ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA

PROTEZIONE CIVILE NAZIONALE

SCUOLA NORMALE SUPERIORE

Probabilistic hazard modeling of secondary pyroclastic avalanches generated by paroxysms at Stromboli (Italy)

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UNIVERSITY of SOUTH FLORIDA 1956 TRUTH WISDOM

NSF

NSF workshop 'PDC dynamics and hazards – Benchmarking of concentrated PDC models and other avenues'
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Problem and approach

At Stromboli (Italy), the remobilization and gravitational collapse of fresh pyroclastic deposits emplaced on steep slopes can produce **secondary pyroclastic density currents** (PDCs), also called pyroclastic avalanches or deposit-derived PDCs.

Most paroxysms produce PDCs in Sciara del Fuoco. In some cases, e.g. in 1944, 1930, and probably 1906, PDCs affected the valleys **outside the Sciara**.

Our target is defining the area potentially invaded by these PDCs, a preliminary step towards **hazard zonation conditional** on the occurrence of this phenomenon.

In summary:

1. we perform a preliminary **sensitivity analysis**, by varying **one by one** the key input parameters;
2. we run a **Monte Carlo simulation** over a multidimensional input space (3125 samples);
3. we evaluate how the PDC source volume can be partitioned in the **main watershed basins**.

We present **preliminary results**, for exploring the input space and the effects of our modeling assumptions.

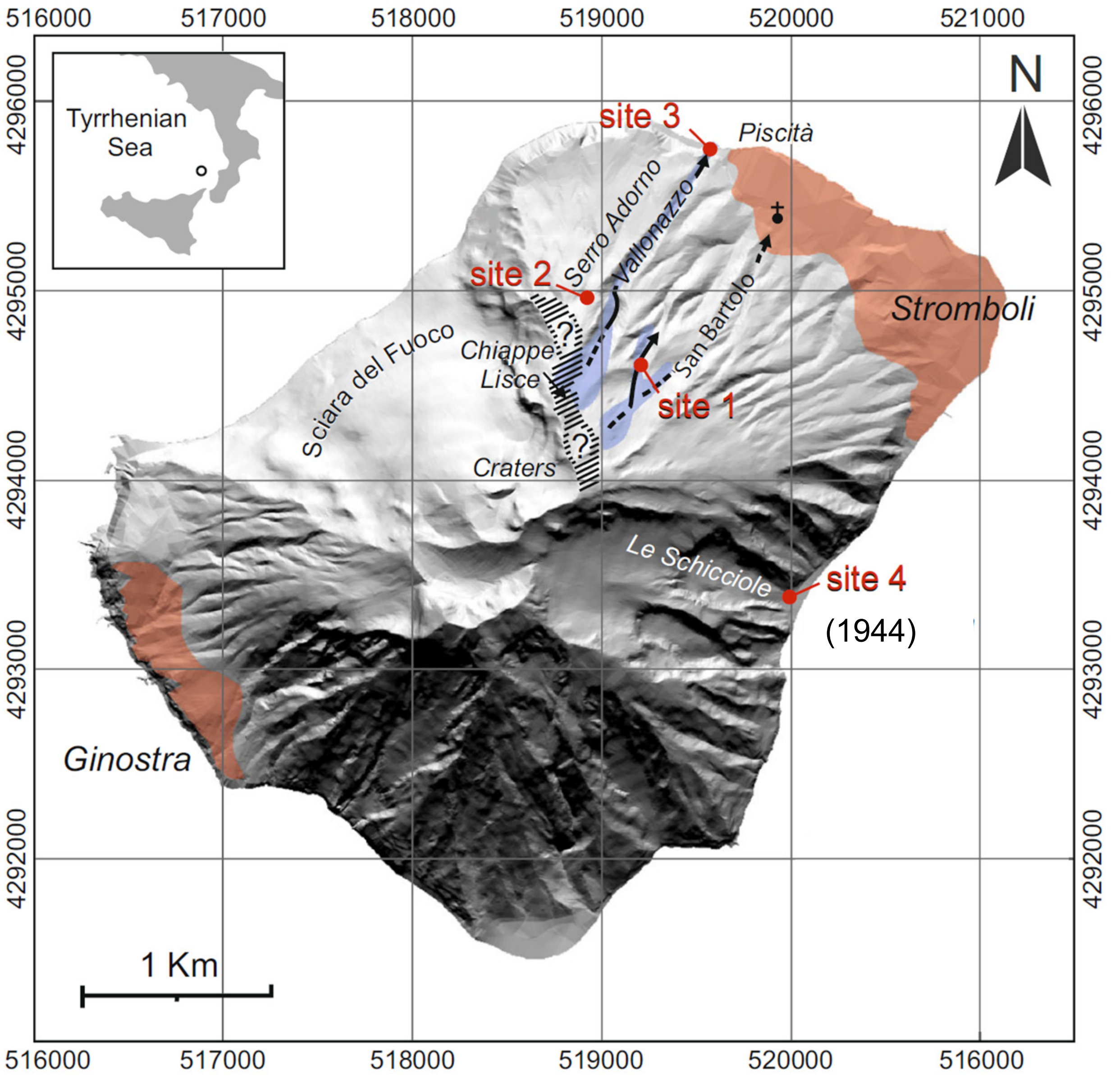


Figure. Overview of 1930 PDC, from Di Roberto et al., 2014.

In light blue the paths of the PDC in Rittmann (1931), black arrows in Abbruzzese (1935).

Possible source areas are dashed in black.

Modeling assumptions and input space

MODELING DURATION

1 simulation

computational time

11' on 16 cores

3125 simulations

2.5 days on 256 cores

Cores Intel Xeon 2.40GHz

LAKI HPC cluster, @ingv.pi

Digital Elevation Map (DEM)

10 m cellsize, total time 7’

We utilize the shallow water numerical solver **IMEX_SfloW2D model** over an input space constrained by previous studies (Di Roberto et al., 2014; Salvatici et al., 2016; de’Michieli Vitturi et al., 2019).

We modeled these flows by using the **Voellmy-Salm rheology** (Voellmy, 1955; Salm, 1993), by assuming:

i) basal friction described by a **constant friction coefficient**, similarly to the Mohr-Coulomb rheology

ii) additional turbulent friction which is proportional to the **square of the local velocity**.

In summary, our Monte Carlo simulation considered the following uncertain parameters:

- two parameters related to the **flow friction** modeling:

1) basal friction parameter - μ
2) turbulent friction parameter - ξ [m^2/s^2]

- three parameters defining the **source area and volume**:

3) distance threshold - D [m]
4) source thickness - H [m]
5) DEM slope threshold - θ

Defining the source area and thickness

LEGEND
source thickness
red > 1.0 m
tomato > 0.5 m
orange > 0.2 m
yellow > 0.1 m

We adopt **a distance-based approach** to constrain the source area, i.e. by using a distance threshold D from the craters.

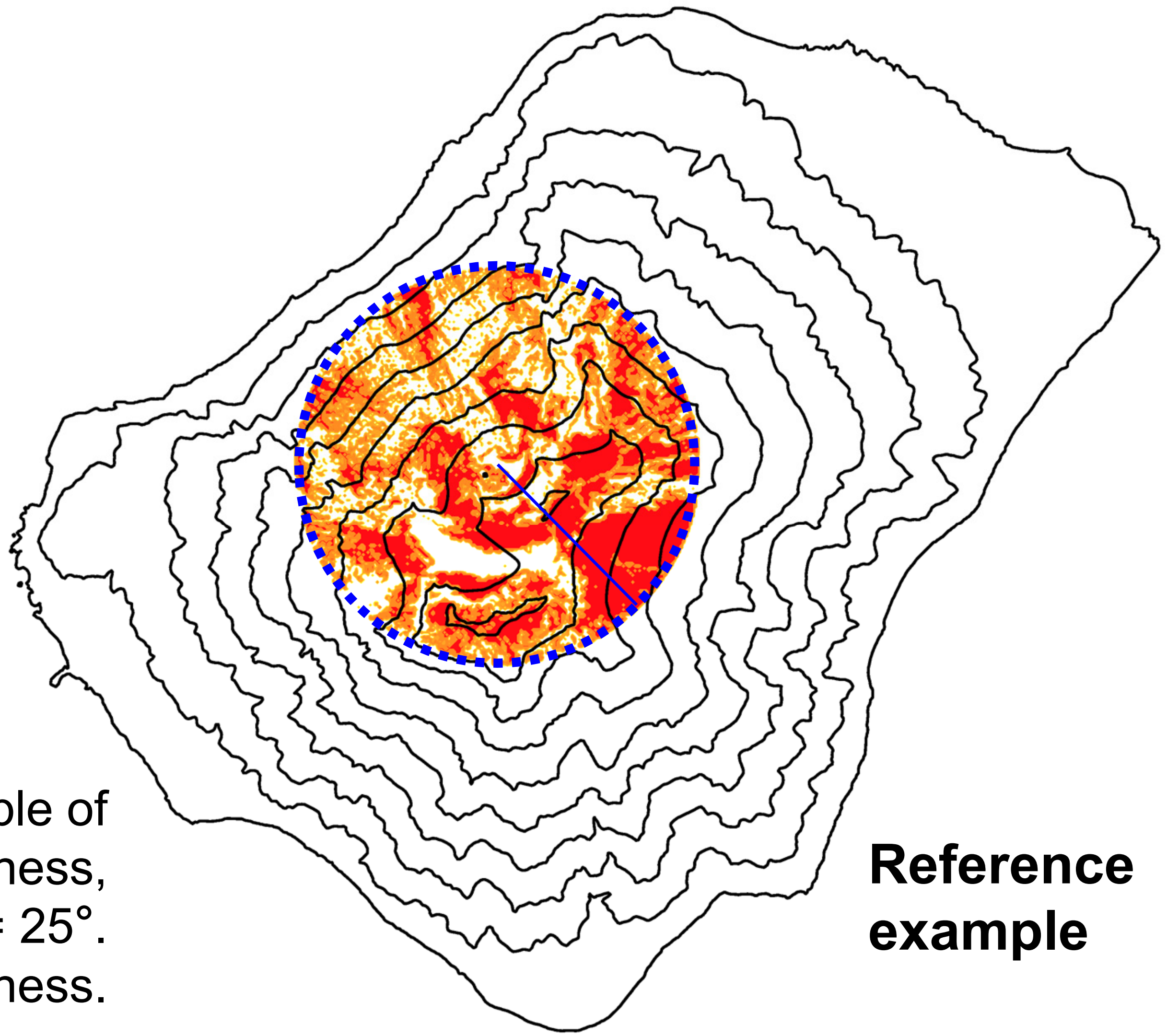
The distance D is a **more physically appropriate** constraint than elevation a.s.l., but not easy to collect from historical accounts of decades-old phenomena.

The **range of distances** that we preliminarily assumed derives from the field observations of the paroxysms that generated PDCs (Bertagnini et al., 2011; Di Roberto et al, 2014).

We define the PDC source by assuming a **constant thickness** H:

- within less than D meters from the craters
&
- where the DEM slope is in the range from θ to θ+10°.

We process a 5 m cellsize DEM, then we do the **average** of the thickness on our computational grid at 10 m cellsize, producing values between 0 and H m.



Reference example

Figure. Reference example of source area and thickness, i.e. D = 875 m, H = 1 m, θ = 25°. Colors express the source thickness.

Watershed basins and source partition

We **partitioned the DEM**, 10 m cellsize, with respect to the watershed basins. We excluded the basins entirely below 500 m a.s.l.

For identification purposes we **grouped the basins** in six zones, i.e. draining towards different sectors of the coast.

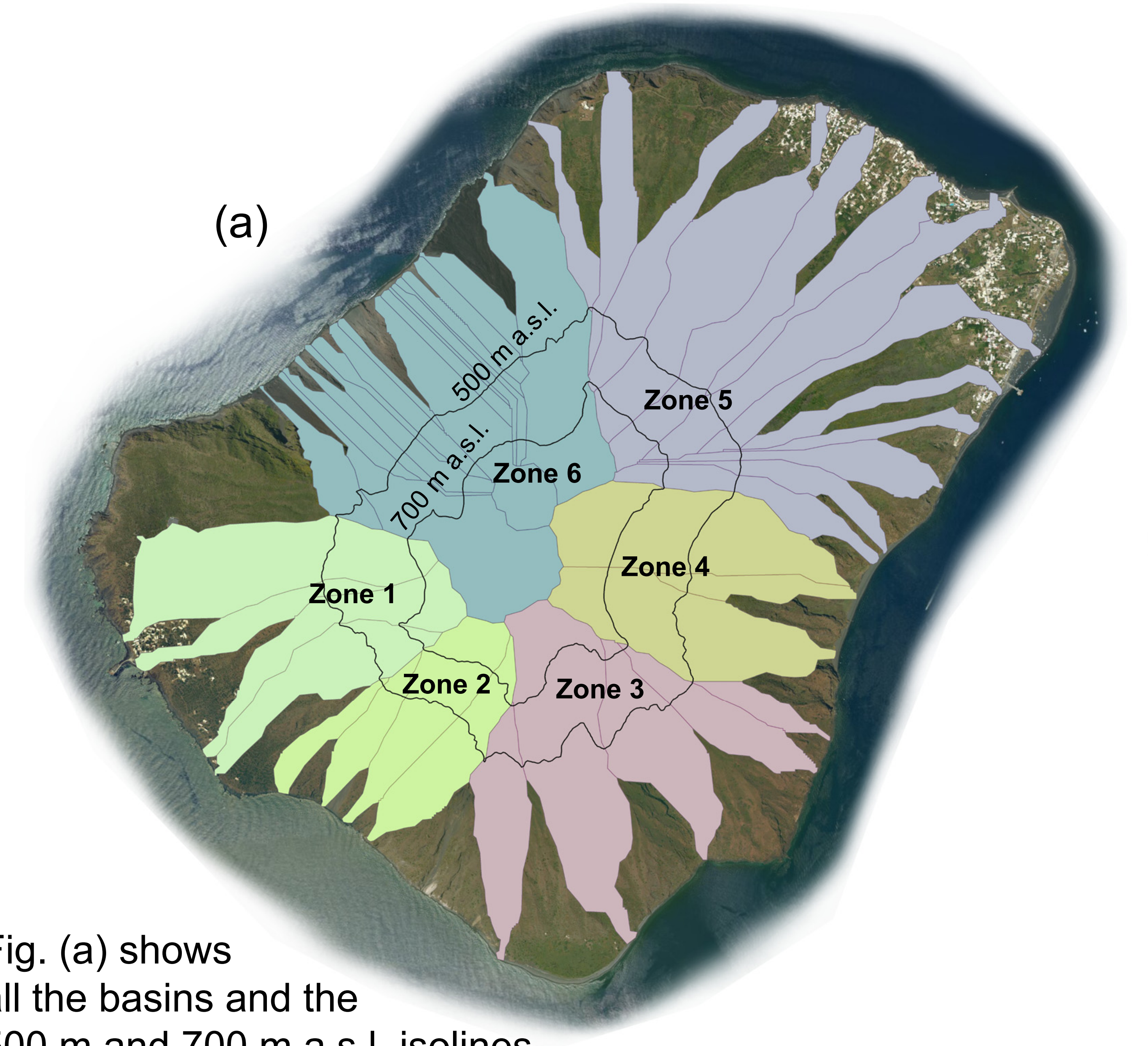


Fig. (a) shows all the basins and the 500 m and 700 m a.s.l. isolines.

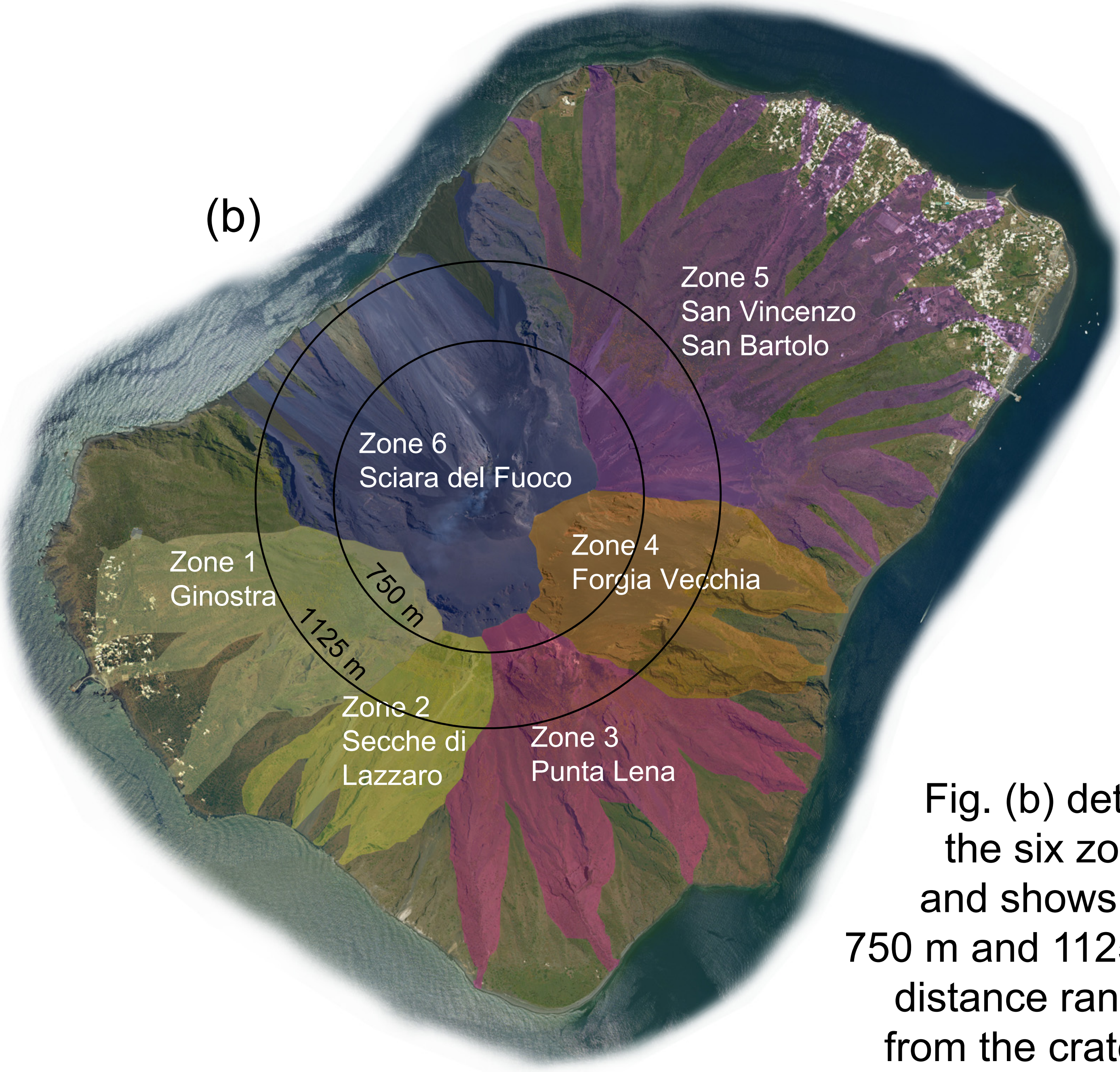
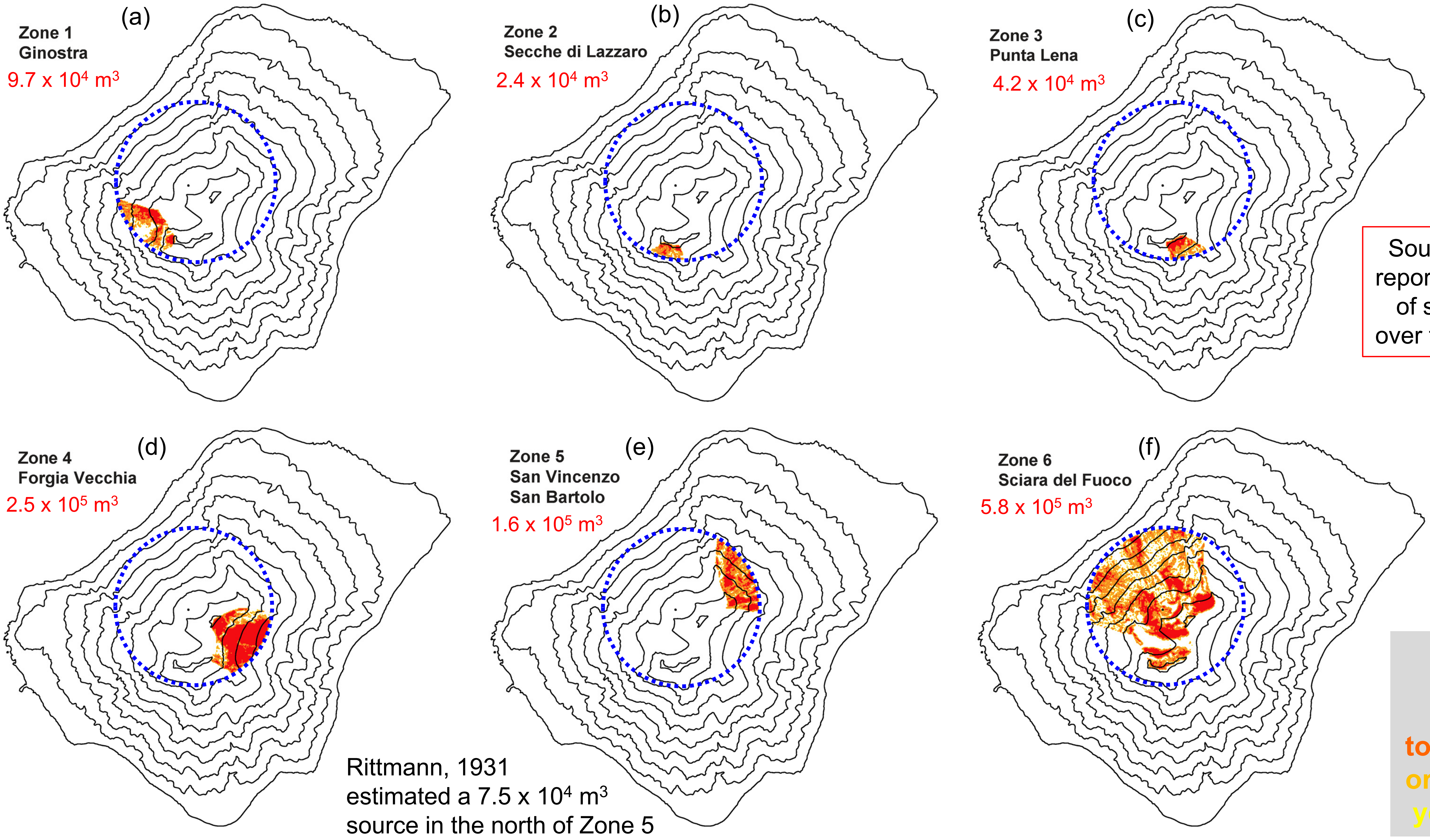


Fig. (b) details the six zones and shows the 750 m and 1125 m distance ranges from the craters.

Partitioned source area and thickness - reference example, D = 875 m, H = 1, θ =25°



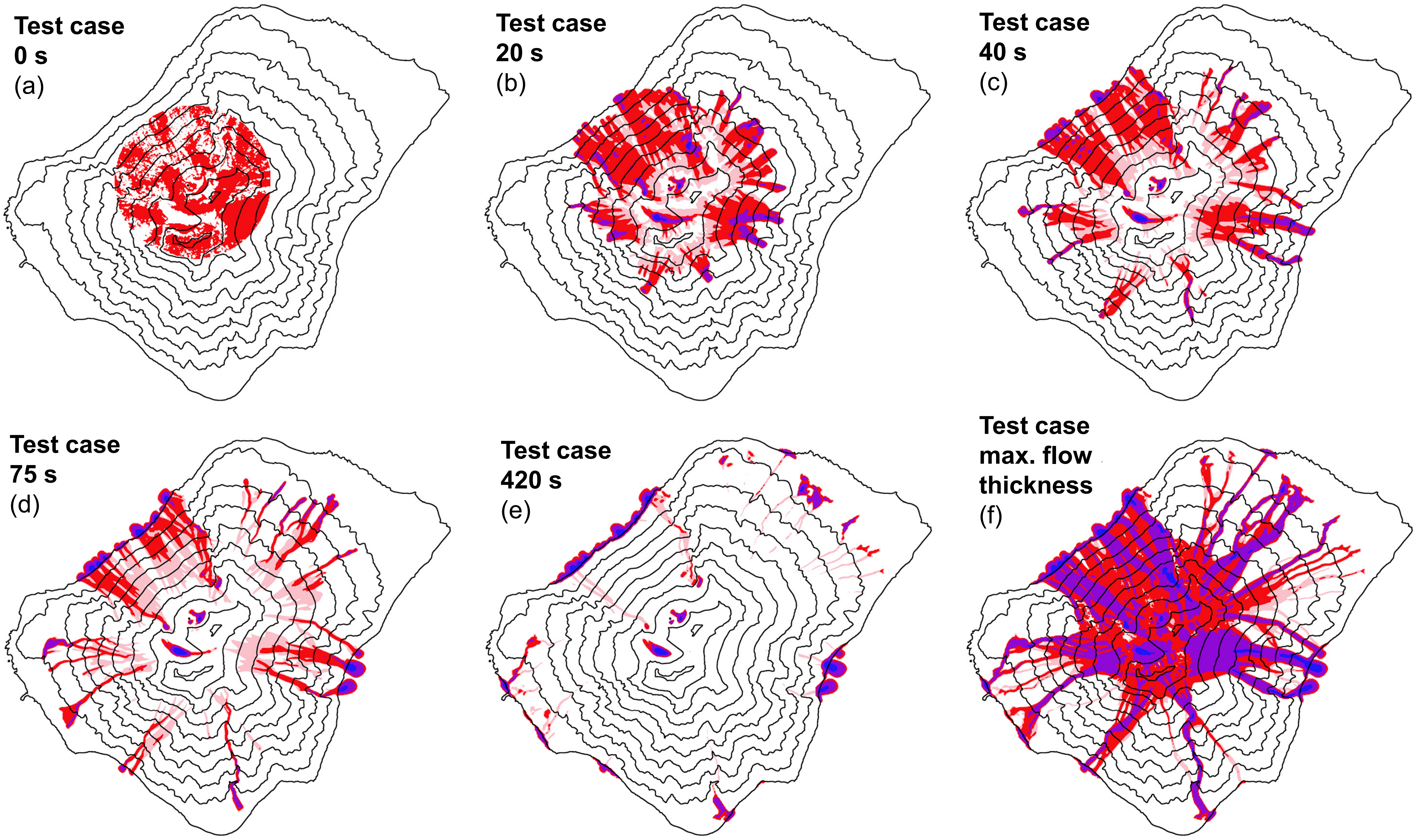
Figures (a-f) decompose the reference **source maps** in the six zones related to the watershed basins.

Source volumes are reported, i.e. the sum of source thickness over the source area.

The two greater volumes are located in Sciara del Fuoco and Forgia Vecchia.

LEGEND
source thickness
red > 1.0 m
tomato > 0.5 m
orange > 0.2 m
yellow > 0.1 m

Reference example PDC simulation (Test case)



INPUT PARAMETERS

$\mu = 0.19$

$\xi = 1000\ m^2/s^2$

Calibrated parameters in Salvatici et al., 2016

$\theta = 25°$

$H = 1\ m$

$D = 875\ m$

Constrained by data from:
Di Roberto et al., 2014
Nolesini et al., 2013

We assume the collapse of pyroclastic deposits in all basins, aiming at constraining the entire area potentially affected by these phenomena.

LEGEND

flow thickness

blue > 5m

violet > 1 m

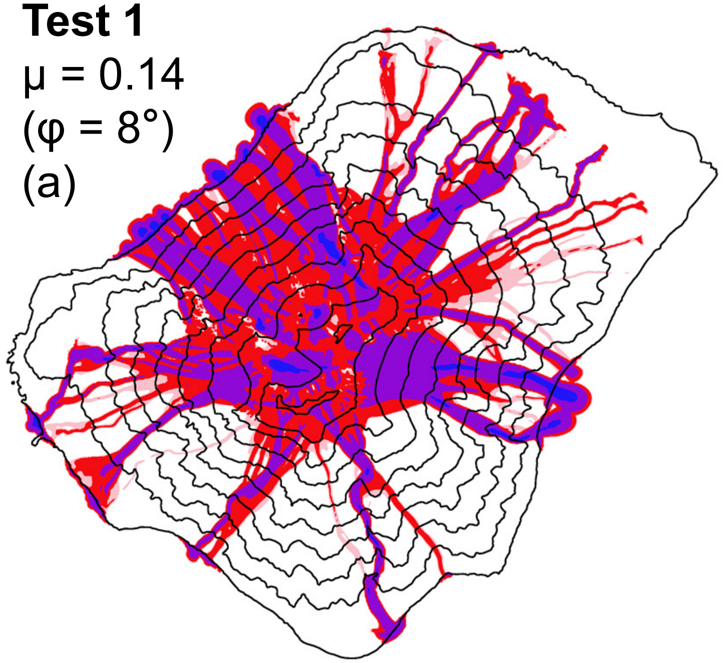
red > 0.1 m

pink > 0.02 m

Sensitivity to the flow friction parameters

basal friction parameter - $\mu \in [0.14, 0.24]$
turbulent friction parameter - $\xi \in [500, 1500]$ m^2/s^2
Morelli et al., 2016; Salvatici et al., 2016; de'Michieli Vitturi et al. 2019

Test 1
$\mu = 0.14$
($\varphi = 8°$)
(a)



Test 2
$\mu = 0.24$
($\varphi = 14°$)
(b)

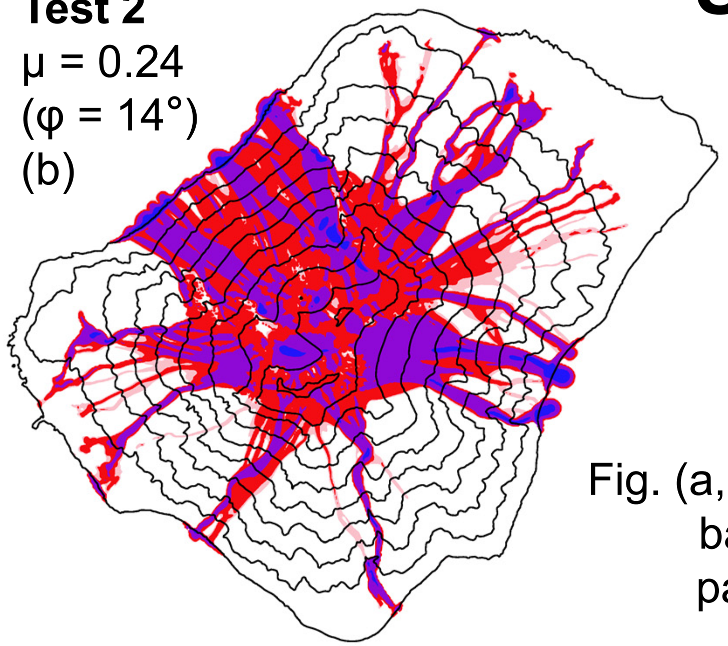
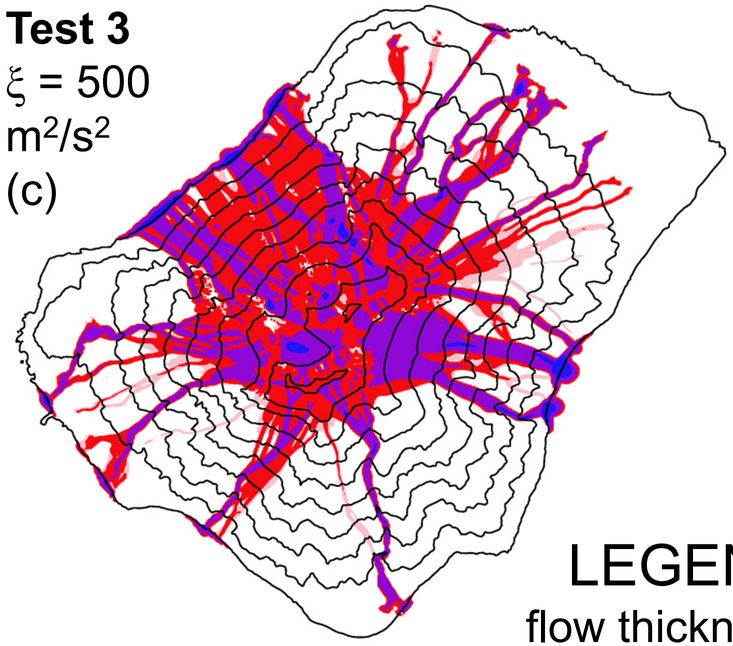


Fig. (a, b) vary the basal friction parameter μ.

Test 3
$\xi = 500$ m^2/s^2
(c)



Test 4
$\xi = 1500$ m^2/s^2
(d)

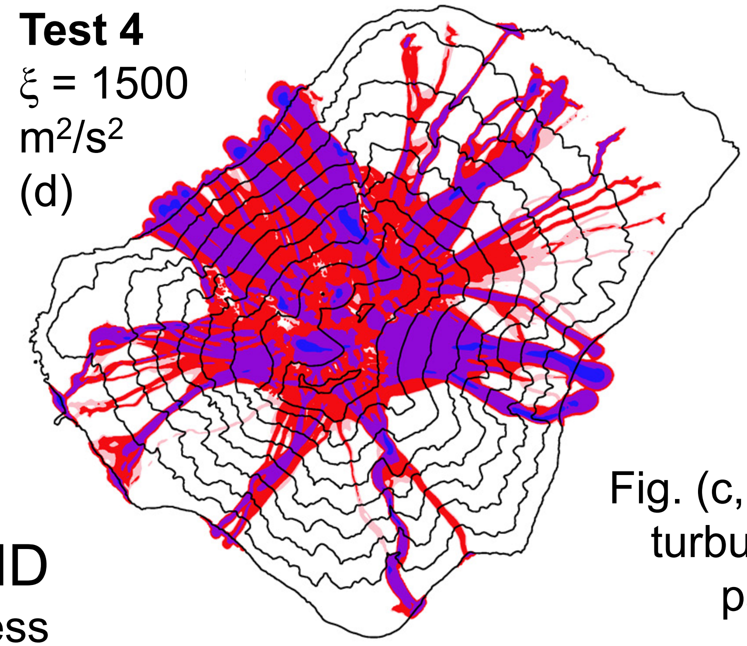


Fig. (c, d) vary the turbulent friction parameter ξ.

LEGEND
flow thickness
blue > 5m
violet > 1 m
red > 0.1 m
pink > 0.02 m

Fig. (a-d) are all related to maximum flow thickness.

2D projection - input of the Monte Carlo simulation

(e)

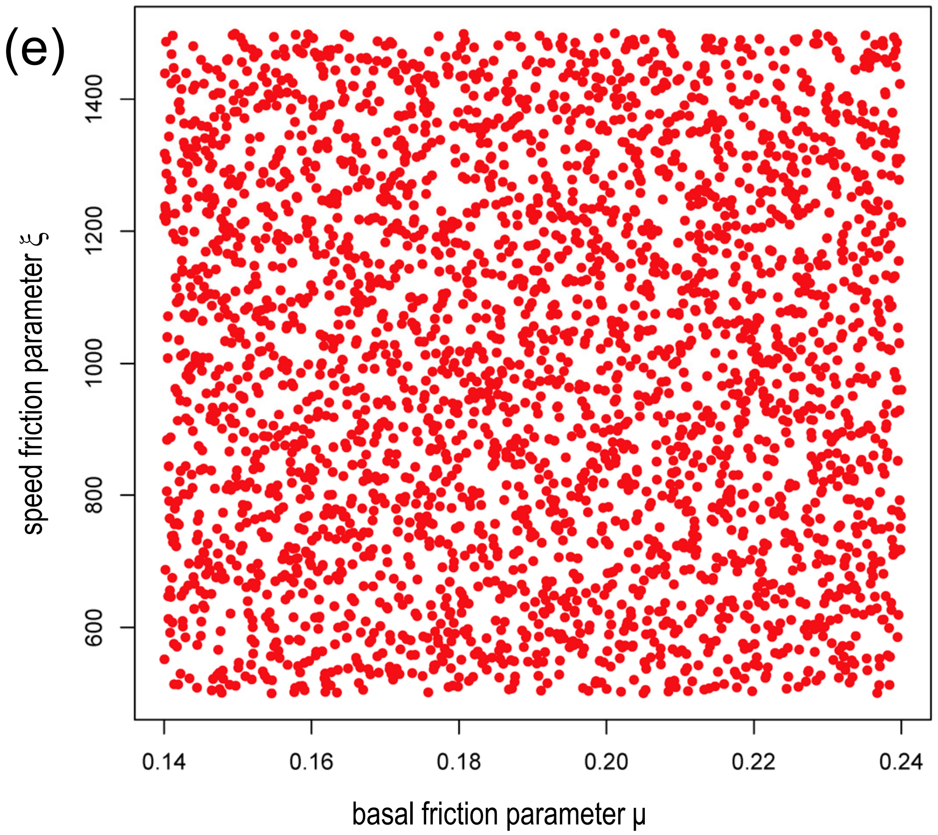
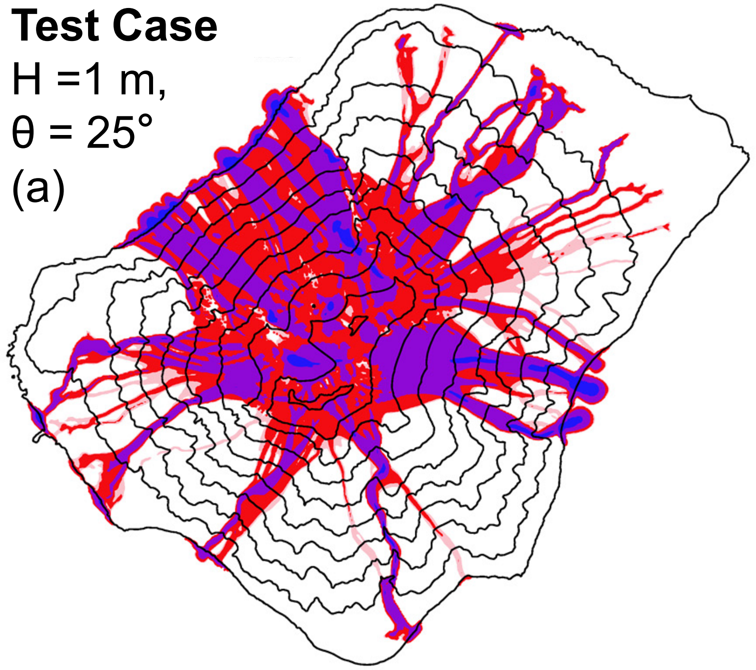


Fig. (e) Uniform LHS enhanced by relying on 5D orthogonal arrays. 3125 samples.
(Bevilacqua et al, 2019; 2021)

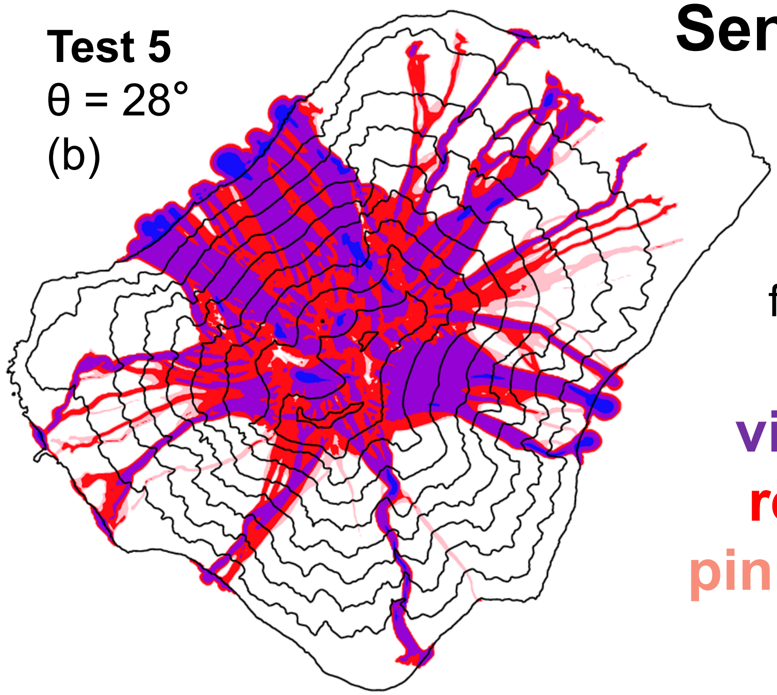
The uncertainty affecting **friction parameters** within the considered ranges **has limited effects** on the invaded areas.
Affected basins do not change and PDCs reach the coast anyway in most valleys.

Sensitivity to source thickness and slope threshold

Test Case
H =1 m,
θ = 25°
(a)



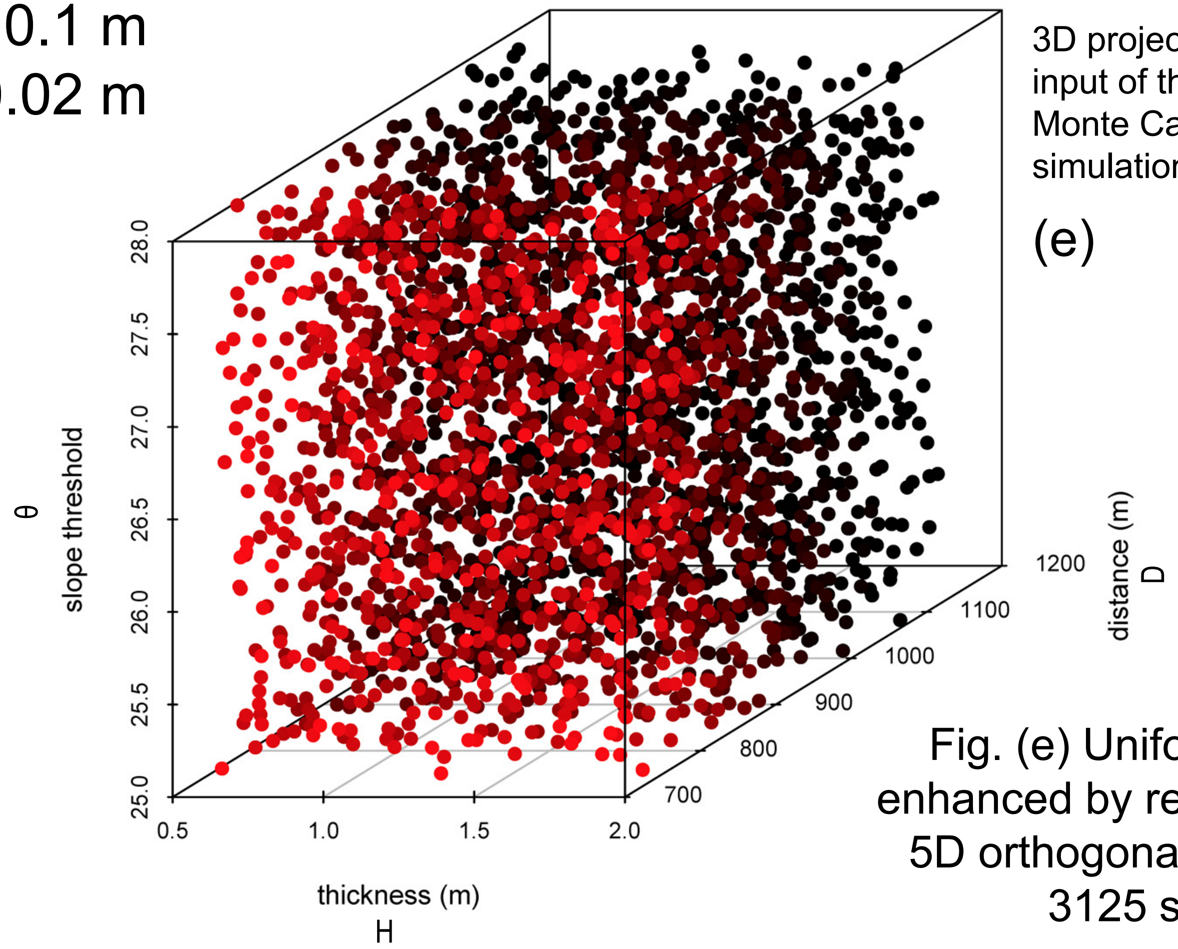
Test 5
θ = 28°
(b)



source thickness - H ∈ [0.5, 2] m
Bertagnini et al., 2011; Di Roberto et al., 2014

DEM slope threshold - θ ∈ [25°, 28°] m
Nolesini et al., 2013; Nemeth and Kereszturi, 2015

LEGEND
flow thickness
blue > 5m
violet > 1 m
red > 0.1 m
pink > 0.02 m

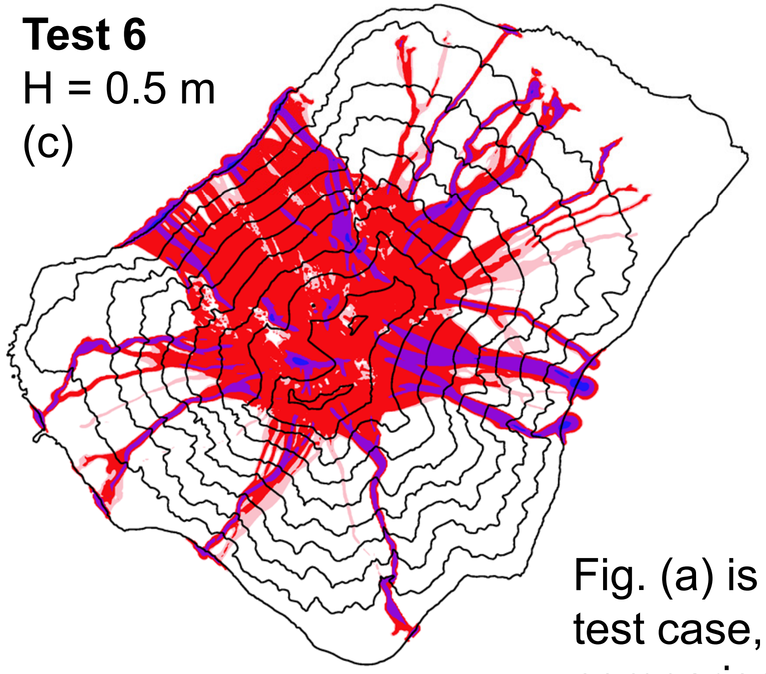


3D projection input of the Monte Carlo simulation

(e)

Fig. (e) Uniform LHS enhanced by relying on 5D orthogonal arrays. 3125 samples.

Test 6
H = 0.5 m
(c)



Test 7
H = 2 m
(d)

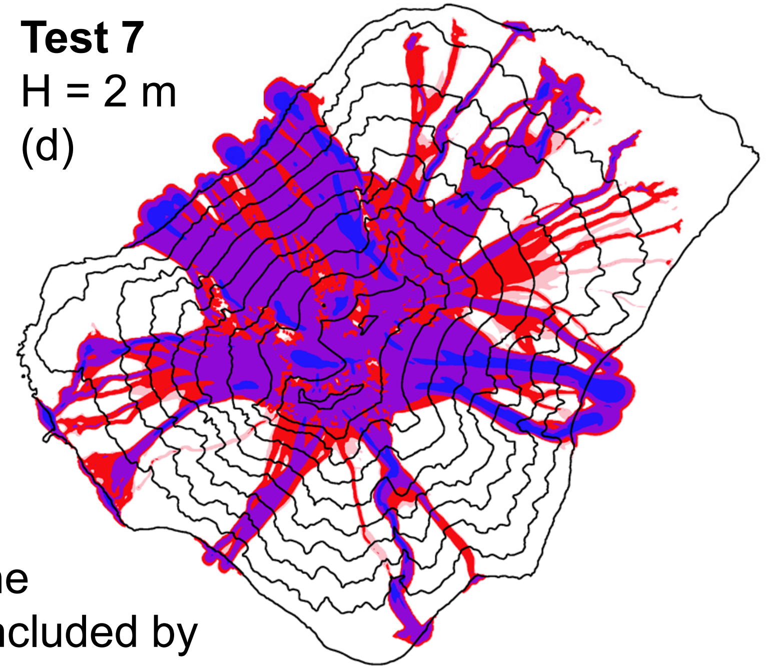


Fig. (a-d) are all related to maximum flow thickness.

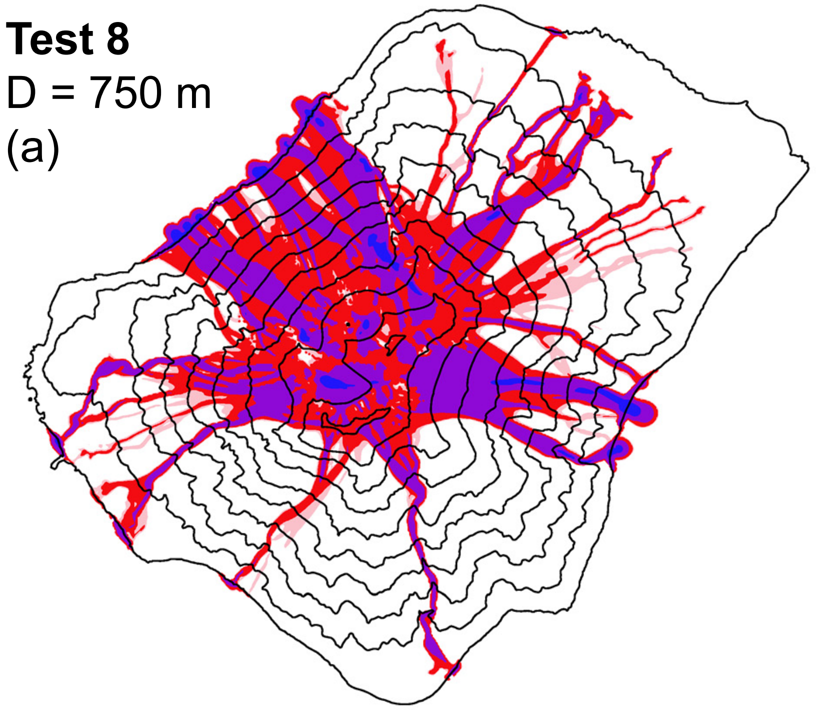
Fig. (a) is the test case, included by comparison.
Fig. (b) varies the DEM slope threshold θ, figs. (c,d) the source thickness H.

The uncertainty affecting **source deposit thickeness H** directly affects the maximum flow thickness, which increases almost linearly with H. Invaded areas are also **enlarged**. The uncertainty affecting **DEM slope threshold θ** has minor effects.

Sensitivity to the distance threshold

These tests do not change the deposit thickness H = 1 m and DEM slope threshold θ = 25°, and assume the same friction parameters of the reference example.

Test 8
D = 750 m
(a)



Test Case
D = 875 m
(b)

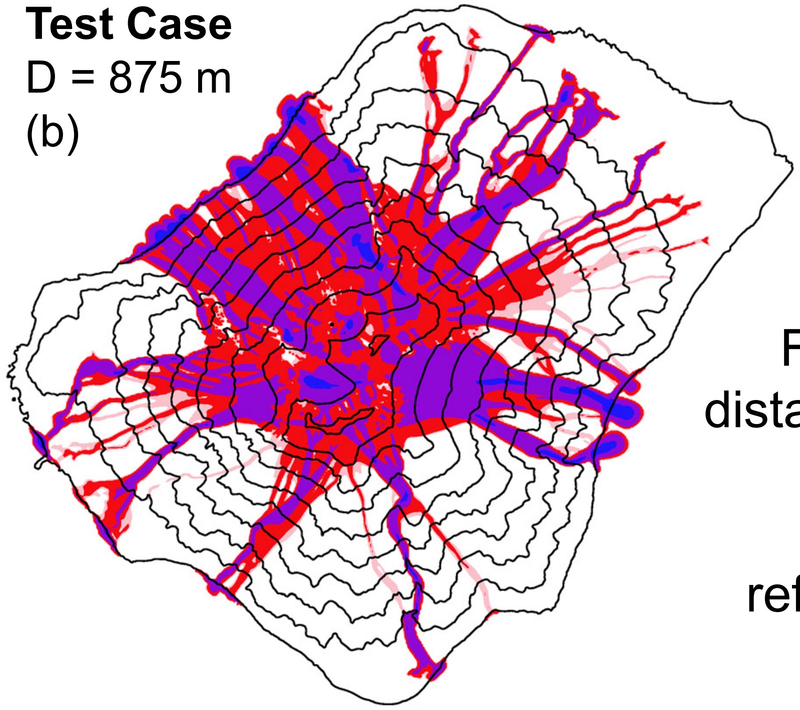
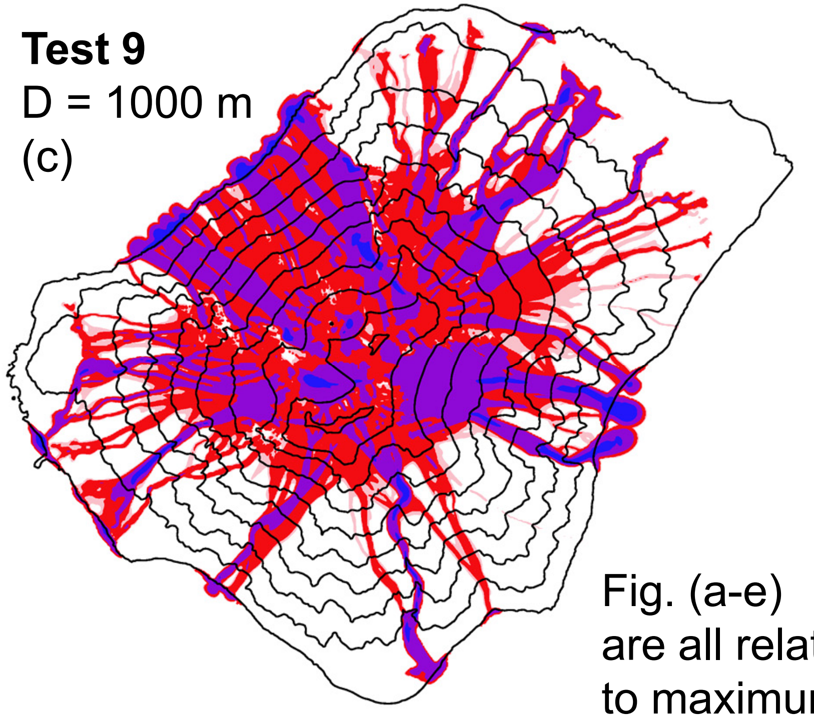


Fig. (a-d) vary the distance threshold D.

Fig. (b) is the reference example, included by comparison.

The uncertainty affecting **distance threshold D has significant effects**, especially on the affected basins and therefore on the invaded area.

Test 9
D = 1000 m
(c)



Test 10
D = 1125 m
(d)

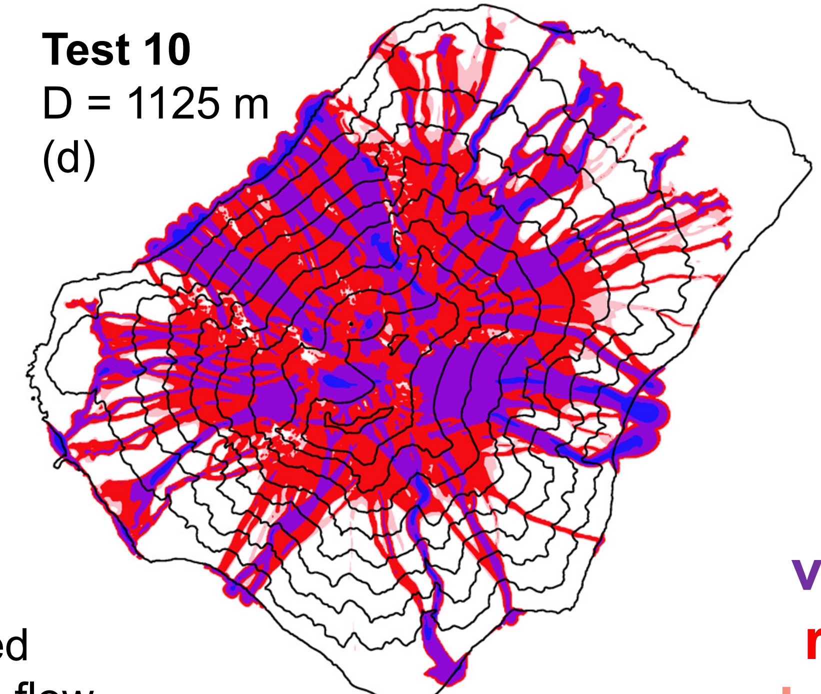
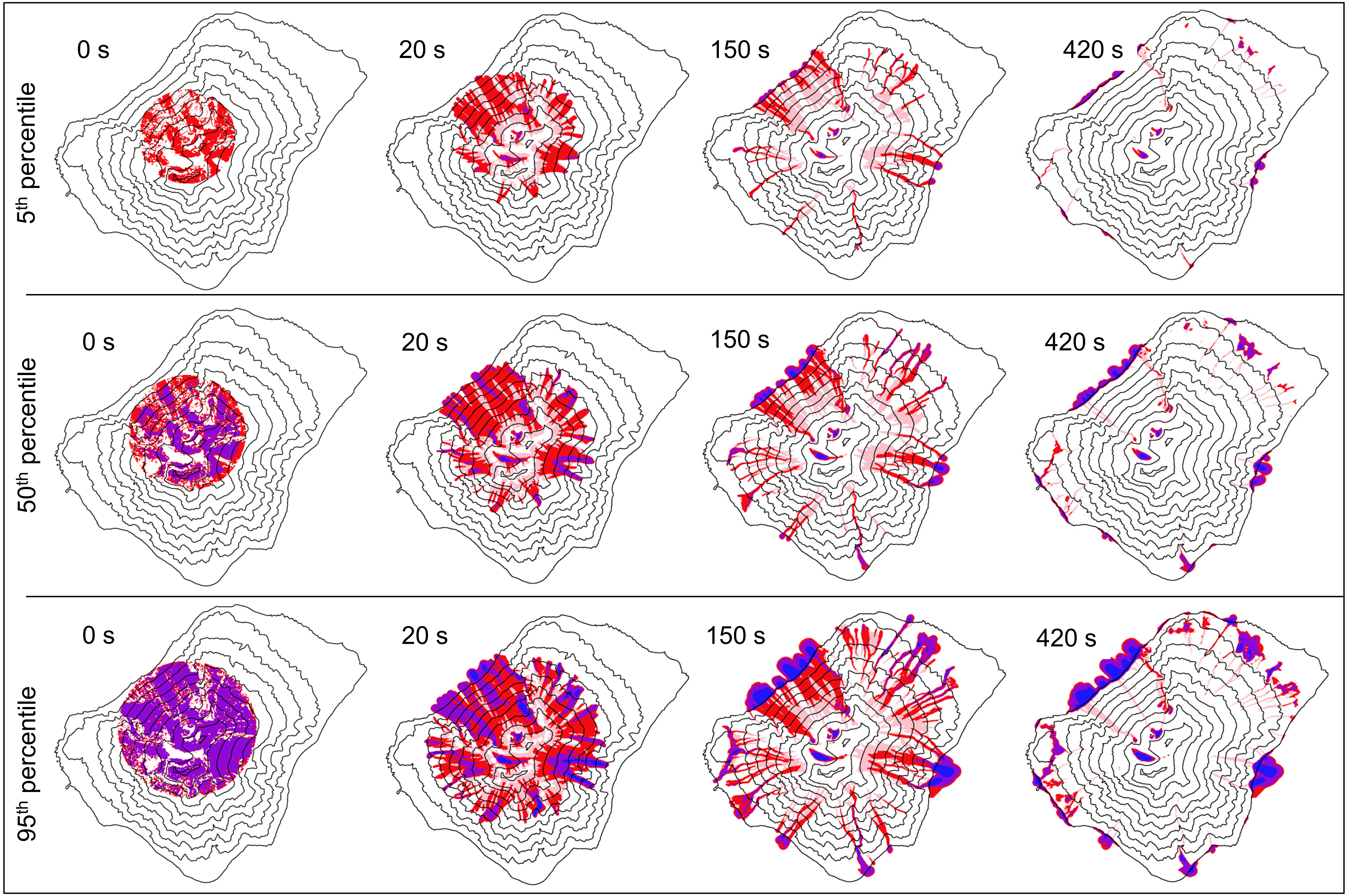


Fig. (a-e) are all related to maximum flow thickness.

LEGEND
flow thickness
blue > 5m
violet > 1 m
red > 0.1 m
pink > 0.02 m

The determination of the appropriate areal extension of the collapsing deposit is particularly important.

Monte Carlo simulation - 5th, 50th, 95th percentile values of flow thickness



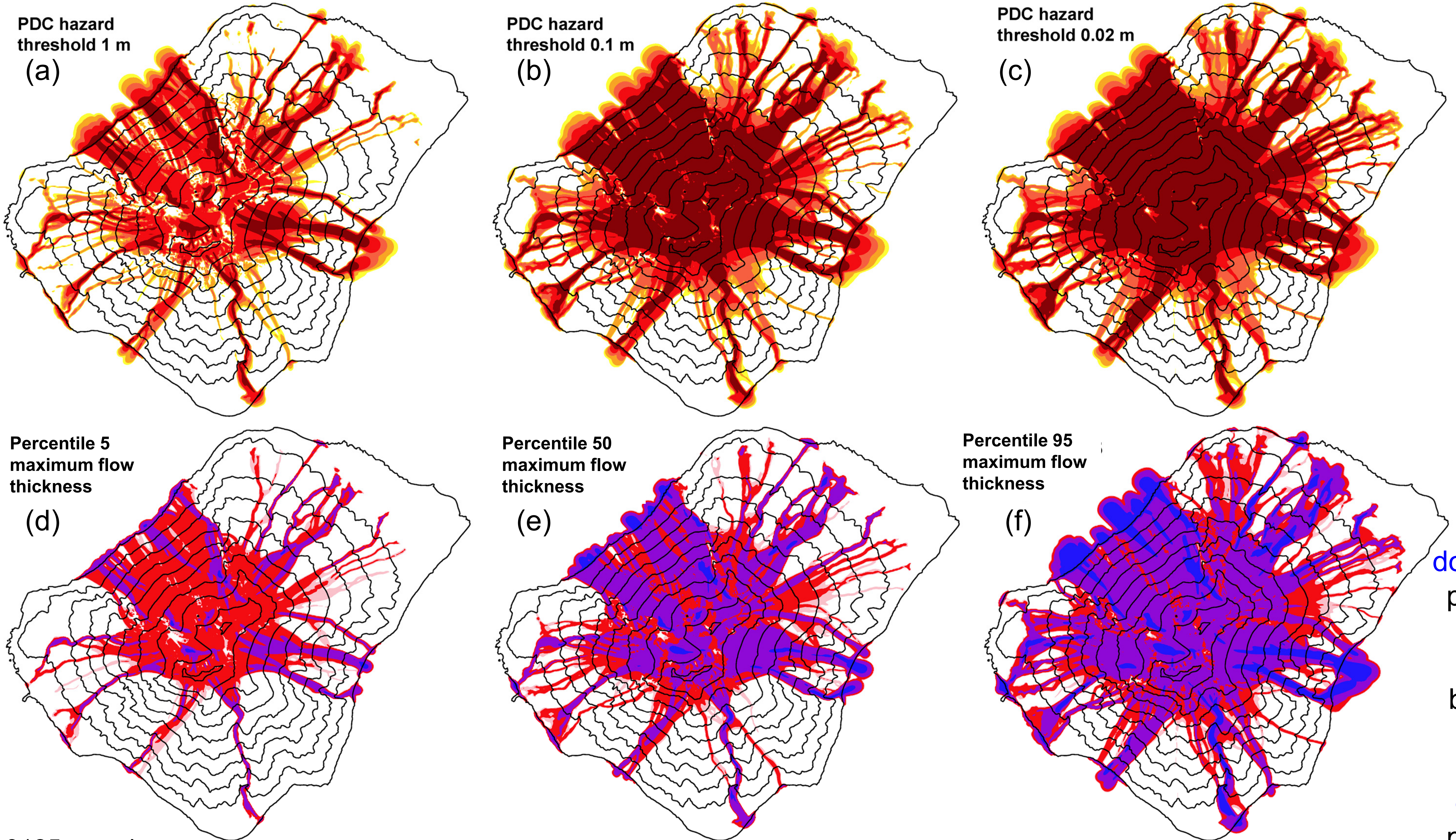
This simulation assumes the collapse of pyroclastic deposits in all basins, aiming at constraining the entire area potentially affected by these phenomena.

Historical PDCs originating from the paroxysms typically affected a limited number of basins.

The partitioning of source area enables restricting the simulations to the PDCs originating in the selected basins.

LEGEND
flow thickness
blue > 5m
violet > 1 m
red > 0.1 m
pink > 0.02 m

Preliminary hazard maps - axisymmetic source area



3125 samples

LEGEND

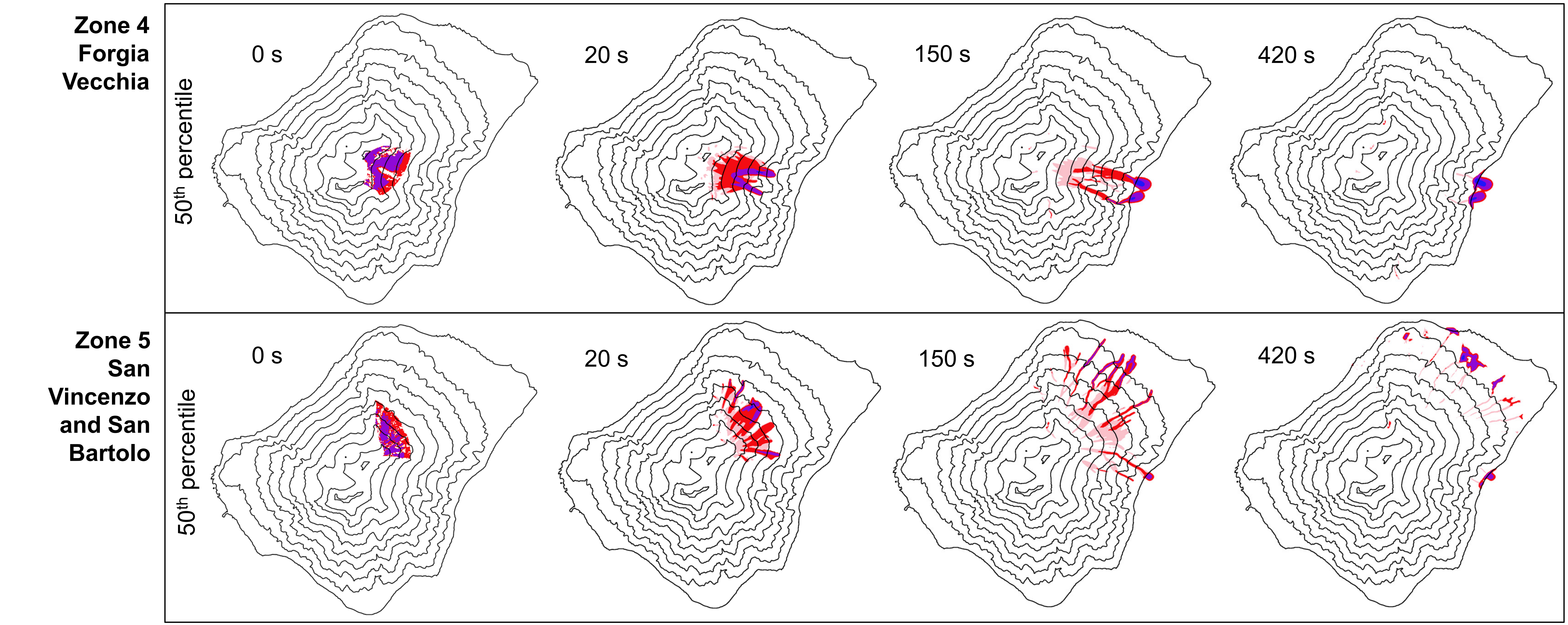
PDC hazard
brown > 95%
red > 50%
tomato > 25%
orange > 10%
yellow > 5%

flow thickness
blue > 5m
violet > 1 m
red > 0.1 m
pink > 0.02 m

Our model focuses on the dominantly-frictional part of these flows.

We are defining a buffer of inundated area for the more dilute and dominantly-inertial part of these flows.

Monte Carlo results of Zones 4 and Zone 5 - median values of flow thickness

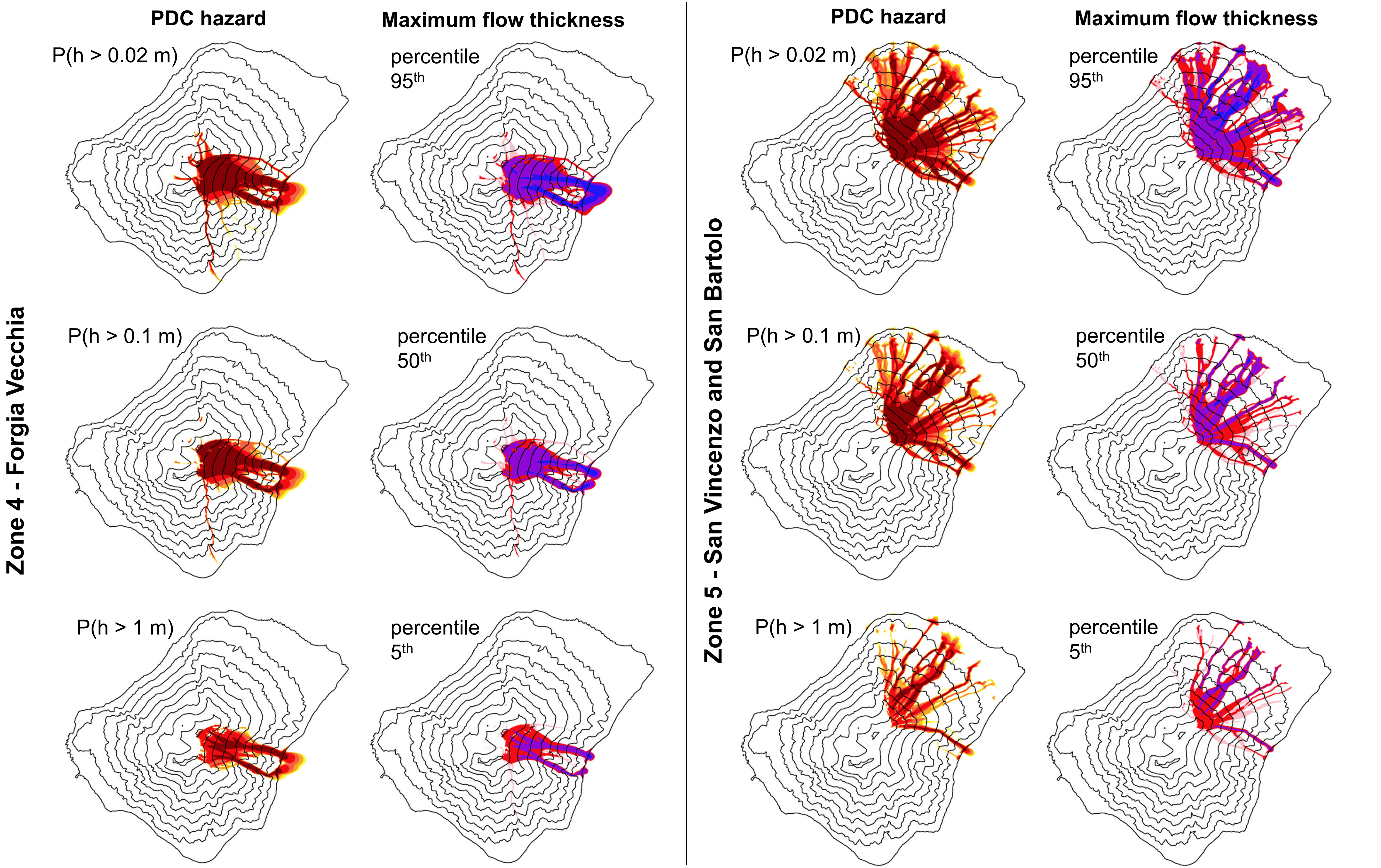


This simulation assumes the collapse of pyroclastic deposits in **two selected basins**, which are those containing the PDCs in 1930 and 1944.

Further decomposition of the basins is under process, e.g. zone 5 (San Vincenzo and San Bartolo) contains the source of 1930 plus a few additional basins.

LEGEND
flow thickness
blue > 5m
violet > 1 m
red > 0.1 m
pink > 0.02 m

Preliminary hazard maps - Zones 4 and 5



Results based on an axysimmetric source deposit are essentially equivalent to **enveloping** those of the single zones.

LEGEND

PDC hazard

brown > 95%
red > 50%
tomato > 25%
orange > 10%
yellow > 5%

flow thickness

blue > 5m
violet > 1 m
red > 0.1 m
pink > 0.02 m

Main results

- We have run Monte Carlo **simulations of secondary PDCs** at Stromboli, testing an input space made of two parameters related to the flow friction and three related to the source area and thickness.

- Our tests of sensitivity highlighted that:
  - friction parameters have small effects within the investigated range: **affected basins do not significantly change**, and most PDCs reach the coastline regardless. **Runouts** do not significantly change also for the PDCs that stop before the coastline.

  - source volume parameters produce greatest, also on the **affected basins**. The deposit thickness H directly influences the flow thickness, and also the distance threshold D can significantly change the **invaded area.**

- **Preliminary hazard maps** are the main product of this analysis.
  We partitioned the source area in six zones related to the basins draining towards different sectors of the coast.

  First we assumed the collapse of pyroclastic deposits in all basins, aiming at constraining the **entire area potentially affected**.
  We found that the maps obtained by the collapse of an axysimmetrically distributed source do not differ significantly from the **envelope** of those related to the examined zones.

Future work will explore:
- the **refinement** of input conditions, by further constraining with 1930/1944 field data, and by studying an arrested flow in 2019;
- the statistics of **invaded areas** by our simulations of the PDCs, also including a buffer for accounting the dilute part of the PDCs;
- preliminary **risk assessments** for the impact of the flows, by comparing the invaded areas with the map of buildings and roads.

This research is funded by the Dipartimento della Protezione Civile (DPC), as a part of the project *SISTEMA UNICO, 2022 - 2024.*
The talk does not necessarily represent official views and policies of DPC. The research is also supported by INGV project "*Reti Multiparametriche, Vulcani A7*".

PROTEZIONE CIVILE NAZIONALE

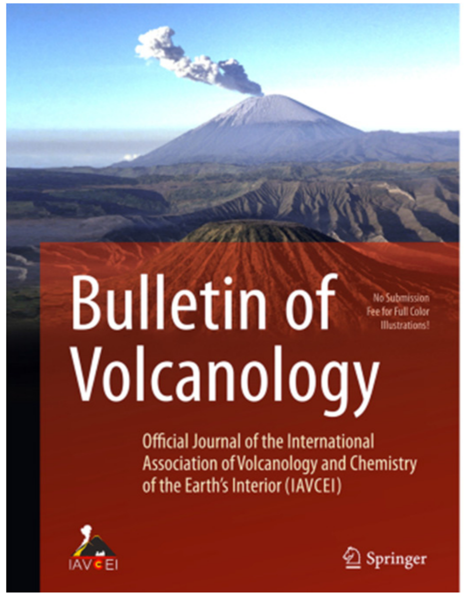
SPECIAL ISSUE:
UNCERTAINTY QUANTIFICATION IN VOLCANOLOGY: OBSERVATIONS, NUMERICAL MODELLING AND HAZARD/RISK ASSESSMENT

Guest Editors: A. Tadini, A. Bevilacqua, S. Massaro, P. Tierz, A. Aravena

We encourage to submit studies about Uncertainty Quantification related to:

- physical processes and/or hazard/risk assessments and maps
- numerical models and laboratory data in volcanology (model validation and benchmarking studies, multi-model approaches)
- hazard and risk communication, education programs and civil protection purposes

Bullettin of Volcanology (soon to be launched)



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Sangay volcano (Ecuador) (photo credits B. Bernard)


Vulcano (Italy) (photo credits S. Massaro)