Can we model lava flows faster than real-time to assist on a first volcanic emergency response?

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11TH EGU GALILEO CONFERENCE

Solid Earth and Geohazards in the Exascale Era

Motivation: the process

Volcanic eruptions are one of the most disruptive processes on Earth:

- transform the landscape
- effects on public health
- socio-economic looses
- long term ecological and social environmental impacts
- multiscale effects

Therefore, volcanic eruptions in populated areas require preparing, planning, and anticipating responses based on different hazard scenarios.

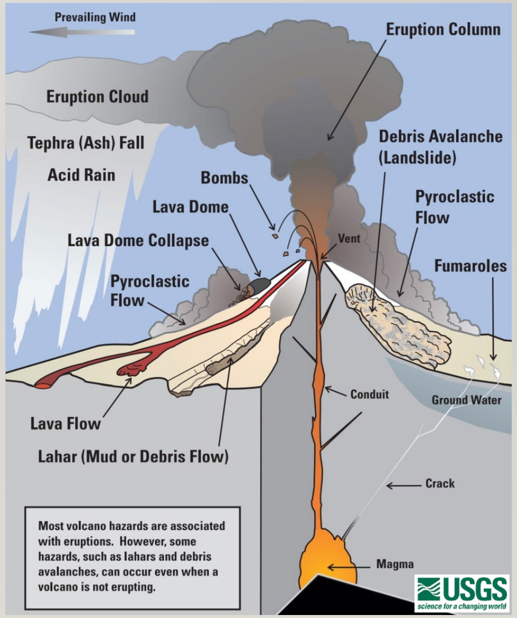
Other than lava flows and explosions, eruptions may create different types of hazards:

- fires started by lava
- toxic gas can come from lava degassin or lava interacting with a body of water
- earthquakes
- terrain landslides and cone collapses
- lahars and jökulhaups result from snow or ice melting

Therefore, volcanic eruptions a complex process to manage.

In the event of a volcanic eruption, emergency management must ensure that systems and services are in place to provide rapid and effective assistance.

Modelling is amongst the tools that may enable forecasts of some processes. Hence, they contribute to better emergency management an territory planning.



Motivation: the chance

In the course of a high-impact eruptive event, lava flow numerical modelling plays a relevant role:

(i) **Pre-eruptive scenario**, before the crisis models are calibrated and validated based on past events ’80s:
Their outputs are useful to inform and educate about hazards and risks , and they provide knowledge to support measures to face the most likely scenarios, from expected volcanic activity to its spatiotemporal probability of emission points.

(ii) **Syn-eruptive scenario**, in the course of the eruption:
Models can be used to predict the path and emplacement of lava flow and to assess potential risk scenarios, mitigation measures (such as to deviate the lava flow) or evacuation strategies.

(iii) **Post-eruptive scenario**, after the eruption, hazard maps should be updated:
Simulations require new topographic data due to the different kinds of landscape changes, new raised or detected hazards.

Critical step is (ii) Faster modelling is amongst the tools that may enable precise & quick forecasts of some processes.

Contributes to better emergency management.

Motivation: the opportunity

La Palma eruption

The 2021 La Palma eruption started on September 19, 2021(14.10h UTC) after eight days of accelerated volcanic unrest, a drastic increase in ground deformation and seismicity.

The volcanic activity started on the western flank of Cumbre Vieja, as a fissure eruption trending NNW-SSW, with different active parallel fissures, continuing for most of the eruption, punctually concentrating at certain vents along the different parallel fissures.

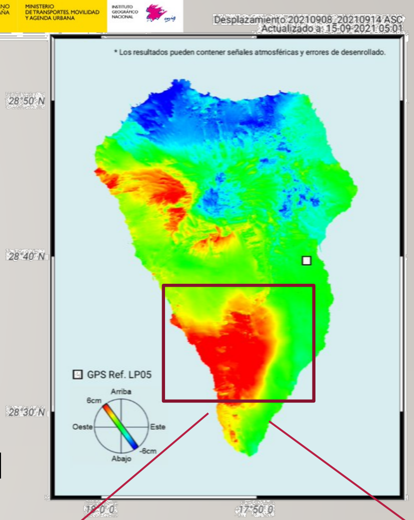
The eruption developed, in terms of volcanic evolution, similar to most of the historical eruptions in La Palma and in the rest of the Canary Islands. The alternation of Strombolian and nearly pure Hawaiian phases was characteristic, varying in intensity throughout the whole eruption.

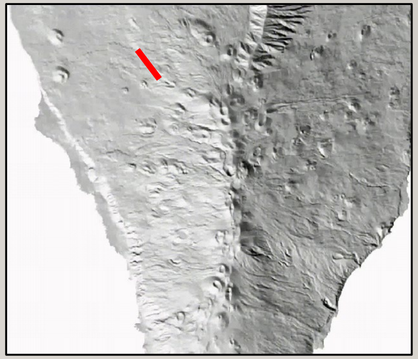
September 25 first cone SW flank collapse. September 28, the lava flow reaches the sea, falling from the coastal cliff.

It was the longest historical eruption at La Palma and the most voluminous, with extruded magma volume exceeding 0.2 km3

The zone impacted by the lava flows, which has represented the main damage caused by this eruption, affected the localities of Todoque, EL Paraiso, and La Laguna, disturbing almost 3000 infrastructures across an area of 12.2 km^{2}, forcing the evacuation of ~7000 residents, and with 73.8 km of roads being buried by lava. None direct deaths.

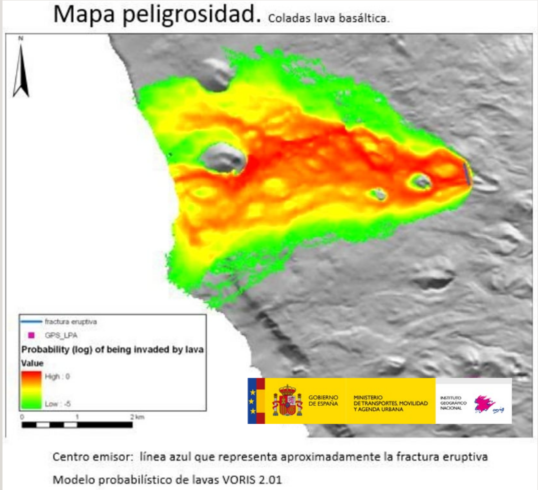
Lasted more than 85 days (December 13, 2021) forming a new edifice on the western flank of Cumbre Vieja volcano.

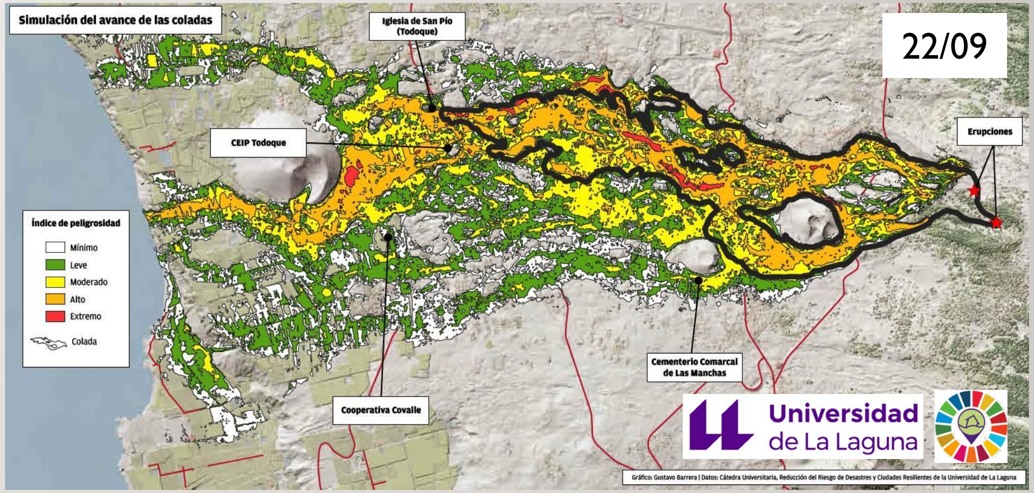




Motivation

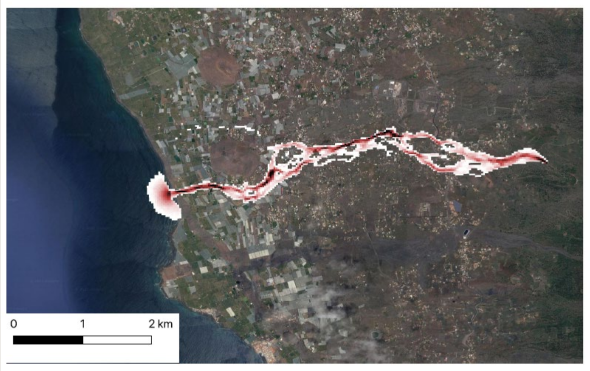
- First modeling-simulations attempts

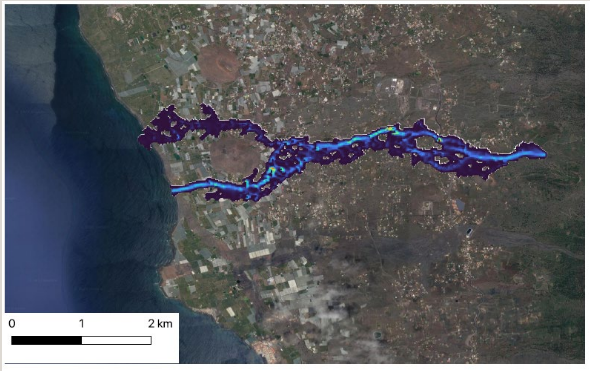




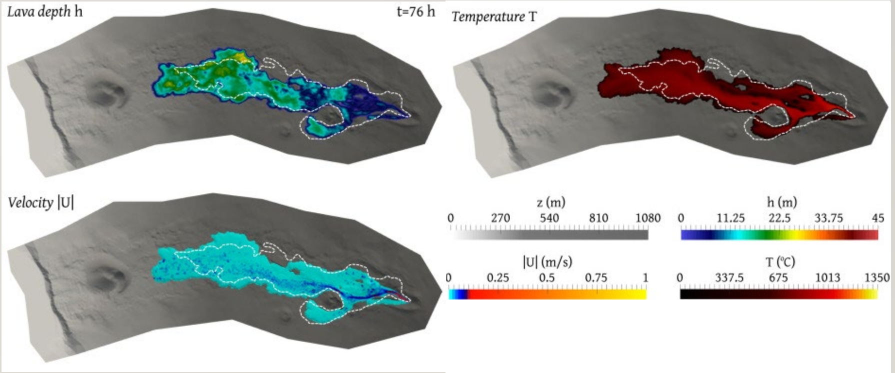
https://volcan.lapalma.es/apps/207ab18c297f41a78458ebb63a47712e/explore

- Post eruption simulation attempts





Lev et al., (2022)
https://ui.adsabs.harvard.edu/link_gateway/2022EGUGA..2410531L/doi:10.5194/egusphere-egu22-10531



Echeverribar el al. (2023)
https://doi.org/10.1016/j.advengsoft.2022.103340

Goals - workflow

Explore the time-cost of whole calibration simulation:

- With the available real time public geospatial information
- With a appropriate process based and validated open source (under agreement) software
- With a reasonable fit to real lava inundation geometry
- For the particular case of La Palma'21 eruption

In this context, the study was performed as follows:

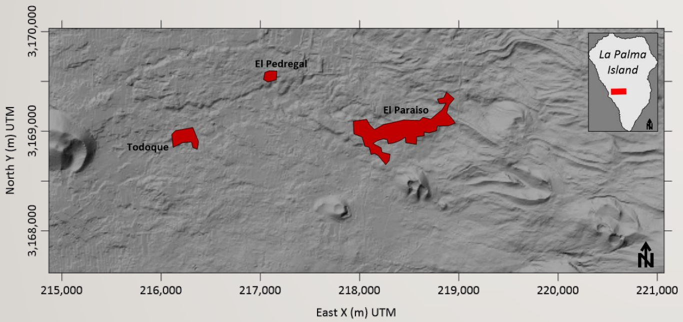
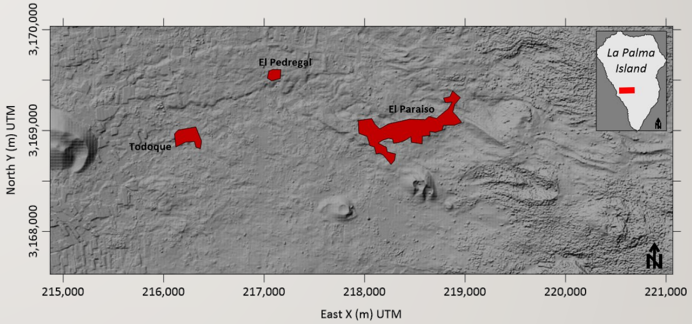
(i) Evaluate the different approximations that could be obtained for the rheology of the lava from remotely obtained information.
Such information included the evolution of the lava's extent during the first 7 days of the event (19--26 September 2021).
This time limit was set to avoid the modelling of the lava flowing down the coastal cliff.

(iii) Evaluate the different CPU time of the suggested scenarios (DTM, eruption evolution, rheological parameters)
Determine the possibility of achieving a total calibration and simulation time shorter than that of the lava flow emplacement.

(iii) Forecast the process of lava flow emplacement for two more days (validation)
Evaluate calibration quality using the best geometric fit assuming different scenarios and hypotheses.

Available real time public geospatial information

- Pre eruption

DTMs: DEM  and DSM  (IGN 2.5 m/px)

sources: IGN

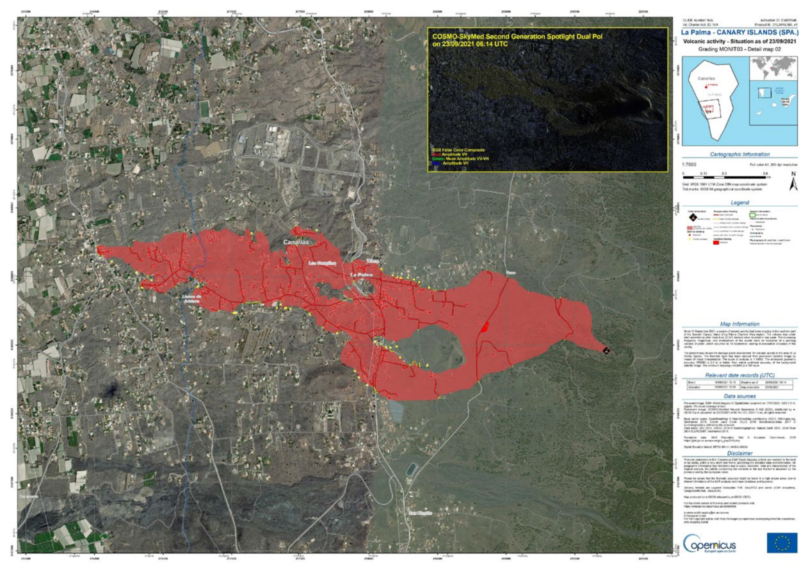
- Sync-eruption

Collected through the use of airborne remote sensing systems or satellite platforms

to locate the emission points of the volcanic products;
to delimit the extent, velocity, flow, heights, temperatures
to determine their emission rate;

strongly affected by the prevailing meteorological conditions and the development of the eruptive ash cloud.

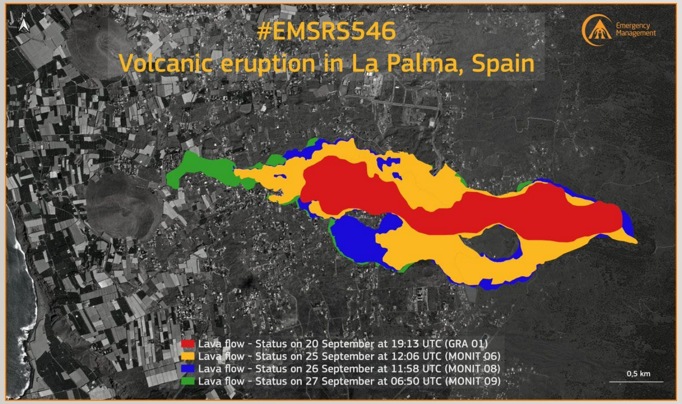
sources: Copernicus (EMSR546) and C. I. La Palma – PEVOLCA - IGME

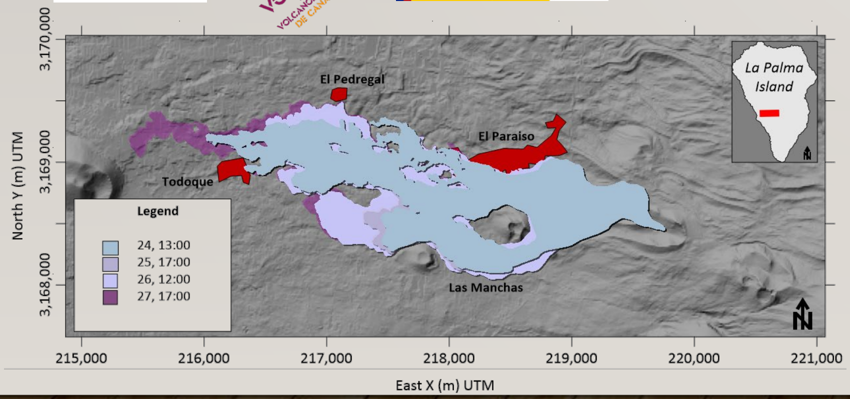


Synthetic aperture radar (SAR), thermal, infrared (IR), and optical sensors are the most commonly used. Copernicus EMS rapid-mapping team provided the interpretation of high-resolution SAR images, gathered by the COSMO-SkyMed Second Generation constellation (GSD 1 m/pixel) and by Copernicus Sentinel-1 A/B (GSD 10 m/pixel, EU ESA). Infrared, optical, and multispectral from ASTER, Pléiades-1 A/B Landsat-8, Sentinel-2, and GeoEye-1.

Available real time public geospatial information

- Sync-eruption - preprocessing





Time UTC t_i (dd/mm/yy-hh:mm)	Distribution Agency	Vehicle	Sensor	Expand Area $[WL]_i$ (0.10^4 m^2)	Max. Length L_{Ai} (m)
t_0 = 19/09/21-14:10	Volcanic eruption starts				
t_1 = 20/09/21-18:50	Copernicus	Cosmo-SM and Sentinel-1A/B	SAR	102.8 [1]	3000
t_2 = 21/09/21-07:14	Copernicus	Cosmo-SM	SAR	154.4 [1]	3297
t_3 = 22/09/21-19:26	Copernicus	Cosmo-SM	SAR	171.1 [1]	3331
t_4 = 23/09/21-06:14	Copernicus	Cosmo-SM	SAR	180.1 [1]	3614
t_5 = 23/09/21-19:44	Copernicus	Cosmo-SM	SAR	190.7 [1]	3614
t'_1 = 24/09/21-13:00	Cabildo La Palma	UAV	Optical	181.7 [2]	3612
t_6 = 25/09/21-06:50	Copernicus	Cosmo-SM	SAR	212.2 [1]	3614
t_7 = 25/09/21-12:06	Copernicus	Cosmo-SM and Pléiades	SAR Panchromatic	210.2 [1]	3614
t'_2 = 25/09/21-17:00	Cabildo La Palma	UAV	Optical	187.1 [2]	3612
t_8 = 26/09/21-07:08	Copernicus	Cosmo-SM	SAR	232.2 [1]	3614
t_9 = 26/09/21-11:58	Copernicus	Pléiades	Panchromatic	237.5 [1]	3629
t'_3 = 26/09/21-12:00	Cabildo La Palma	UAV	Optical	231.9 [2]	3612
t_{10} = 27/09/21-06:50	Copernicus	Cosmo-SM	SAR	257.9 [1]	4312
t'_4 = 27/09/21-17:00	Cabildo La Palma	UAV	Optical	252.2 [2]	4296

[1] Satellite imagery from Copernicus EMSR546. [2] UAV image flights from Cabildo Insular de La Palma.

Available software for simulation

In the last decades, several calculation and numerical simulation tools have been developed

The main challenge in designing these models is to simulate the complex thermo–fluid–mechanical interactions that determine the morphology, distribution, texture, thickness, and extent of the emplacement process of a lava flow.

Based on the thermo-rheological behaviour of lava in its evolution to reproduce its trajectory over the terrain's topography.

Computer codes were based on:

- cellular automata schemes

MAGFLOW, SCIARA, FLOWFRONT, MOLASSES

- complete thermorheological

FLOWGO

- conservation of depth-averaged velocity, temperature, and flow thickness SWE

VolcFlow, RHEOLEF, IMEX-SfloW2D

- 3D CFD

OpenFOAM

- Particle mesh free

GPUSPH; NB3D

Physically-based approximation used here of lava flow moving over a complex topography

Assumes:

(i) continuous incompressible molten fluid of constant density.
(ii) vertical accelerations are negligible compared with the horizontal dynamics
(iii) Vertically homogeneous flow, rheology and constant

(iv) force balance in vertical direction expressed by hydrostatic pressure balance
(v) rheology simple enough to be estimated with the available data

(vi) isothermal 2D behavior
(vii) lava behaves as a single-phase molten material

The main factors controlling the extent and type of lava flow are:

- rheological characteristics of the lava
- flow rate at which it is emitted

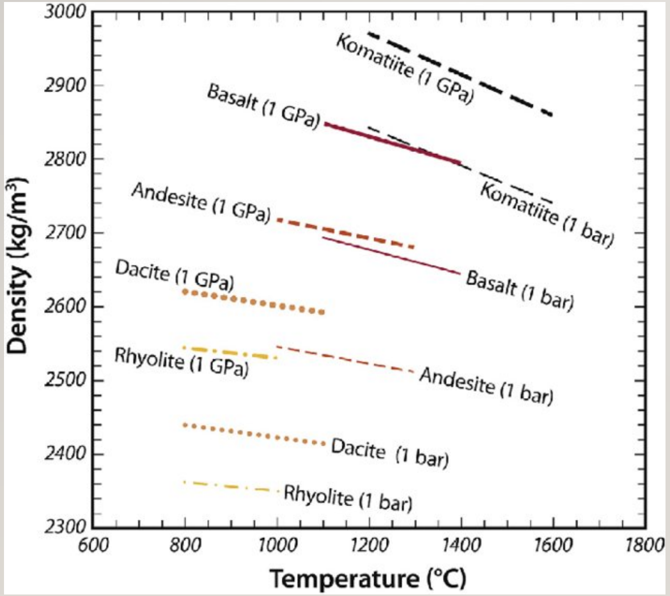
Controlling factors of extent: determination

- Density ρ

Little variation between lava types

Typically ranging from 2300 to 2800 kg/m3 for lavas under atmospheric

This value remains almost constant when the lava has solidified



Lesher and Spera (2015)
https://doi.org/10.1016/B978-0-12-385938-9.00005-5

- Viscosity η

There are techniques that allow lava viscosity to be estimated in the field or in the laboratory, these approaches require experimental analyses the silica content; the volume fraction of crystals; crystal size, shape, and, mainly, the temperature.

Although accurate, are costly and time-consuming and would hinder reaching the real-time target.

Morphometric approach assumes Newtonian fluid

$$\eta_1 = \rho g h^2 sin(\alpha)/nu$$

$$\eta_2 = \rho g h^3 W sin(\alpha)/nQ$$

Nichols (1939), Jeffreys (1925)

n = 3 wide n = 4 narrow flows

gives an a priori estimate of the apparent viscosity from depth-averaged measurements of the heterogeneous lava flow by taking an average thickness and velocity, an estimated value of its density, and the average slope of the terrain if it does not undergo major changes in relief.

Controlling factors of extent: determination

- Velocity *u*

Can be estimated from the interpretations of satellite images provided by emergency mapping services as measurements of the geometry changes of the lava flow evolution: expansion or advance

Average velocities, of expansión

$$u_{WLi} = [WL]_i / \Delta t_{0i}$$

of advance

$$\Delta t_{0i} = t_i - t_0$$

$$u_i = L_{Ai} / \Delta t_{0i},$$

Instantaneous velocities, of expansión

$$([WL]_{i+1} - [WL]_i) / \Delta t_{i+1i},$$

of advance

$$\Delta t_{i+1i} = t_{i+1} - t_i$$

$$(L_{Ai+1} - L_{Ai}) / \Delta t_{i+1i}.$$

- Flow rate *Q*

Lava is placed through a volume-limited flow:

$$Q_1 = \frac{1}{dt} \int_{\Omega} d\Omega \cong \frac{h[WL]}{\Delta t}$$

$$Q_3 = \frac{uh[WL]}{L_A}$$

When stopped by cooling-limited flow:

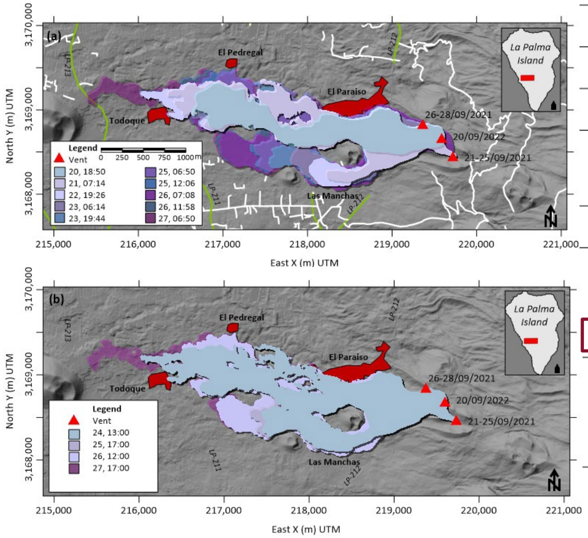
$$Q_2 = \frac{\kappa G_z [WL]}{h}$$

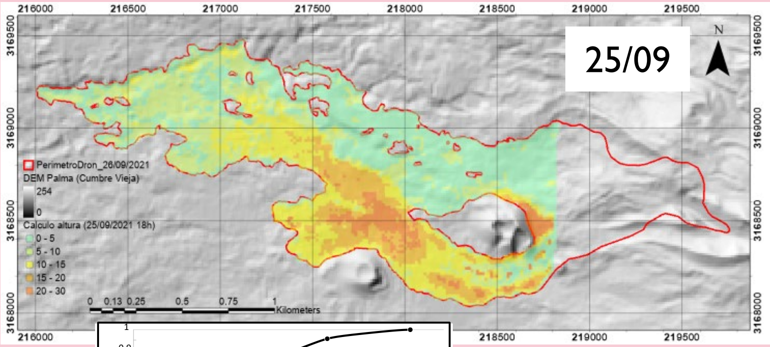
thermal diffusivity is involved through the Grätz number Gz $\in$[100,300]
(dimensionless quantity used in volcanology that expresses the balance between the heat transported by lava and the heat lost by thermal conduction)

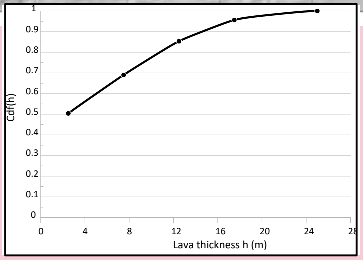
Controlling factors of extent: morphometric determination

Time UTC t_i (dd/mm/yy-hh:mm)	Distribution Agency	Vehicle	Sensor	Expand Area $[WL]_i$ (0.10^4 m^2)	Max. Length L_{Ai} (m)
t_0 = 19/09/21-14:10	Volcanic eruption starts				
				102.8 [1]	3000
				154.4 [1]	3297
				171.1 [1]	3331
				180.1 [1]	3614
				190.7 [1]	3614
				181.7 [2]	3612
				212.2 [1]	3614
				210.2 [1]	3614
				187.1 [2]	3612
				232.2 [1]	3614
				237.5 [1]	3629
				231.9 [2]	3612
				257.9 [1]	4312
				252.2 [2]	4296

[1] Satellite imagery from Copernicus EMSR546. [2] UAV image flights from Cabildo Insular de La Palma.

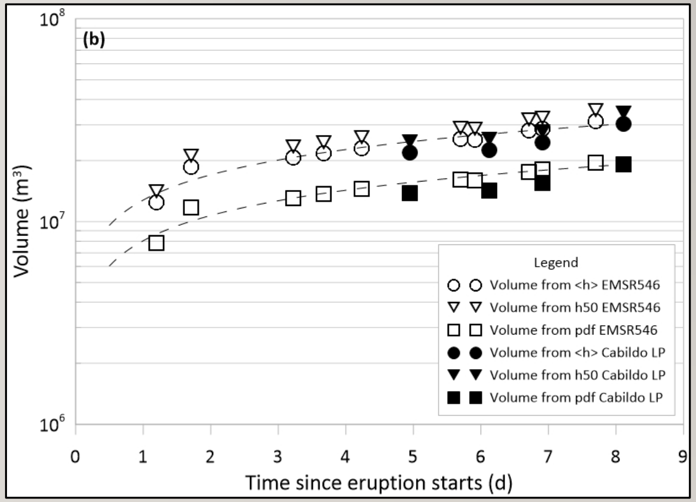


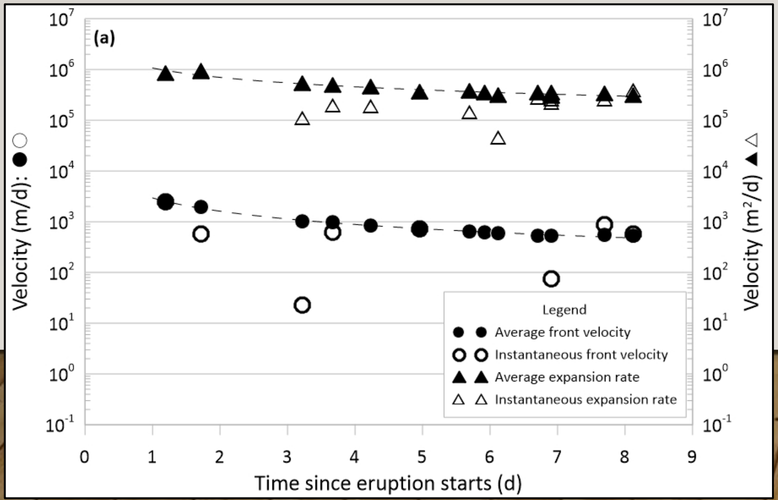


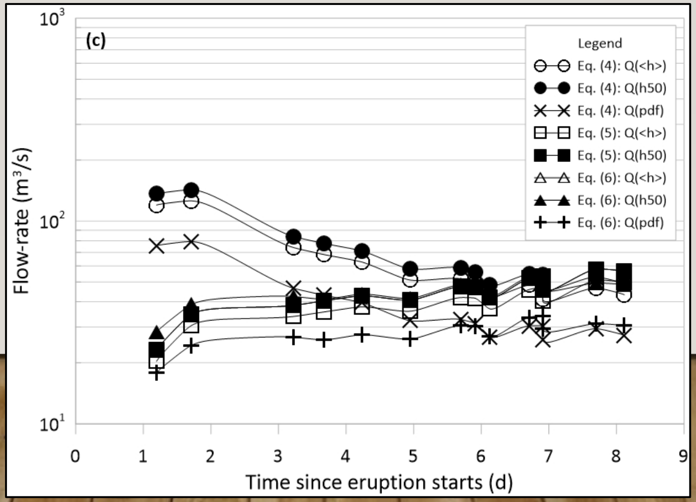


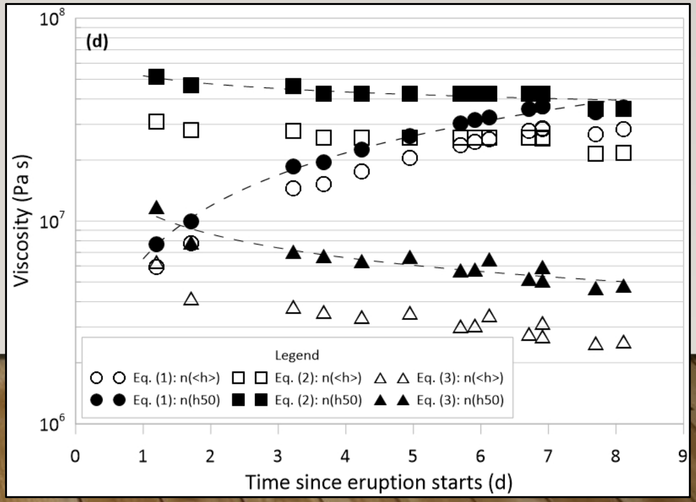
$$V_i \simeq \Sigma_j f_j h_j^* [WL]_i$$

shape factor f_i = {<h>, h50, pdf}









Mathematical model of lava flow

Simulations in this study were carried out with VolcFlow:

Depth-average approximation of shallow-water equations of mass and momentum balance or shallow-water equations (SWE):

$$\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = 0$$

$$\frac{\partial (hu)}{\partial t} + \frac{\partial (hu^2)}{\partial x} + \frac{\partial (huv)}{\partial y} = ghsin\alpha_x - \frac{1}{2} k_{actpass} \frac{\partial}{\partial x}(gh^2 cos\alpha) + \frac{R_x}{\rho}$$

$$\frac{\partial (hv)}{\partial t} + \frac{\partial (hv^2)}{\partial y} + \frac{\partial (huv)}{\partial x} = ghsin\alpha_y - \frac{1}{2} k_{actpass} \frac{\partial}{\partial y}(gh^2 cos\alpha) + \frac{R_y}{\rho}$$

to solve:

h = h(x,y,t), the thickness

u = (u(x,y,t),v(x,y,t)), the flow velocity

for a fluid with constant density that moves over a terrain of slope α(x, y)

numerically uses finite difference with a Eulerian upwind integration scheme

MATLAB

Kelfoun & Druitt (2005)

Laboratoire Magmas et Volcans

https://lmv.uca.fr/volcflow/

Mathematical model of lava flow

Several rheological models are incorporated in VolcFlow:

$$\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = 0$$

$$\frac{\partial (hu)}{\partial t} + \frac{\partial (hu^2)}{\partial x} + \frac{\partial (huv)}{\partial y} = ghsin\alpha_x - \frac{1}{2}k_{actpass}\frac{\partial}{\partial x}(gh^2cos\alpha) + \frac{R_x}{\rho}$$

$$\frac{\partial (hv)}{\partial t} + \frac{\partial (hv^2)}{\partial y} + \frac{\partial (huv)}{\partial x} = ghsin\alpha_y - \frac{1}{2}k_{actpass}\frac{\partial}{\partial y}(gh^2cos\alpha) + \frac{R_y}{\rho}$$

Through earth pressure coefficient:

the ratio of the stress parallel to the ground to the normal stress of the ground

$$k_{act/pass} = \begin{cases} 2\frac{1 \pm [1 - cos^2\varphi_{int}(1+tan\varphi_{bed})]^{1/2}}{cos^2\varphi_{int}} - 1; \varphi_{bed} < \varphi_{int} \\ \frac{1+sin^2\varphi_{int}}{1-sin^2\varphi_{int}}; \varphi_{bed} \geq \varphi_{int} \end{cases}$$

Through R = (Rx,Ry):

the basal shear stress that depends on the different rheological behavior in the lava flow

$$R = R_{Coulomb} + R_{Viscous} + R_{Turbulent} + R_{Plastic}$$

$$\mathbf{R} = \rho h\left(gcos\alpha + \frac{\mathbf{u}^2}{r}\right)tan\varphi_{bed}\frac{\mathbf{u}}{\|\mathbf{u}\|} + 3\eta\frac{\mathbf{u}}{h} + g\rho\|\mathbf{u}\|\mathbf{u}/\xi + R_0\frac{\mathbf{u}}{\|\mathbf{u}\|}$$

Kelfoun & Druitt (2005)

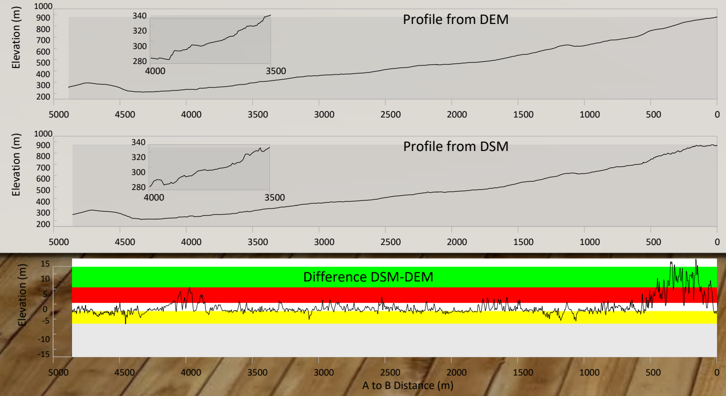
Laboratoire Magmas et Volcans

https://lmv.uca.fr/volcflow/

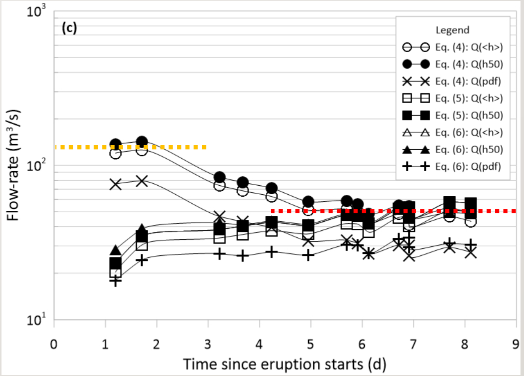
Numerical simulation of lava flow: calibration

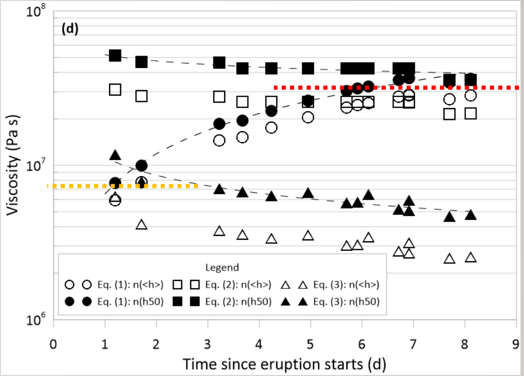
- Several scenarios examined in this study: SS1 to SS7 aimed to capture the conditioning possible factors in calibration.

Simulated Scenario	DTM	Resolution (m/px)	No. Vents	Coords (Long. Lat.)	Time Span (dd/mm–dd/mm)
SS1	DEM	12	V1	17°52′03″ W 28°36′53″ N	20–25 September
SS2	DEM	12	V1 V2	17°52′03″ W 28°36′53″ N 17°51′57″ W 28°36′46″ N	20–21 September 21–25 September
SS3	DEM	6	V1	17°52′03″ W 28°36′53″ N	20–25 September
SS4	DSM	6	V1	17°52′03″ W 28°36′53″ N	20–25 September
SS5	DEM	6	V1 V2	17°52′03″ W 28°36′53″ N 17°51′57″ W 28°36′46″ N	20–25 September 21–25 September
SS6	DSM	6	V1 V2	17°52′03″ W 28°36′53″ N 17°51′57″ W 28°36′46″ N	20–25 September 21–25 September
SS7	DEM	6	V1 V2 V3 (SW flank collapse)	17°52′03″ W 28°36′53″ N 17°51′57″ W 28°36′46″ N 17°52′10″ W 28°36′56″ N	20–25 September 21–25 September 25–27 September
SS8	DSM	6	V1	17°52′03″ W 28°36′53″ N	20–27 September

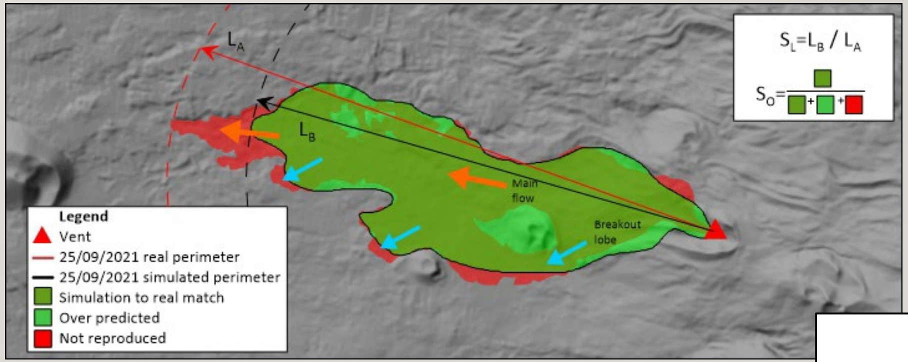


- Initial estimated parameters Q and η





- Objective function (19/09 – 25/09)

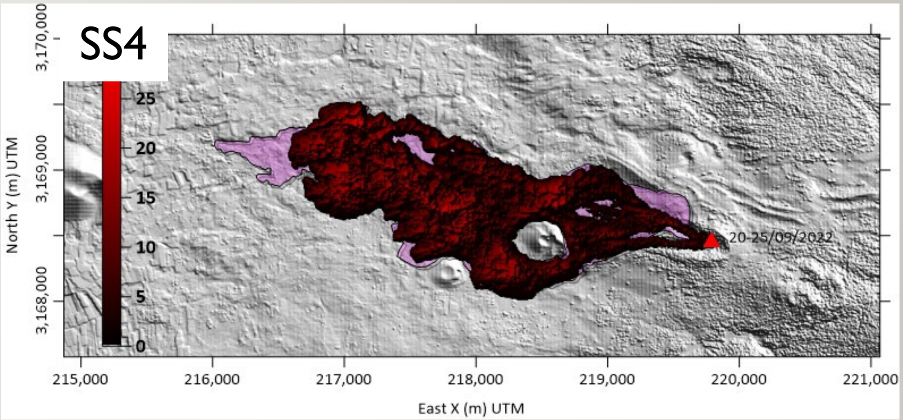


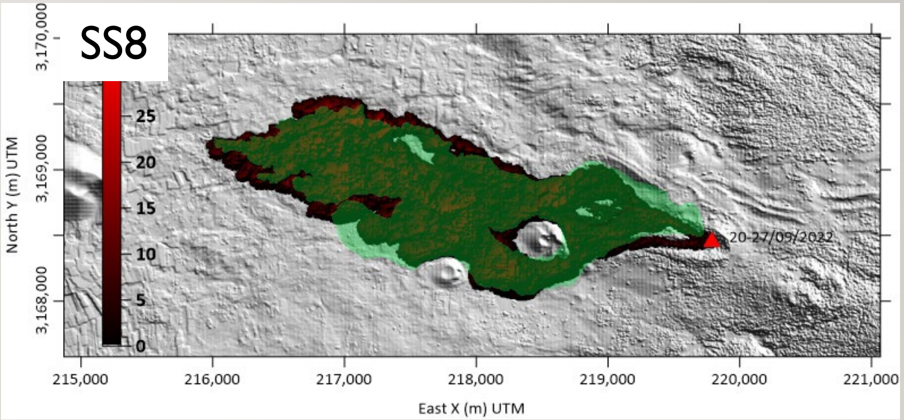
Maximize: $$S_O = \frac{|A \cap B|}{|A \cup B|}$$

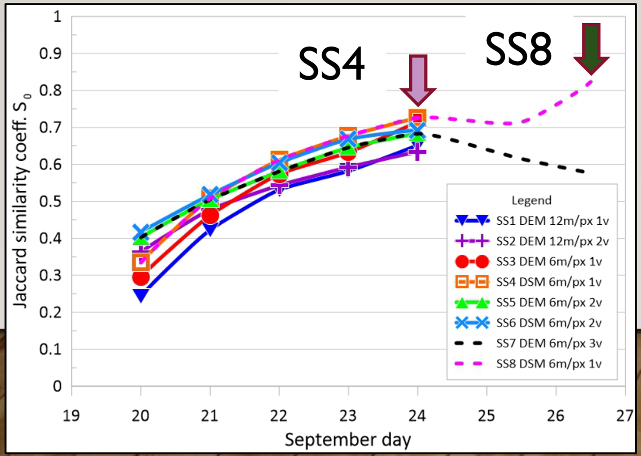
Numerical simulation of lava flow: results

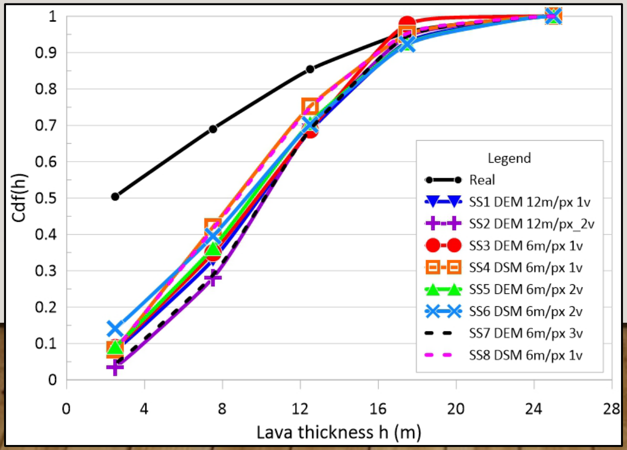
- Best fit in this study: SS4 → Best forecast in this study: SS8

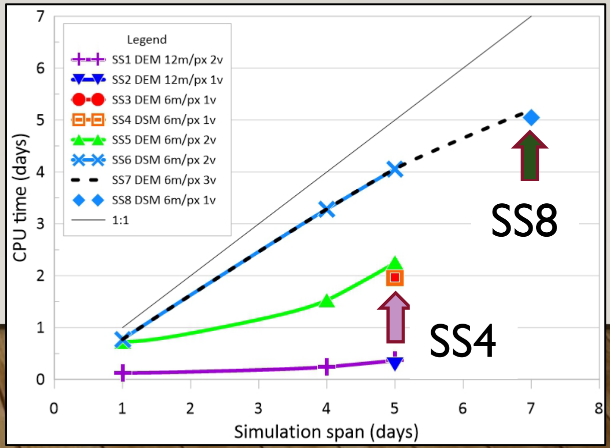
Simulated Scenario	Initial Estimated Flow Rate Q	Initial Estimated Viscosity η (Pa s)	Best-Fit Flow Rate Q (m³/s)	Best-Fit Viscosity η (Pa s)	Bes- Fit $\varphi_{int}, \varphi_{bed}, R_0$ (Pa)
SS1	$Q_1 = 50$	3×10^7	$Q_1 = 65.21$	2.9×10^5	$5°, 0°, 36 \times 10^3$
SS2	$Q_1 = 131$ $Q_2 = 50$	7.6×10^6 3×10^7	$Q_1 = 140.20$ $Q_2 = 58.34$	2.4×10^3 2.9×10^5	$2.5°, 0°, 42 \times 10^3$ $2.5°, 0°, 35 \times 10^3$
SS3	$Q_1 = 50$	3×10^7	$Q_1 = 65.21$	2.9×10^5	$5°, 0°, 36 \times 10^3$
SS4	$Q_1 = 50$	3×10^7	$Q_1 = 65.21$	2.9×10^5	$5°, 0°, 36 \times 10^3$
SS5	$Q_1 = 131$ $Q_2 = 50$	7.6×10^6 $3\ 10^7$	$Q_1 = 140.20$ $Q_2 = 58.34$	2.4×10^3 2.9×10^5	$2.5°, 0°, 42 \times 10^3$ $2.5°, 0°, 35 \times 10^3$
SS6	$Q_1 = 131$ $Q_2 = 50$	7.6×10^6 $3\ 10^7$	$Q_1 = 140.20$ $Q_2 = 58.34$	2.4×10^3 2.9×10^5	$2.5°, 0°, 42 \times 10^3$ $2.5°, 0°, 35 \times 10^3$
SS7	$Q_1 = 131$ $Q_2 = 50$ $Q_3 = 50$	7.6×10^6 $3\ 10^7$ $3\ 10^7$	$Q_1 = 140.20$ $Q_2 = 58.43$ $Q_3 = 57.25$	2.4×10^3 2.9×10^5 2.9×10^5	$2.5°, 0°, 42 \times 10^3$ $2.5°, 0°, 35 \times 10^3$ $2.5°, 0°, 35 \times 10^3$
SS8	$Q_1 = 50$	$3\ 10^7$	$Q_1 = 63.63$	2.9×10^5	$5°, 0°, 36 \times 10^3$











Some thoughts…

Regardless if the strategy follows cellular automata , finite differences, elements, or volumes, they all need input data that are usually not easy to obtain.
They requires specific measurements and observations during events and their immediate public release.

The morphometric values of perimeter, volumes, emission rates, velocities, and thickness of lava could be provided with enough accuracy,

- we estimated an average asymptotic volume, emission rate, velocity and viscosity
- the results of the viscosities obtained with Jeffrey's formulae differ by one to two orders of magnitude from those obtained by numerical calibration.

So, their uncertainties estimated and checked with other estimation tools.

Some important differences that arise when performing simulations on a DEM and on a DSM helped to identify the effects on the evolution of the lava tongue.

CPU time is less than simulated evolution time, but it is not enough as for a calibration process hundreds must be run.

In Spain, the civil protection authorities suggested: early warnings may be effective if dispatched at least one hour in advance of the hazard.

Therefore, in case of an emergency, a quick response time is more essential than the delay that can be caused by working with complex models that demand a large volume of data for their calculation.

These results are a promising step toward real-time forecasting as it can already be achieved using the calibration in this study for a similar scenario.
It also means that manual or automatic calibration would require much faster computation depending on the number of runs required to undertake such calibration, with a rough estimate of at least 10× faster.

Some thoughts… go to the next step

Workflow requirements to "real time"

Initial conditions:

- Algorithm "semi-automatic" since eruption starts
- Quality DTM: lidar or UAV based (6-12 m/px)
- Rheology pre-knowledge: morphometric, field, laboratory experiments
- Remote sensing from UAV or sat: DTM(t), h(x,y,t), Q(x,y,t),… v(x,y,t), T(x,y,t)

Introduce other metrics as objective function

- Geometry based: perimeter evolution from remote sensing (UAV, sat): RMSD, Hausdorff, Jaccard
- Function based: include h(x,y,t), **v**(x,y,t)
- Probability based

Computational effort

- Use numerical optimization metaheuristic methods : evolutionary, swarm, trajectory
- Incorporate eruption time line
- GPU-HPC SWE + (thermo?) rheological model (100+1 24h… <10min each)

As the mathematical formulation of this problem with a complex objective function (geometry, thicknesses, and velocities) is hard to numerically solve, a semiautomatic calibration through hundreds of simulations is required to locate the minimum of the problem. Therefore, to answer the question posed, we cannot claim that it is actually possible to achieve real-time lava flow estimation of sufficient quality and starting in a zero-knowledge state to inform a volcanic emergency response, although **we are on the way to further improvements**.

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Today, to the audience, thanks for your attention