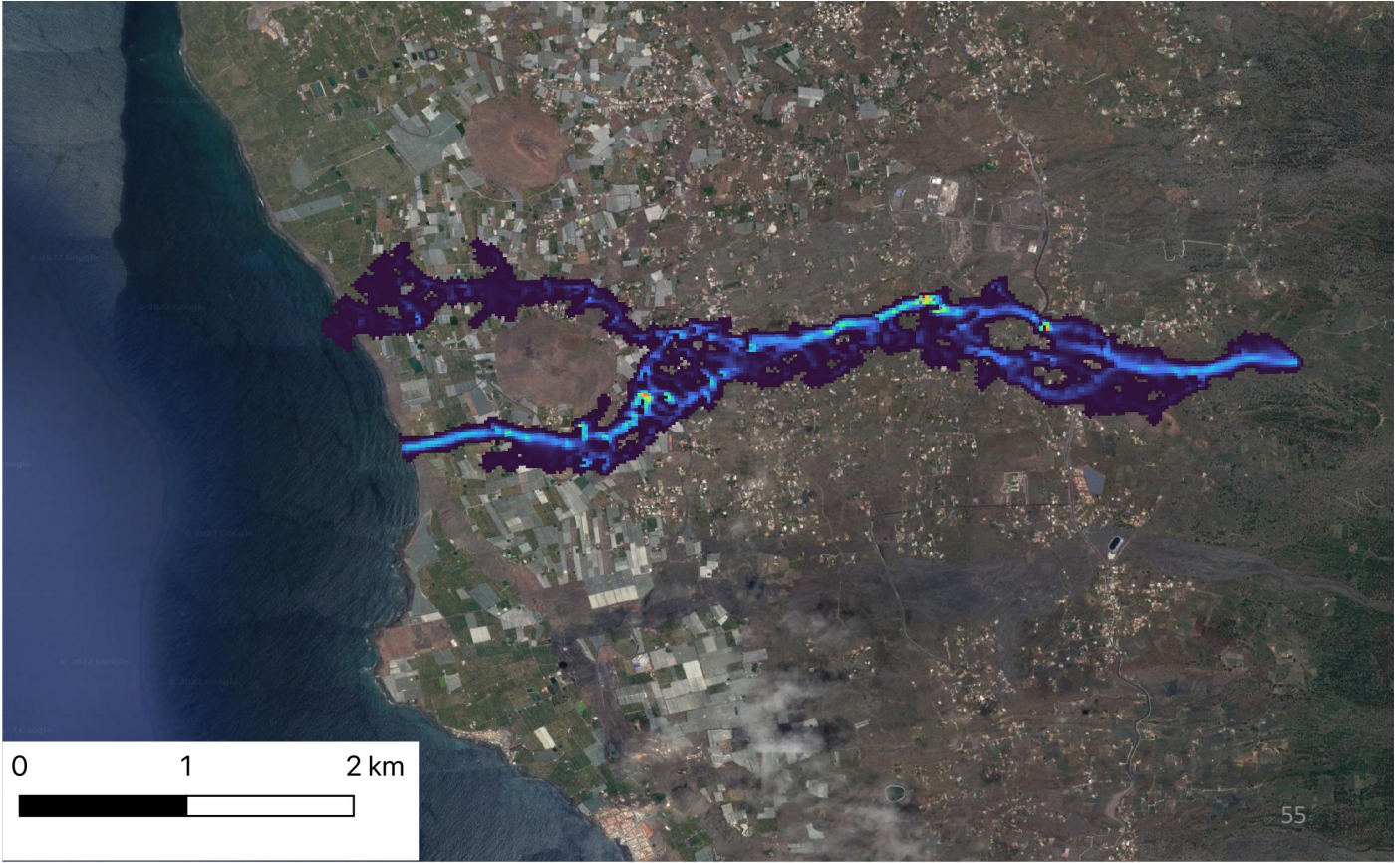
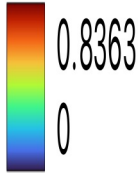
Cumbre Vieja,
2021



Physics-based models match velocities

Using IMEX-Lava

Cumbre Vieja,
2021



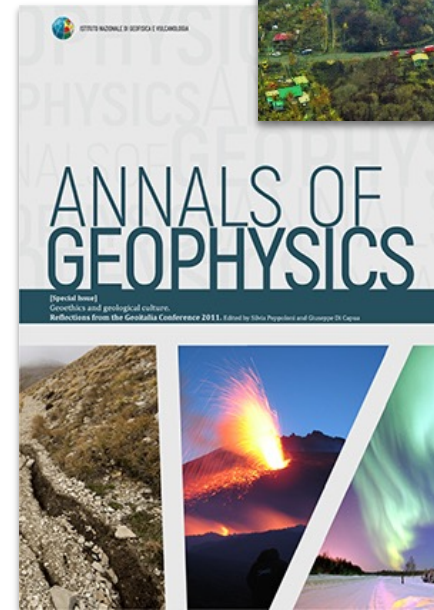
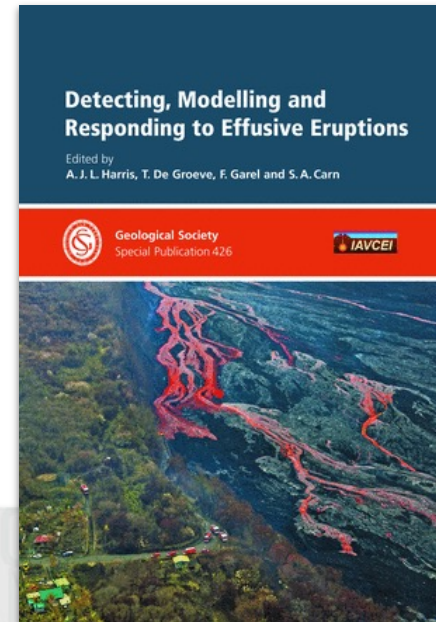
Lava model benchmarking and comparison on VICTOR

- Show notebook

Lots of useful information in a two recent special volumes:

- 2015 Geological Society
- 2018 Annals of Geophysics

Observation and modeling methods, and their application in response to eruptive crisis



Summary

1. Many factors impact where lava would go, mainly:

Effusion rate (with time), topography, lava properties

2. Many models available, at varying levels of complexity

→ Users should consider their goal and select the appropriate tool

→ Benchmarks and intercomparisons help users make informed choices

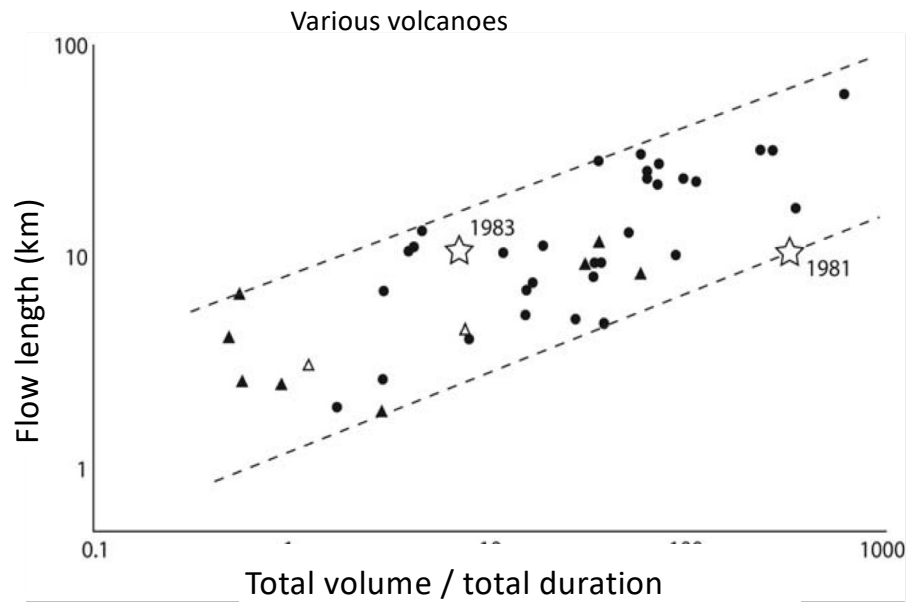
Thank you!



Structure of this talk

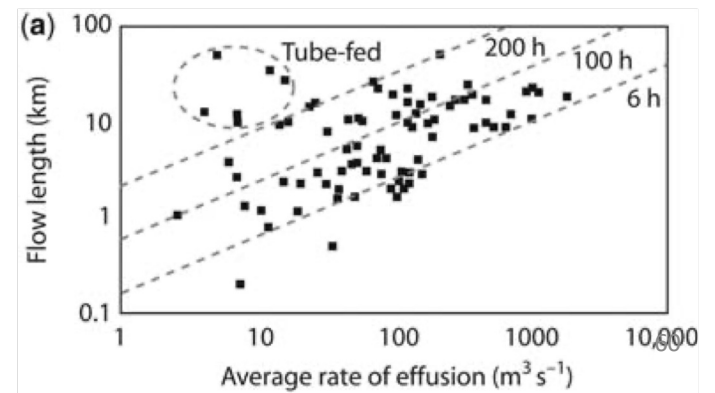
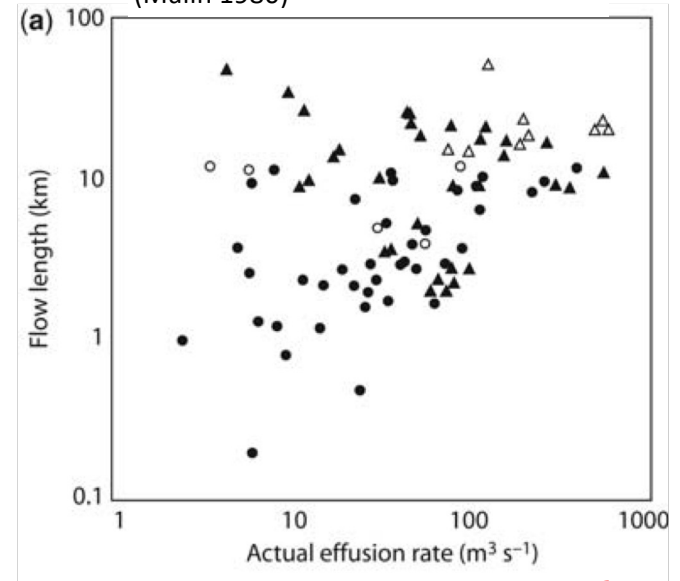
1. Factors that impact lava flow emplacements
 - Effusion rate(s)
 - Topography at all scales (overall slope, obstacles, bed roughness)
 - Lava rheology/viscosity
2. Current models of lava flow emplacement
3. How models are validated and compared

Effusion rate and flow length



Pinkerton and Wilson, 1994

Hawaiian volcanoes
(Malin 1980)

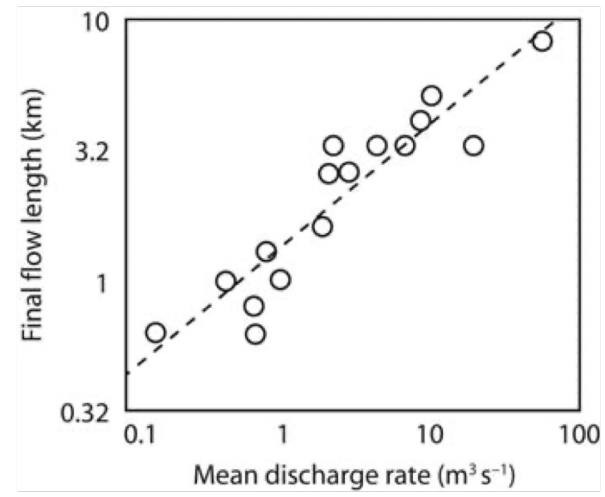


Etna studies

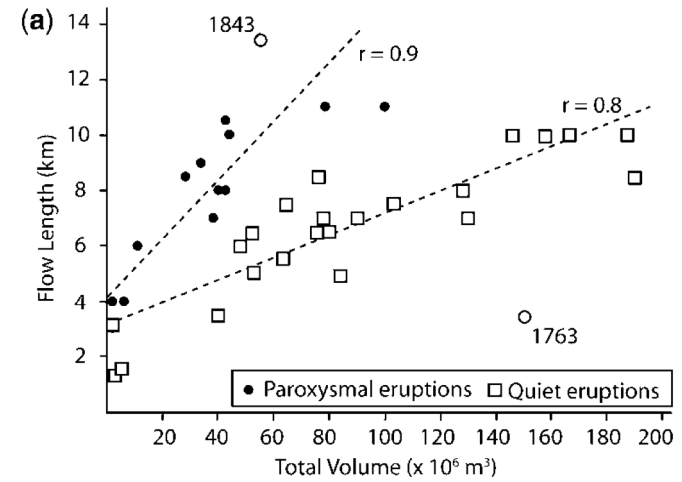
Distance (km)

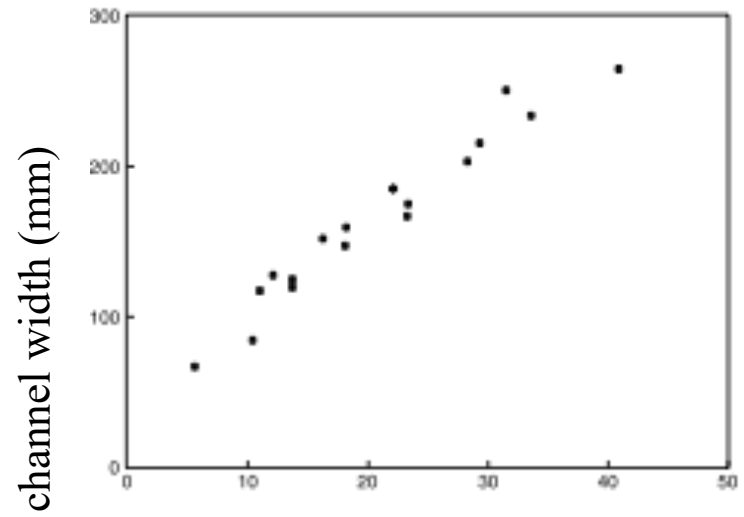
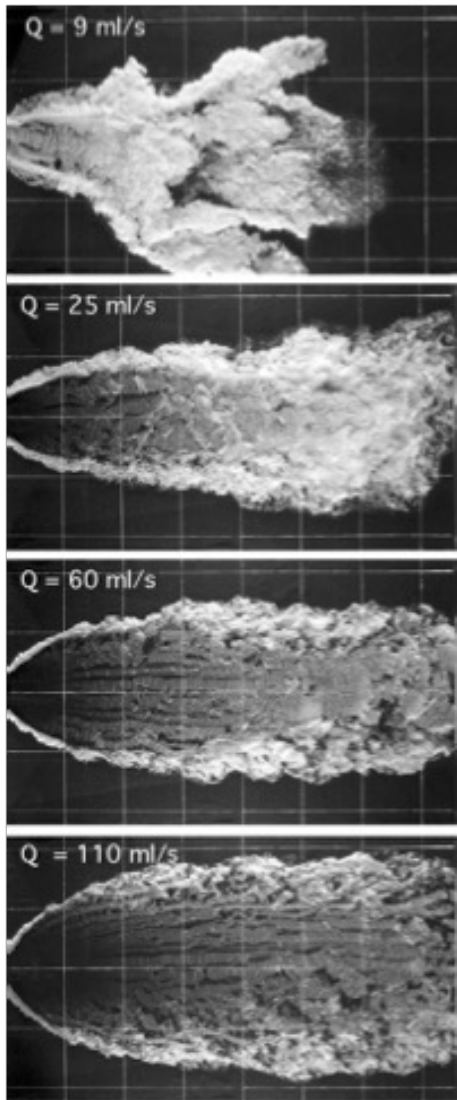
(Wadge 1978)

(Calvari and Pinkerton 1998)



Effusion rate (m³/s)



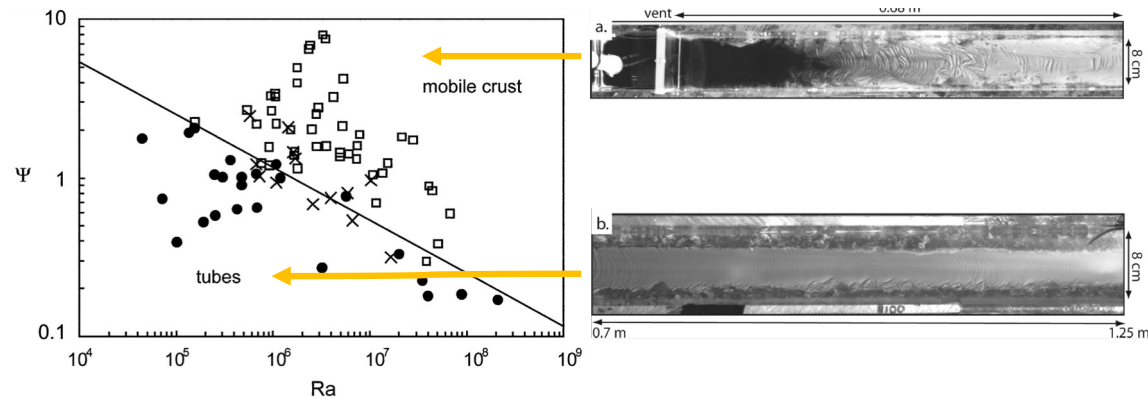


$$(g^2 \Delta \rho^2 Q^7 \mu^4 \cos^9 \theta \sin^{-7} \theta)^{1/13}$$

Tube formation

- Two dimensionless numbers to describe the flows:

$$\psi = \frac{U_0 t_s}{H_0} = \frac{\text{Solidification}}{\text{Advection}} \qquad Ra = \frac{g\alpha(T_e - T_s)H_0^3}{\kappa\nu_0} = \frac{\text{Conduction}}{\text{Convection}}$$

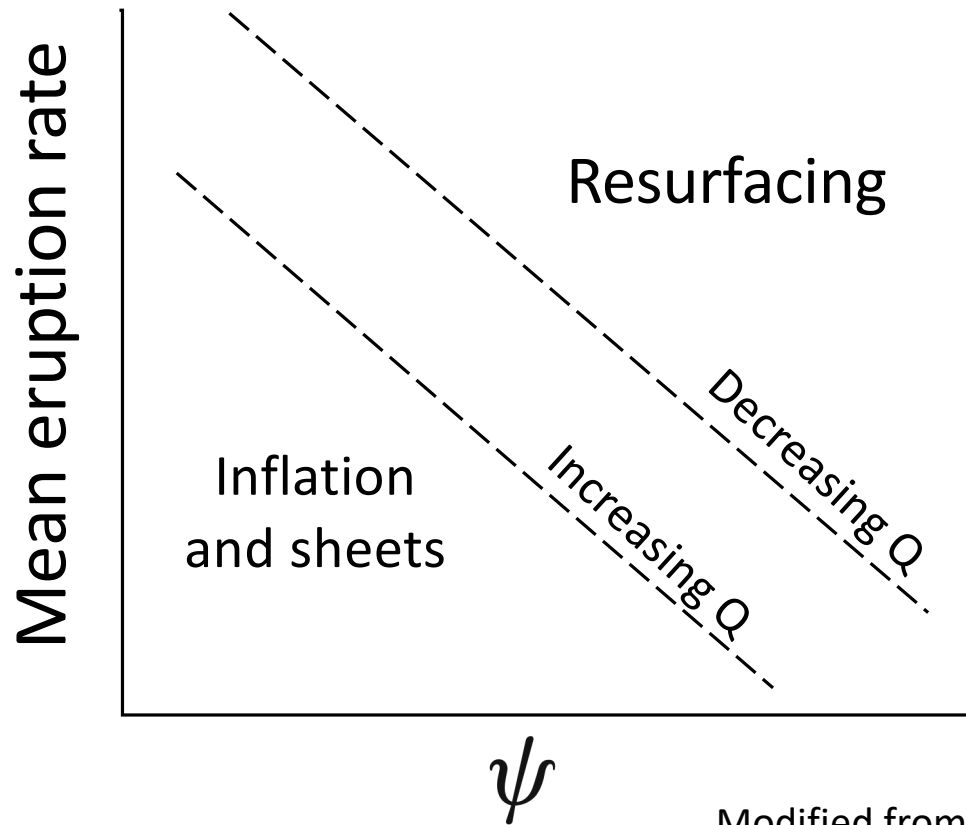


- Regime transition line: $\psi = (25 \pm 3)(Ra/R_0)^{-1/3}$ ($R_0 \approx 100$)
- Define: $\vartheta = \psi(Ra/R_0)^{1/3}$

$$\vartheta < 25 \rightarrow \text{tube}$$

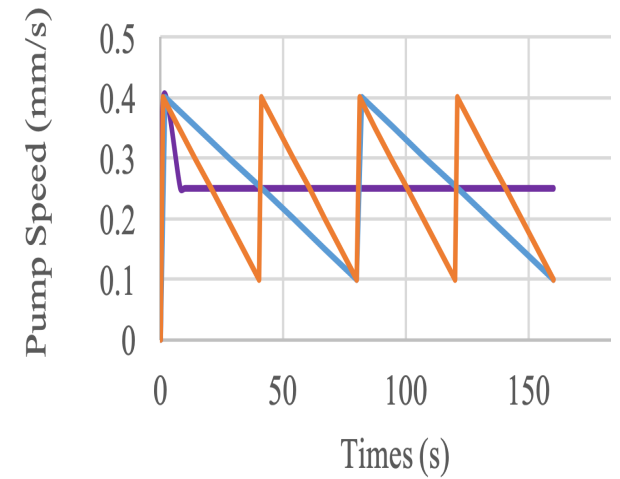
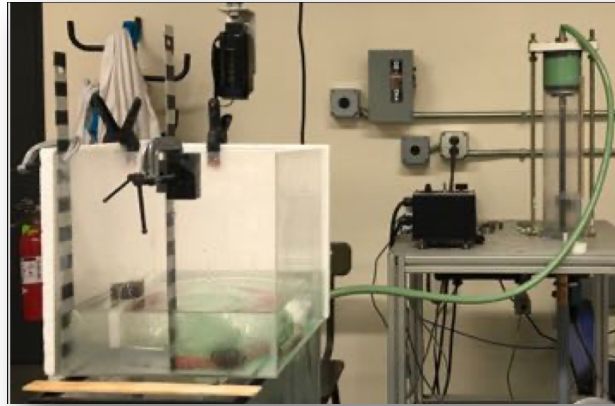
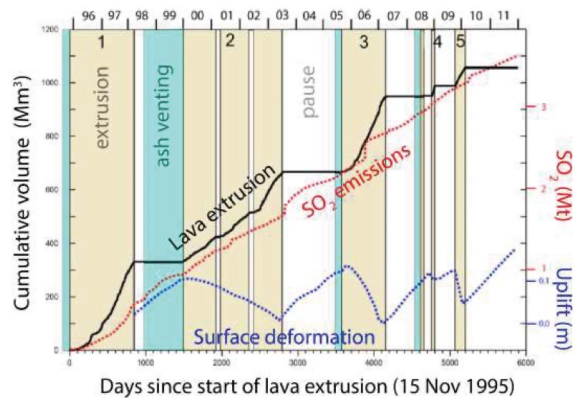
$$\vartheta > 25 \rightarrow \text{mobile crust.}$$

Impact on flow style

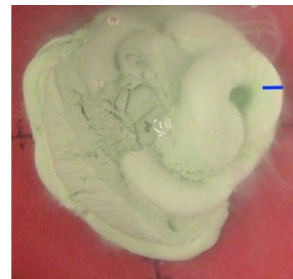


Variable effusion rate

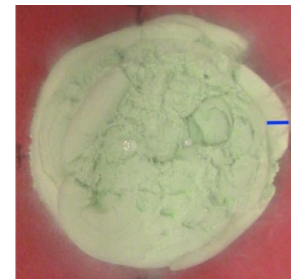
Montserrat dome extrusion



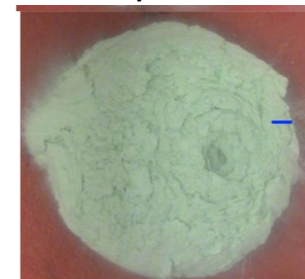
Constant



2-peak



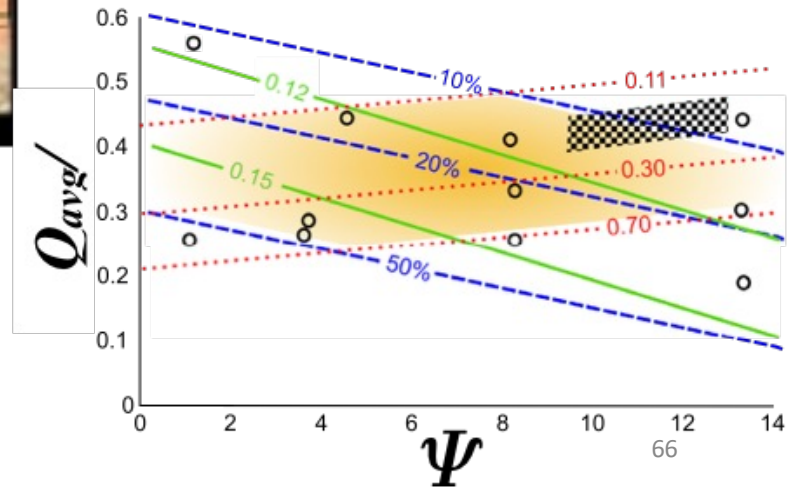
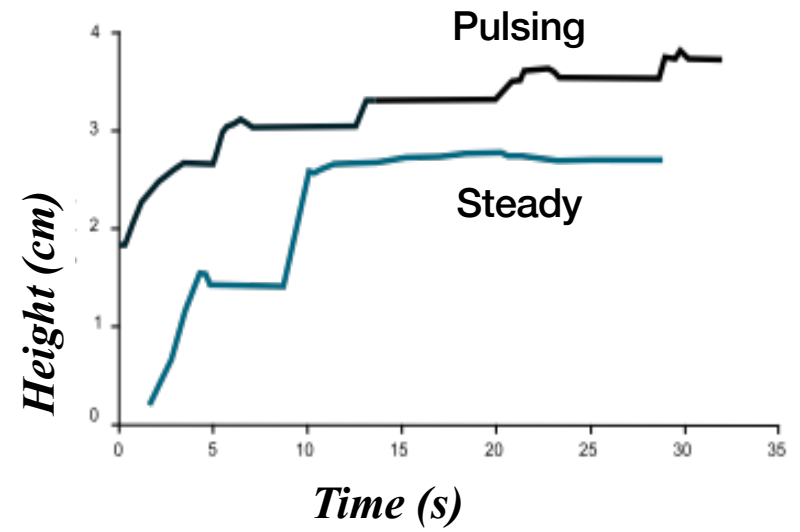
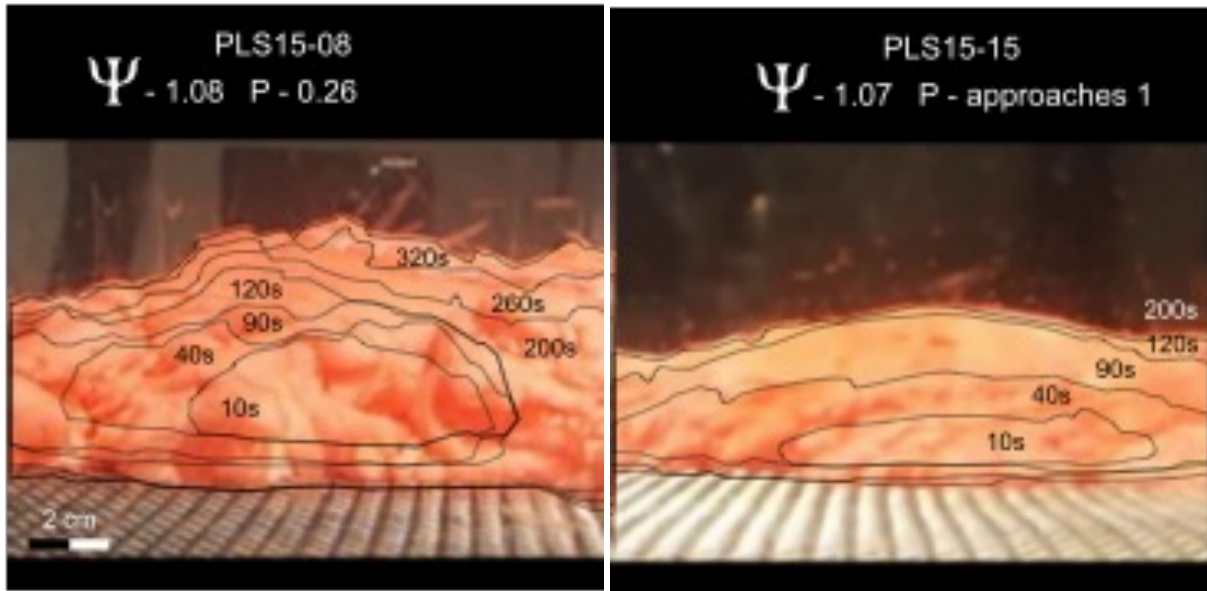
4-peak



Wadge et al., 2014

Lev et al., 2019

Impact on final flow dimensions



Topography

DEM
resolution and
flow routing
forecasts

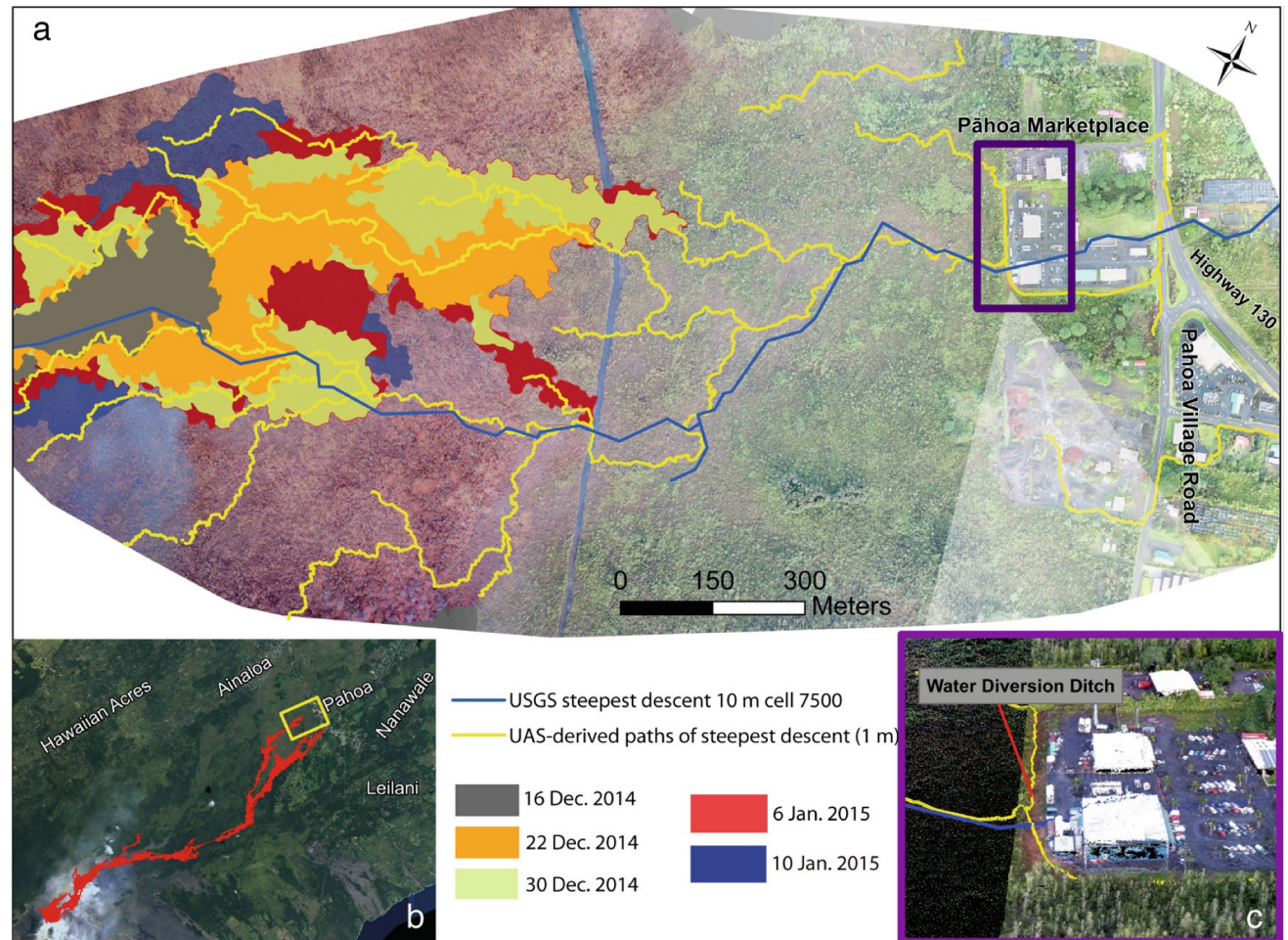
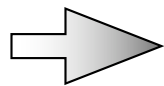
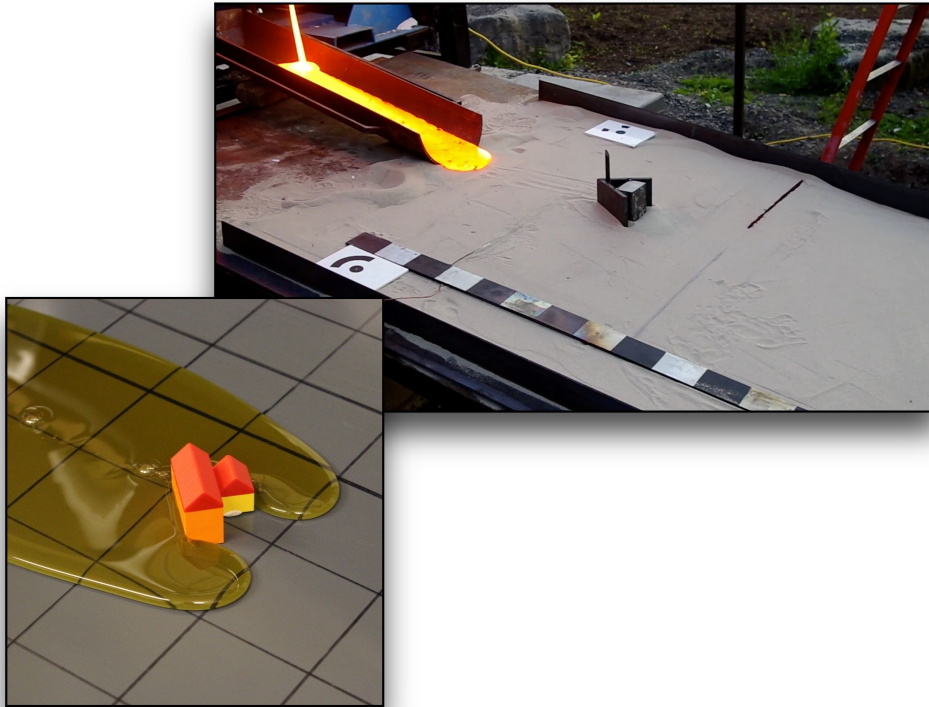
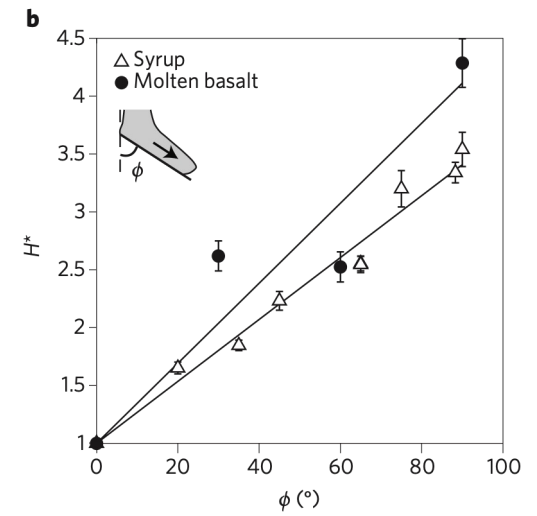
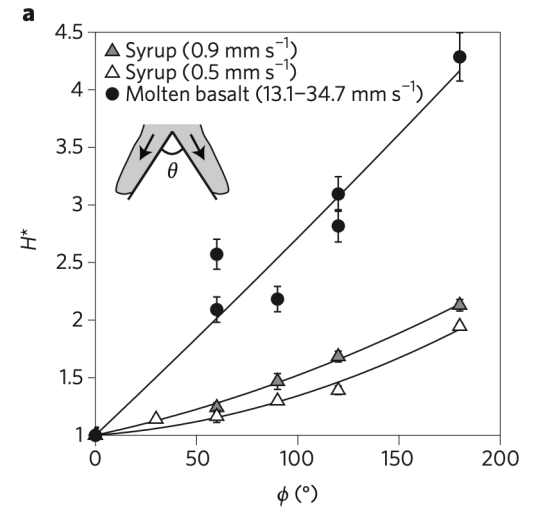


Fig. 3 a Comparison between 1 m UAS-derived flow paths (yellow lines) and 10 m USGS DEM (blue lines). The advancing lava flow is depicted as a series of flow outlines produced from HVO field mapping from Dec 16, 2014 through Jan 10, 2015. The 1 m UAS flow paths were generated from data collected on Dec 16, 2014 – Dec 17, 2014. The purple box highlights the area of panel c. Refer to USGS, 2017 to search for June 27th flow maps. **b** Final extent of the June 27th lava flow. **c** UAS-derived 3D point cloud showing the 5 m ditch surrounding the Pāhoia Marketplace, a topographic feature that was not identified from the 10 m USGS DEM due to coarse spatial resolution

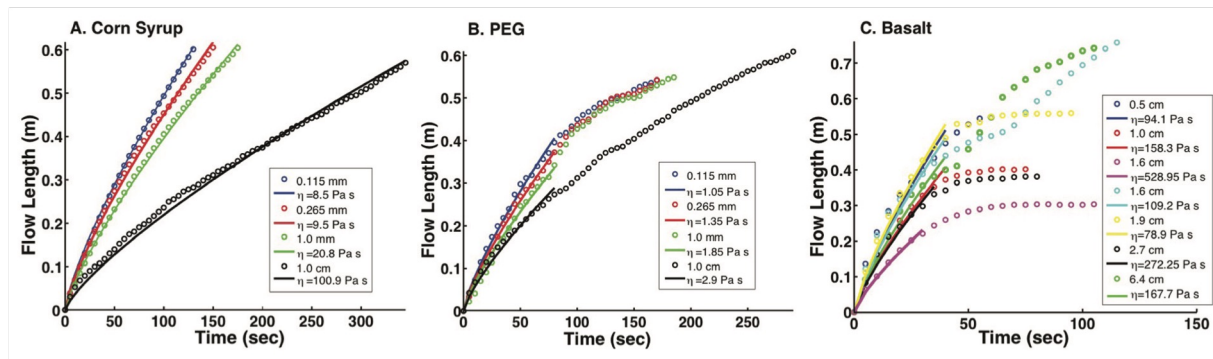
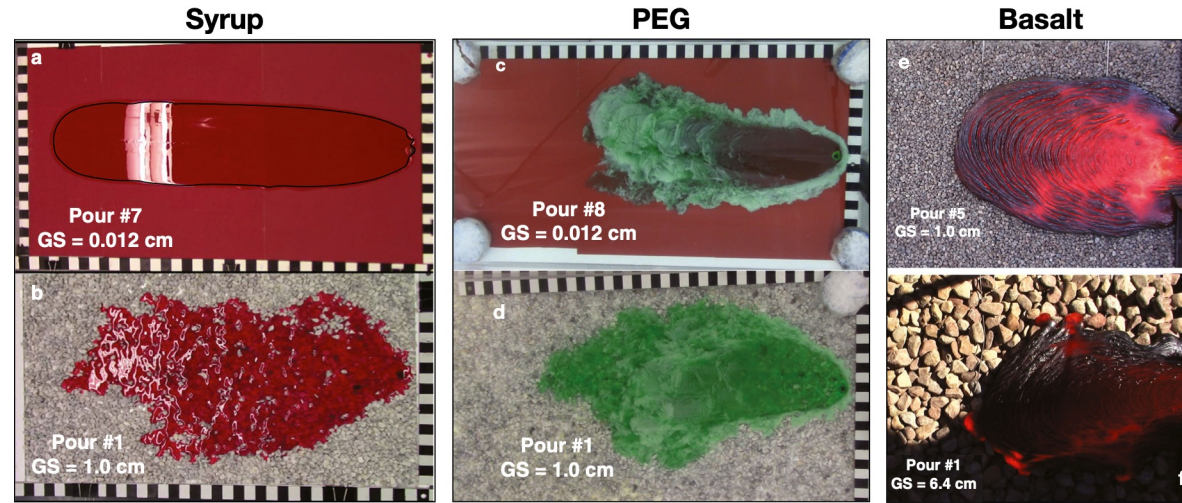
Interaction with Large Obstacles



New designs for flow diversion and deceleration

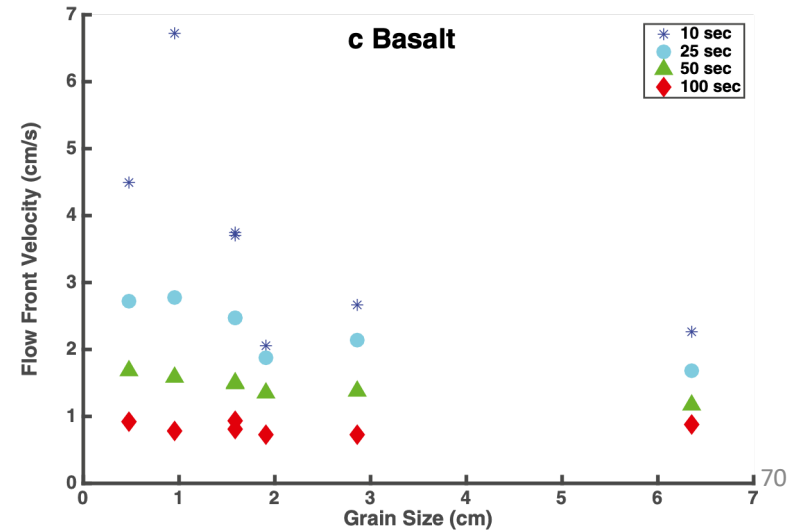
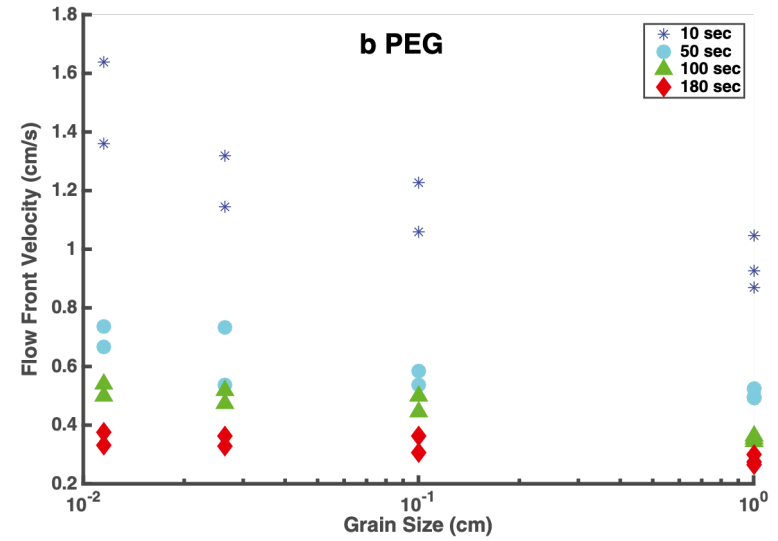
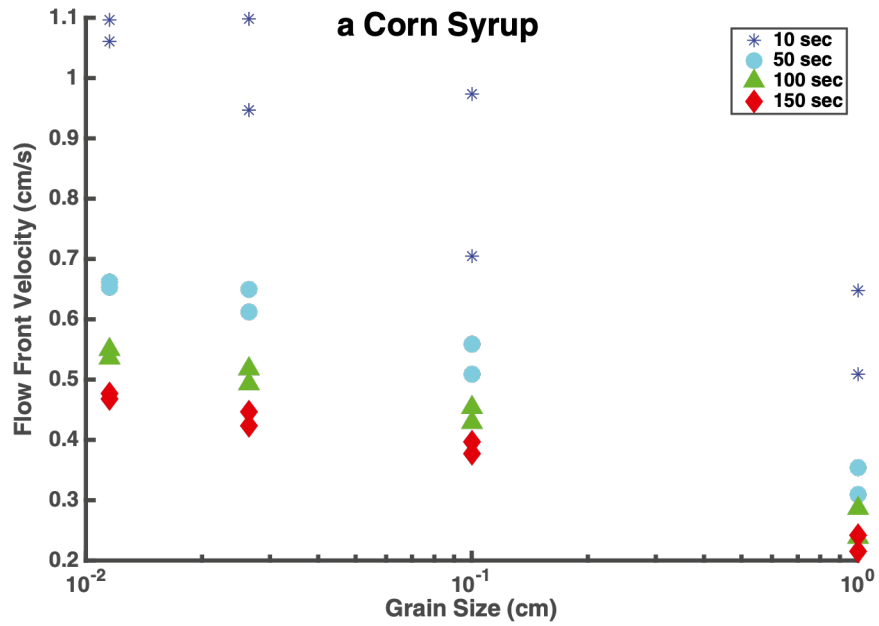


Bed roughness



Rumpf et al., 2018

Bed roughness



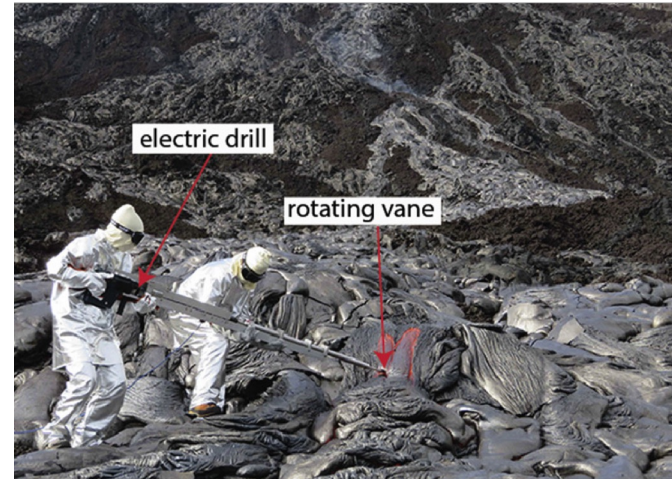
Flow front velocity is strongly reduced by rougher beds at all times

Lava rheology



Tolbachik, 2013
Penetrometer

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



Kilauea
Rotational viscometer

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

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

$$\tau = \frac{M}{2\pi h R_i^2}$$

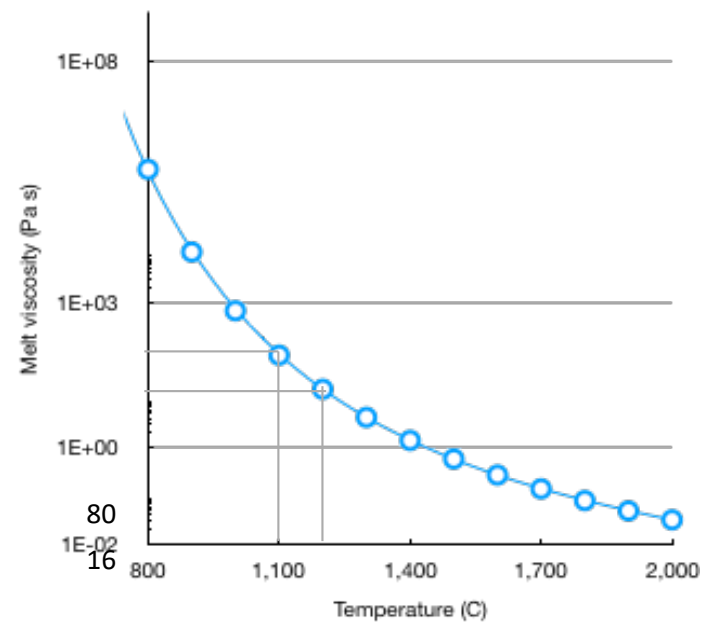
Expected rheology for East River Plain Lavas

1. Melt viscosities

Average Hells Half Acre basalts

SiO ₂	46.4
TiO ₂	3.1
Al ₂ O ₃	15.1
Fe ₂ O ₃	2.4
FeO	12.1
MnO	.20
MgO	6.8
CaO	9.6
Na ₂ O	2.7
K ₂ O	.65
P ₂ O ₅	.86
H ₂ O ⁺	.33
Total	100.2

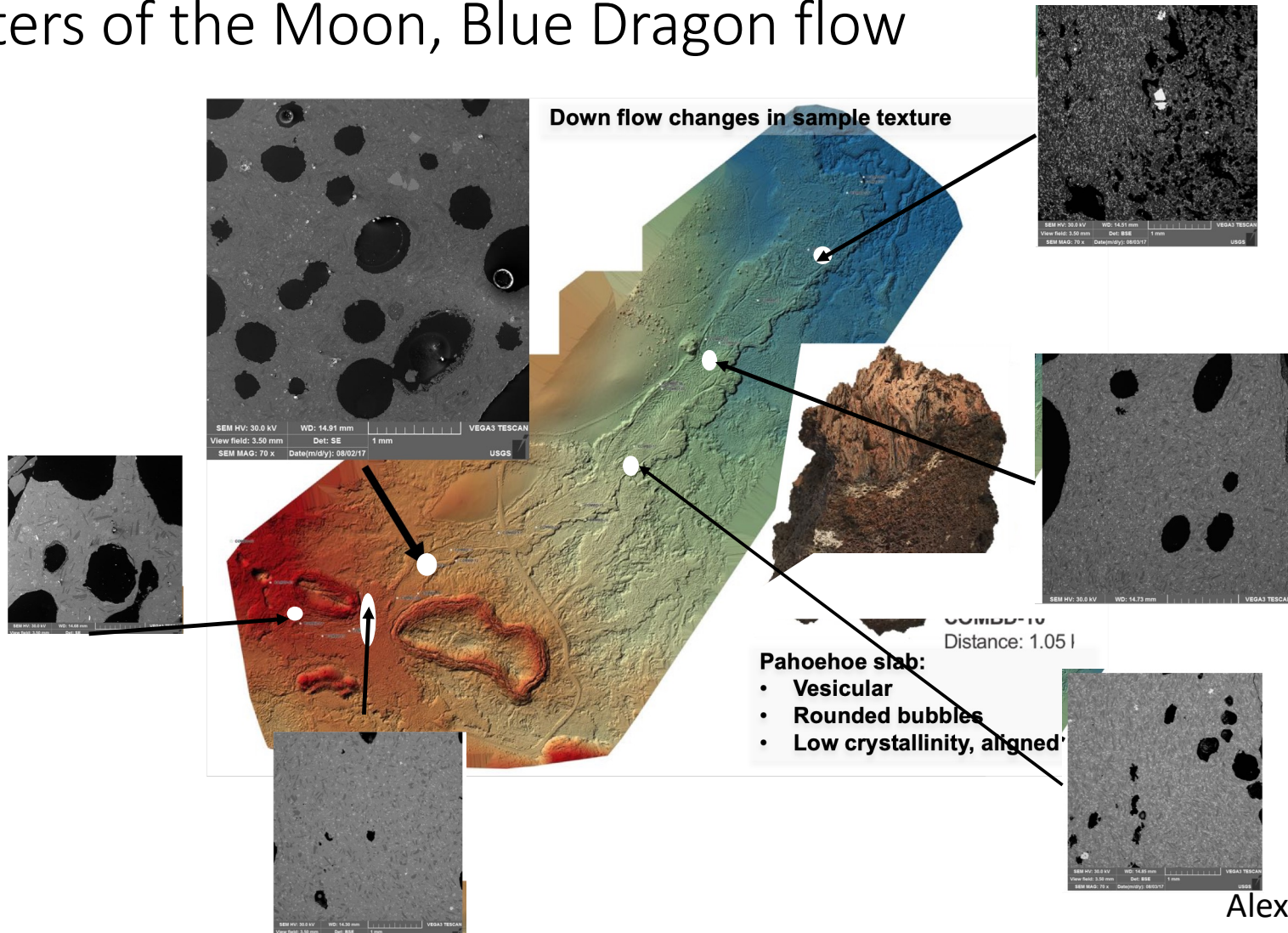
Using GRD
calculator



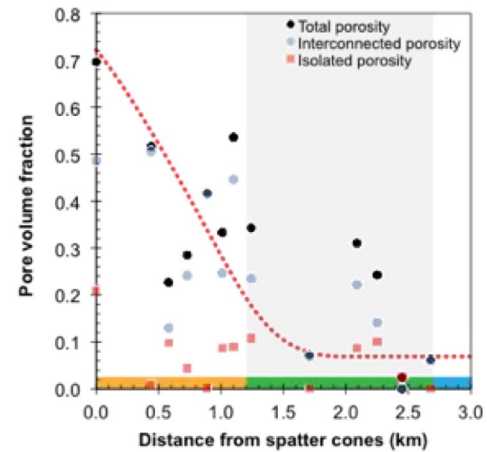
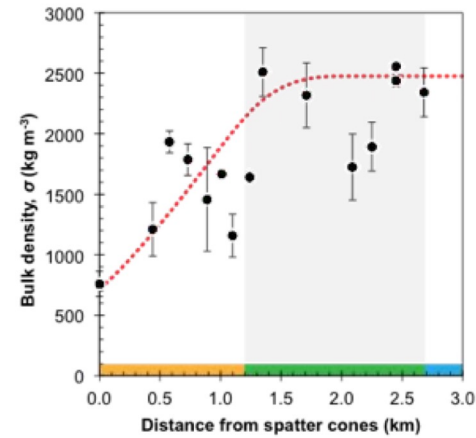
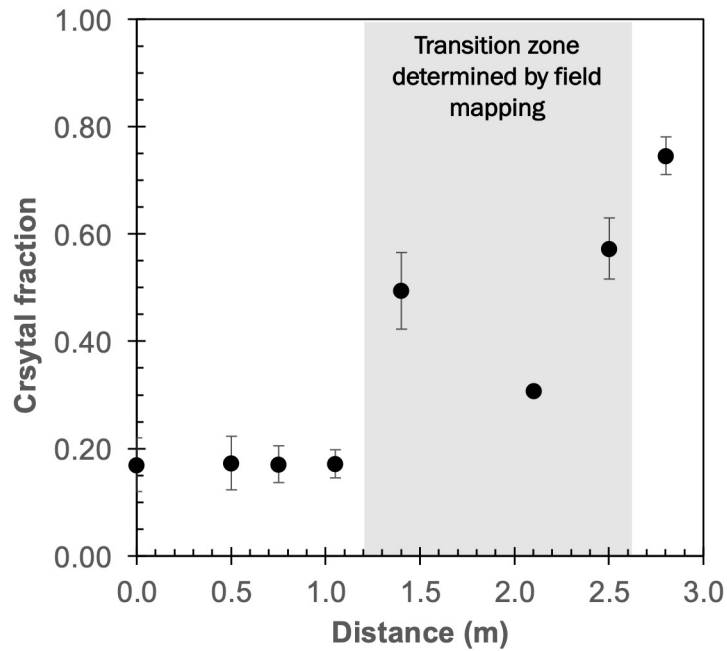
2. Two- and three-phase rheology

Kuntz and Dalrymple, 1979

Craters of the Moon, Blue Dragon flow



Craters of the Moon, Blue Dragon flow



Seeing trends with flow distance in

- Crystallinity
- Bulk density
- Pore space

Alex Sehlke, NASA