ISTITUTO NAZIONALE
DI GEOFISICA E VULCANOLOGIA

PROTEZIONE CIVILE NAZIONALE

# Probabilistic hazard mapping of secondary pyroclastic density currents generated by paroxysm events at Stromboli (Italy)


Andrea Bevilacqua[(1)], Zeno Geddo[(1,2)], Alessio Di Roberto[(1)], Mattia De Michieli Vitturi[(1)], Tomaso Esposti Ongaro[(1)], Marina Bisson[(1)], Federico Di Traglia[(3)], Alessandro Fornaciai[(1)], Antonella Bertagnini[(1)], Massimo Pompilio[(1)], Patrizia Landi[(1)], Paola Del Carlo[(1)], Augusto Neri[(1)]

(1) *Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Pisa, Italia*
(2) *Scuola Normale Superiore, Classe di Scienze, Pisa, Italia*
(3) *Istituto Nazionale di Oceanografia e Geofisica Sperimentale*, Centro Ricerche Sismologiche, Trieste, Italia


Cities on
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Special session 2 - Impact of volcanic activity crises in places of tourist interest: Stromboli, Vulcano, White Island, Cumbre Vieja and other case studies


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# Problem and approach

The remobilization and gravitational collapse/sliding of fresh pyroclastic deposits emplaced on steep slopes can produce **secondary pyroclastic density currents** (PDC) at Stromboli, also called **pyroclastic avalanches**.

Most paroxysms produce PDCs in Sciara del Fuoco. In some cases, e.g. in 1944, 1930, and probably 1906 and others, PDCs affected the valleys **outside the Sciara**. In 1930 the PDC related to a paroxysmal eruption caused **four casualties**.

Our target is constraining the area potentially invaded by these PDC, a preliminary step towards hazard zonation **conditional** on the occurrence of such phenomenon.

Esposti Ongaro & De'Michieli Vitturi (2022), Session 2.02

We utilize the shallow water numerical solver **SW_VAR_DENS_MODEL** (https://github.com/demichie/SW_VAR_DENS_MODEL) over an input space constrained by previous studies (Di Roberto et al., 2014; Salvatici et al., 2016; de'Michieli Vitturi et al., 2019).

In particular:

1. we perform a preliminary **sensitivity analysis**, varying **one by one** six key input parameters;
2. we run the **Monte Carlo simulation** over a multidimensional input space (3125 samples);
3. we test the effect of constraining the source volume by the **elevation a.s.l.** or by the **distance from the craters**;
4. we evaluate how such source volume can be partitioned in the **main watershed basins**.

We present **preliminary results**, aimed at the exploration of the input space and of the effect of modeling assumptions.

# 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

DEM 10 m cellsize, total time 7'

We adopt **two alternative approaches** to constrain the source volume extent, i.e. by using an elevation threshold Y or a distance threshold D.

The distance D is a **more physically appropriate** constraint than elevation Y, but less easy to collect from historical accounts and field observations of past deposits.

The range of distances that we preliminarily assumed is generally consistent with:
- field observations of the paroxysms that generated PDCs (Di Roberto et al, 2014)
- elevation thresholds, in terms of covered area, but not equivalent.

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

- two parameters related to the flow friction modeling:
1) dry friction parameter - μ
2) viscous-turbulent friction parameter - ξ [$m^2/s^2$]
(Voellmy, 1955; Salm et al., 1990; Salm, 1993)

- four parameters related to the source volume:
3a) elevation threshold - Y alternative to
3b) distance threshold - D

4) source thickness – H
5) slope threshold - min(θ)

INPUT PARAMETERS' RANGE
1) dry friction parameter - $\mu \in [0.14, 0.24]$
2) viscous-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

3a) elevation threshold - $Y \in [500, 700]$ m a.s.l.
3b) distance threshold - $D \in [750, 1125]$ m

4) source thickness - $H \in [0.5, 2]$ m
Bertagnini et al., 2011; Di Roberto et al., 2014

5) $\min\theta \in [25°, 28°]$; $\max\theta \in [35°, 38°]$
We assume $\max\theta = \min\theta + 10°$
Nolesini et al., 2013; Di Roberto et al., 2014;
Nemeth and Kereszturi, 2015

# Watershed basins and source partition

We **partitioned the Digital Elevation Map**, 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.

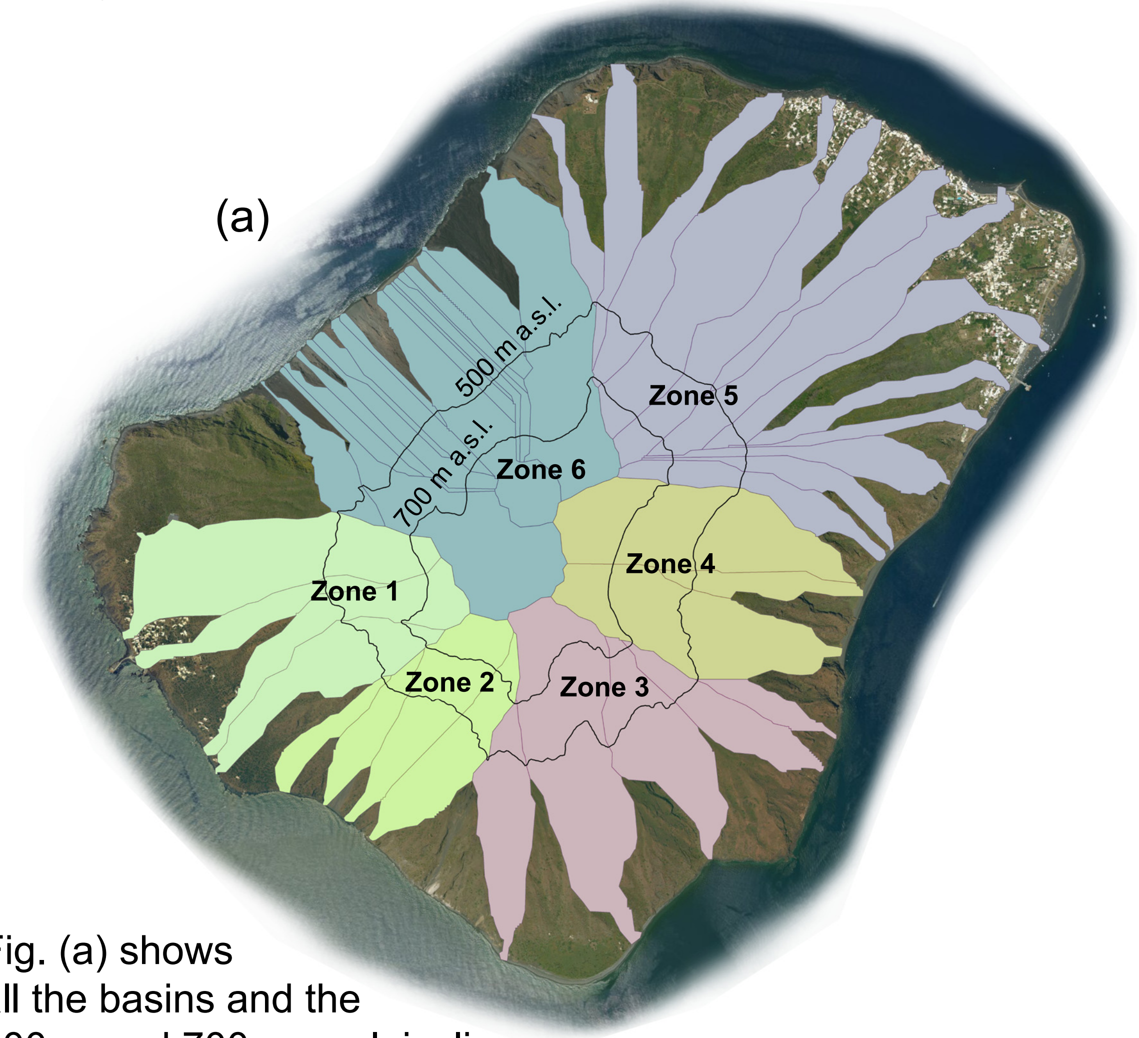



Fig. (a) shows all the basins and the 500 m and 700 m a.s.l. isolines.

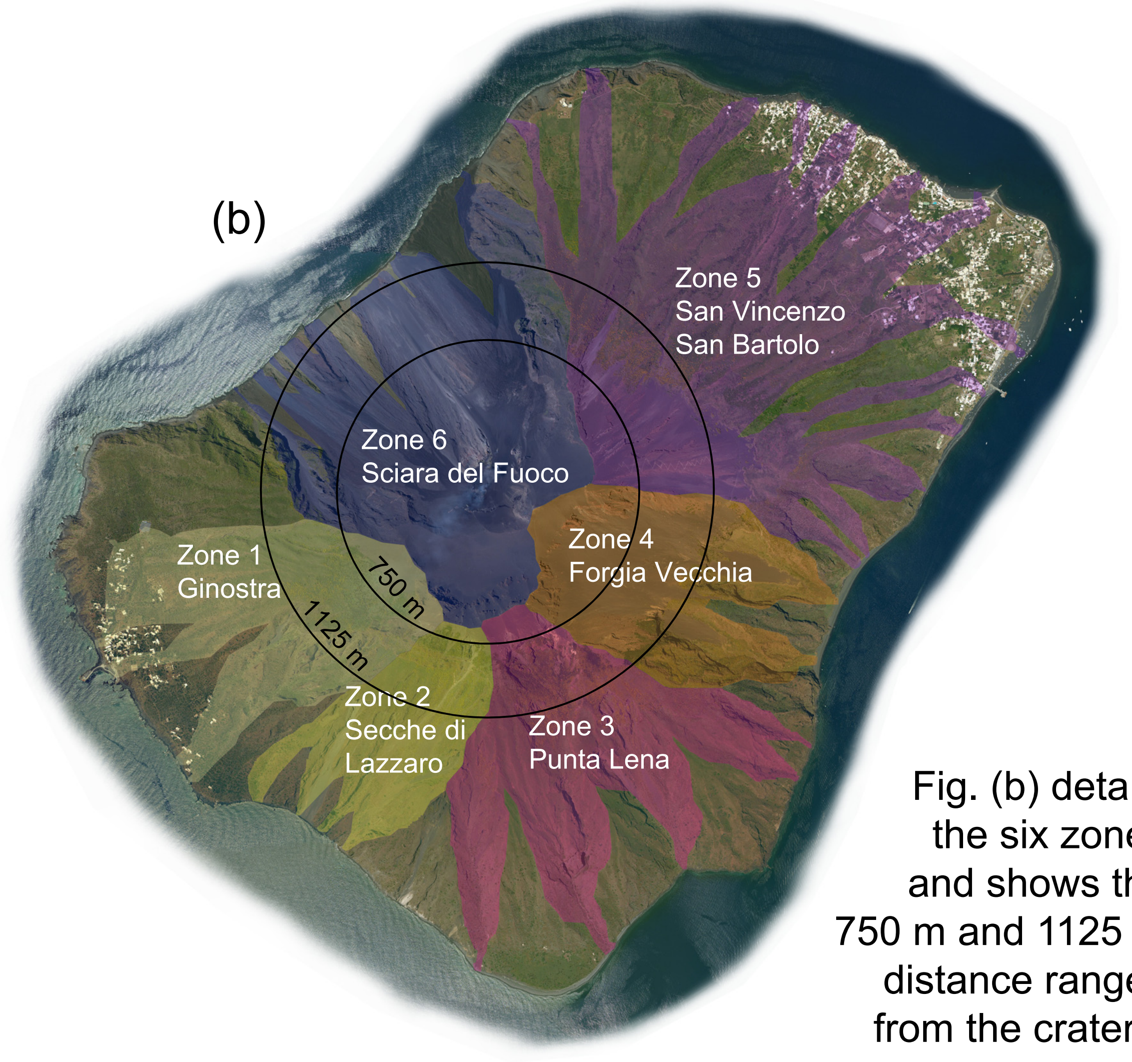
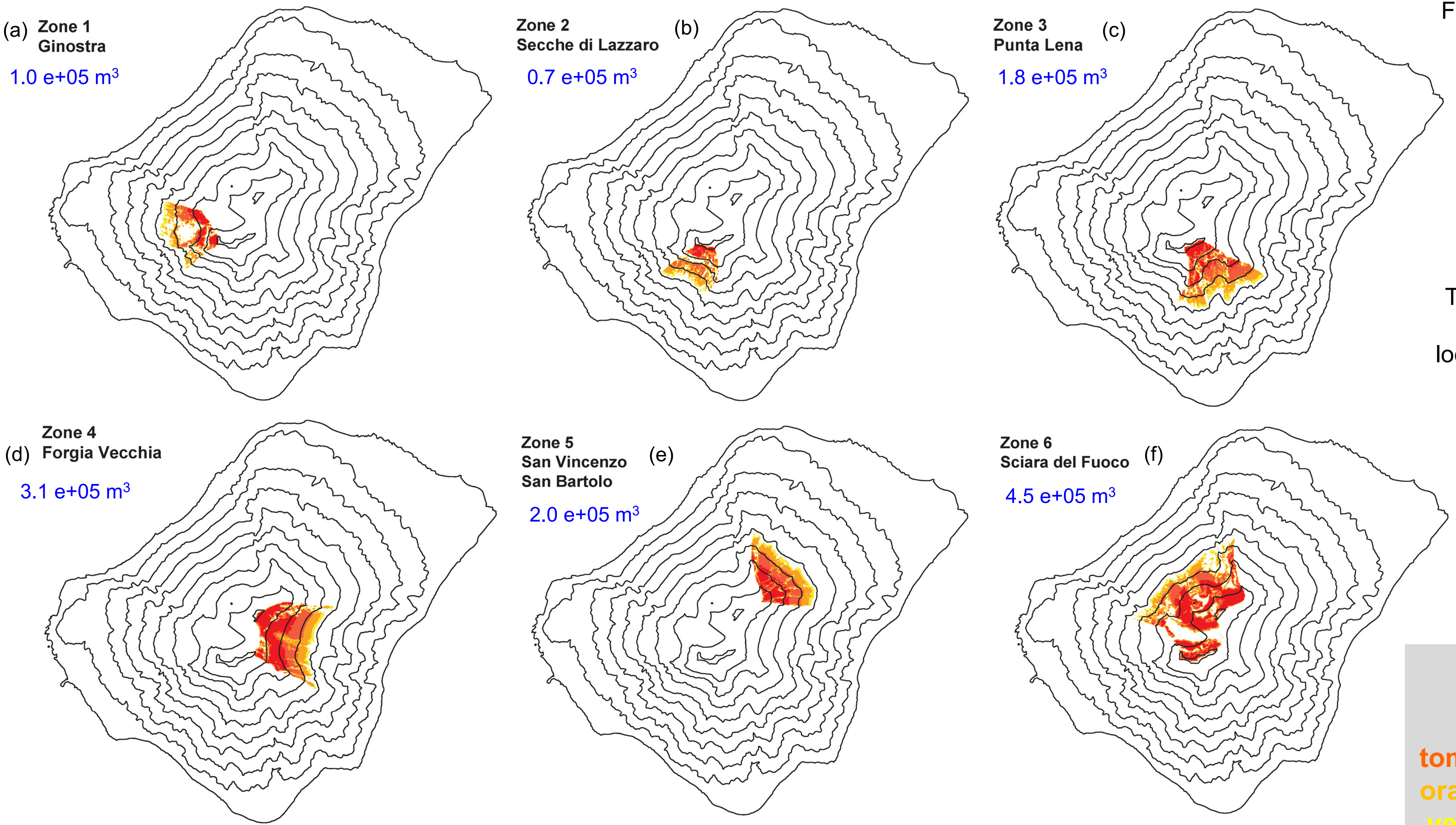



Fig. (b) details the six zones and shows the 750 m and 1125 m distance ranges from the craters.

# Partitioned source area – elevation threshold




Figures (a-f) are **the mean source maps** based on the elevation threshold.

Mean volumes are reported.

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

LEGEND

source thickness

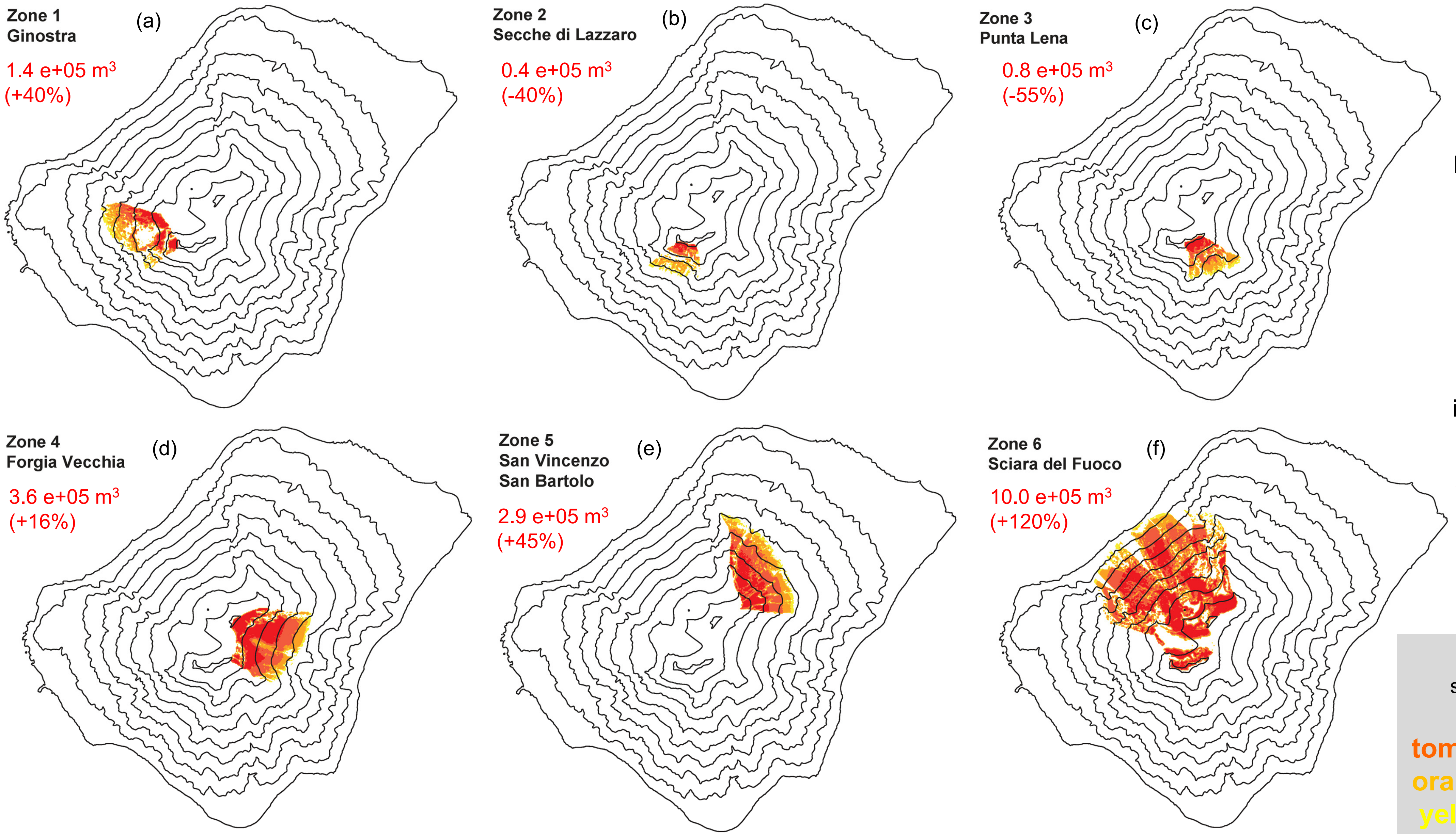
**red** > 1.0 m

**tomato** > 0.5 m

**orange** > 0.2 m

**yellow** > 0.1 m

# Partitioned source area – distance threshold



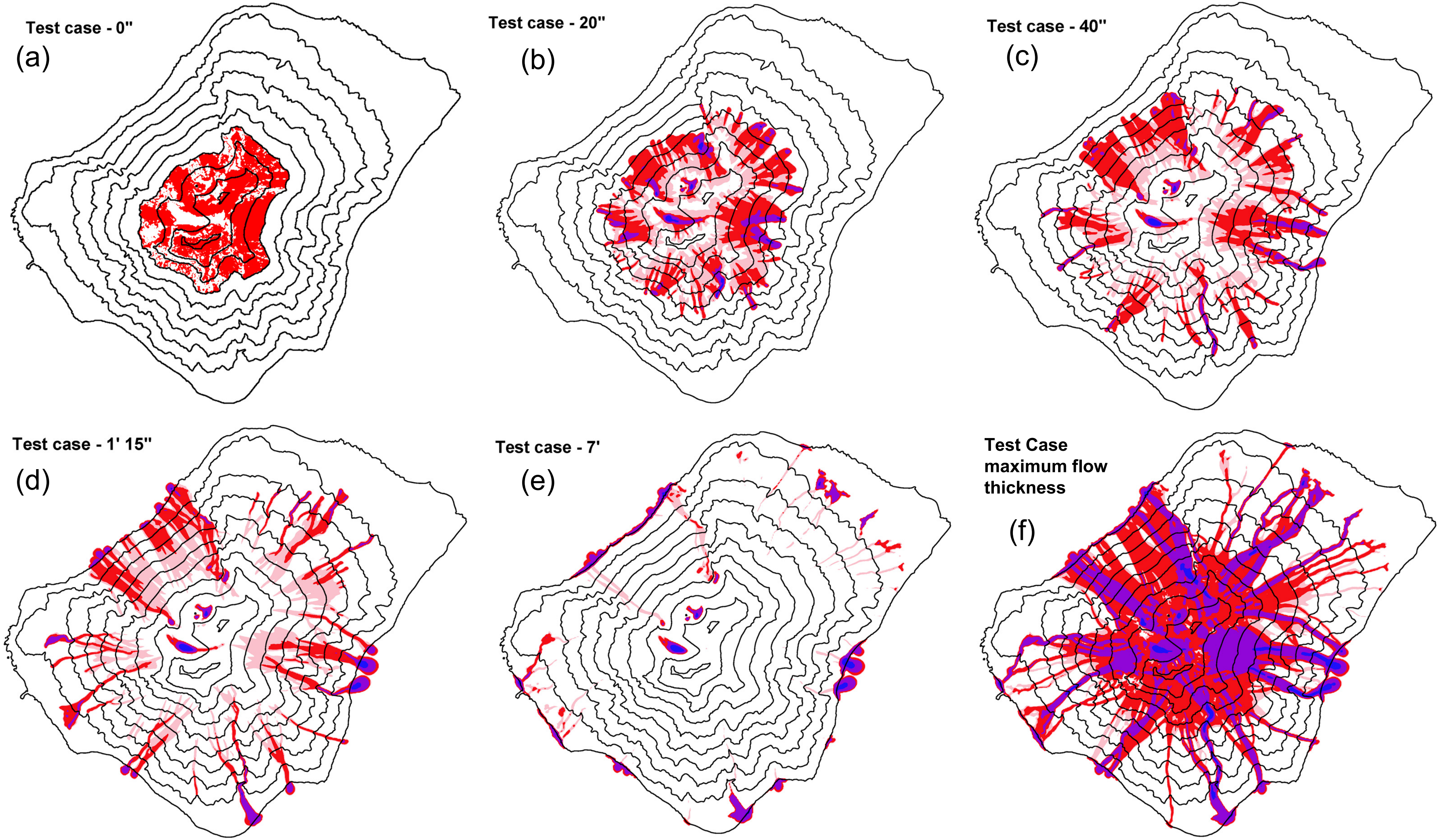

Figures (a-f) are the **mean source maps** based on the distance threshold.

Mean volumes are compared with those based on the elevation threshold.

The greatest increments are in **Sciara del Fuoco, San Vincenzo/San Bartolo, Ginostra**.

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

# Reference simulation – elevation threshold




<u>INPUT PARAMETERS</u>

$\mu = 0.19$

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

Calibrated parameters in Salvatici et al., 2016

$\theta \in [25°, 35°]$

H = 1 m

Y = 600 m a.s.l.

Di Roberto et al., 2014

Nolesini et al., 2013

These first simulations are based on the elevaton threshold.

LEGEND

flow thickness

**blue** > 5m

**violet** > 1 m

**red** > 0.1 m

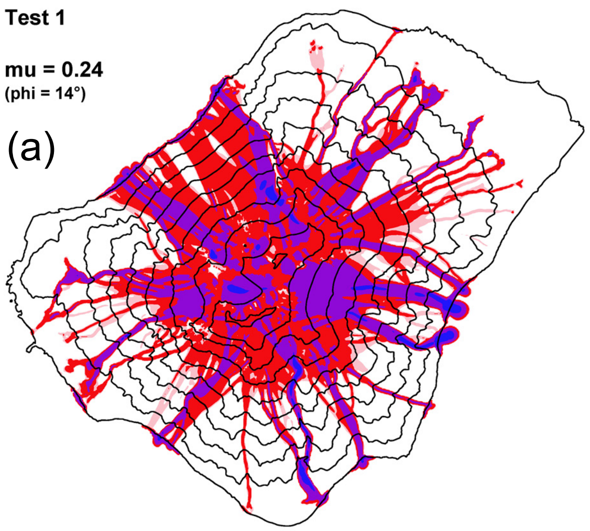
**pink** > 0.02 m

# Sensitivity to the flow friction parameters

Examples based on elevation threshold

dry friction parameter - μ ∈ [0.14, 0.24]

turbulent-viscous friction parameter - ξ ∈ [500, 1500] $m^2/s^2$



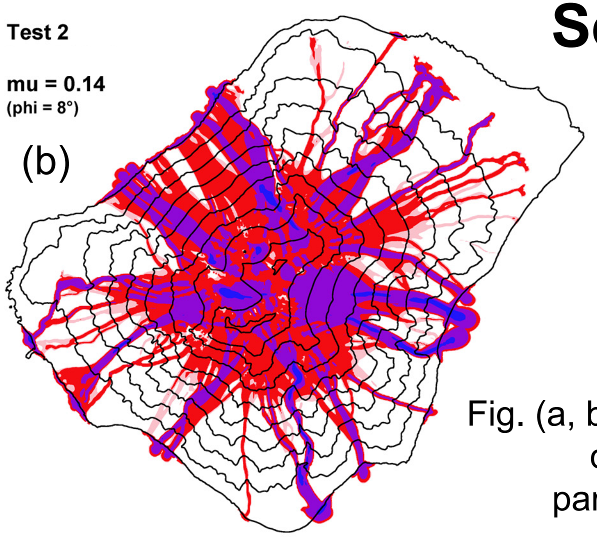
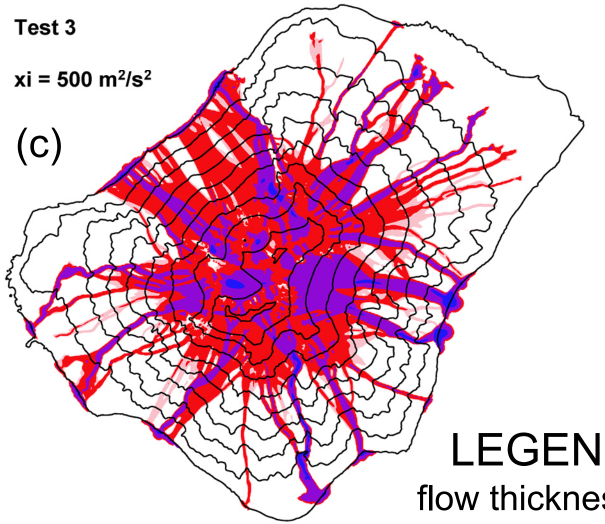




Fig. (a, b) vary the dry friction parameter μ.



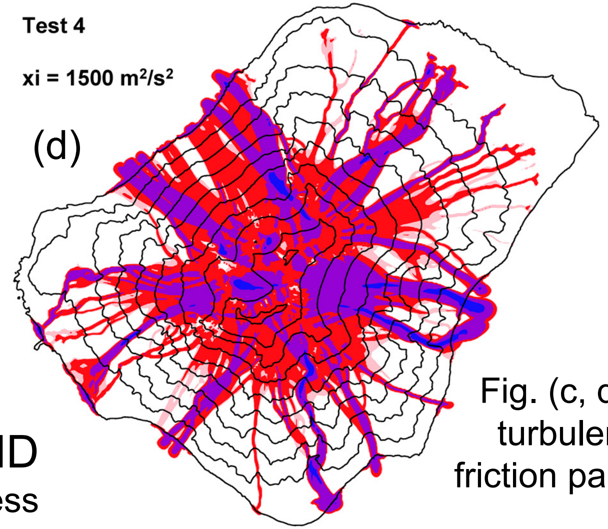




Fig. (c, d) vary the turbulent-viscous friction parameter ξ.

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.

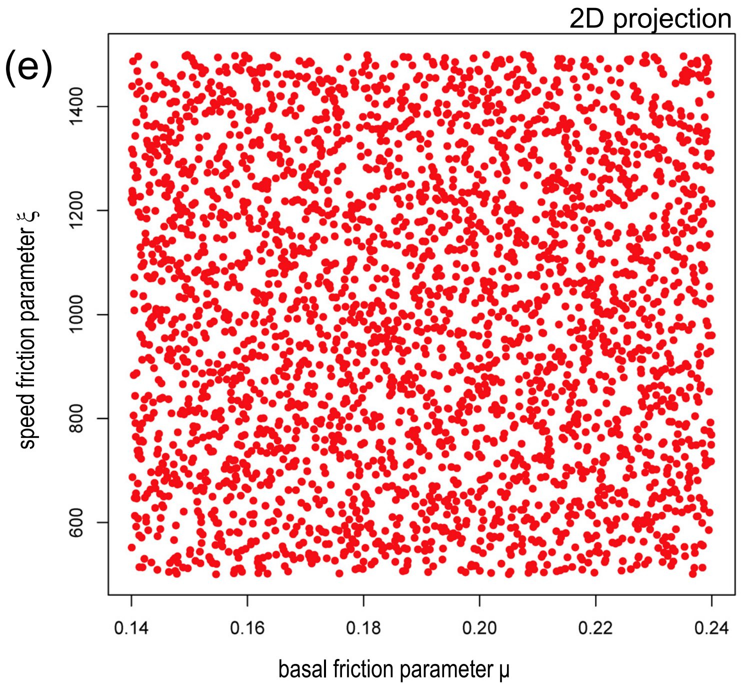
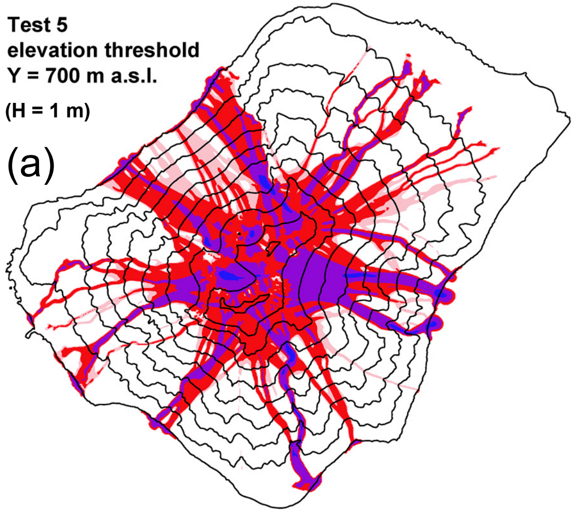



Fig. (e) Uniform LHS enhanced by relying on 5D orthogonal arrays. 3125 samples.
(Bevilacqua et al, 2019; 2021)

The uncertainty affecting **friction variables has limited effects** on the PDC propagation. Affected basins do not change and PDCs reach the coast anyway in most valleys.

# Sensitivity to elevation and thickness

elevation threshold - Y ∈ [500, 700] m a.s.l.
source thickness - H ∈ [0.5, 2] m



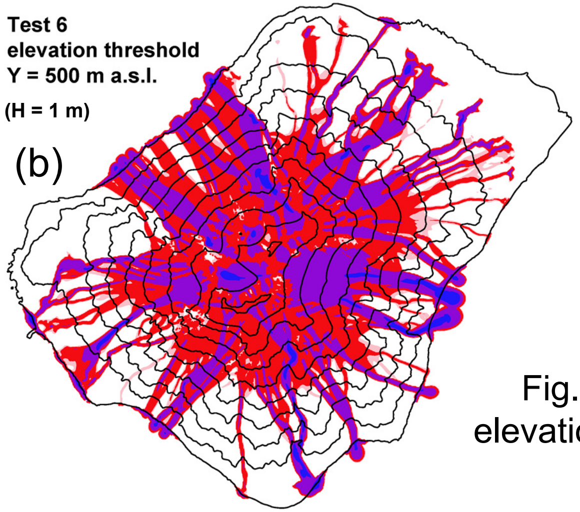




Fig. (a, b) vary the elevation threshold Y.

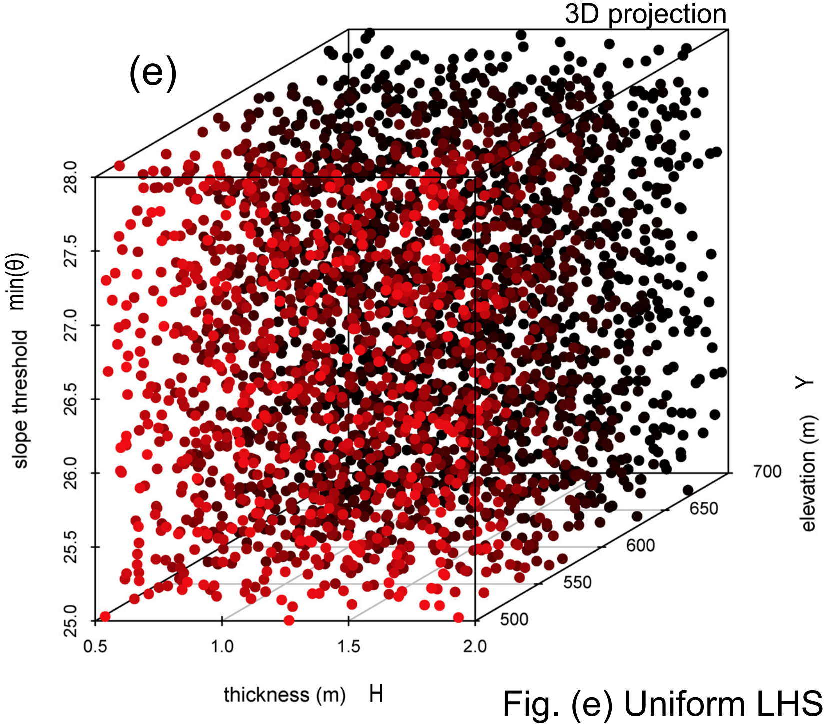
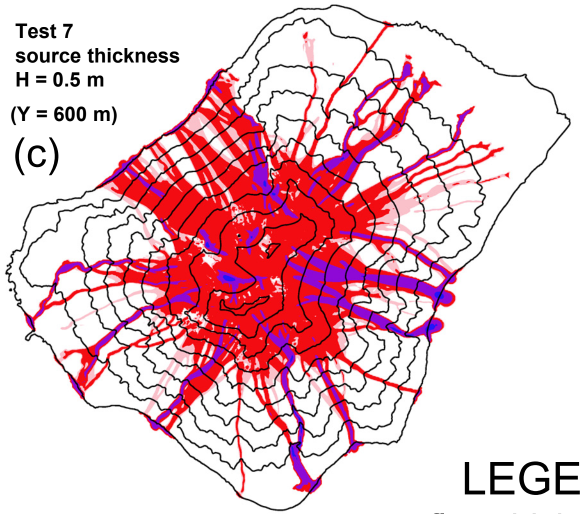



Fig. (e) Uniform LHS enhanced by relying on 5D orthogonal arrays. 3125 samples.



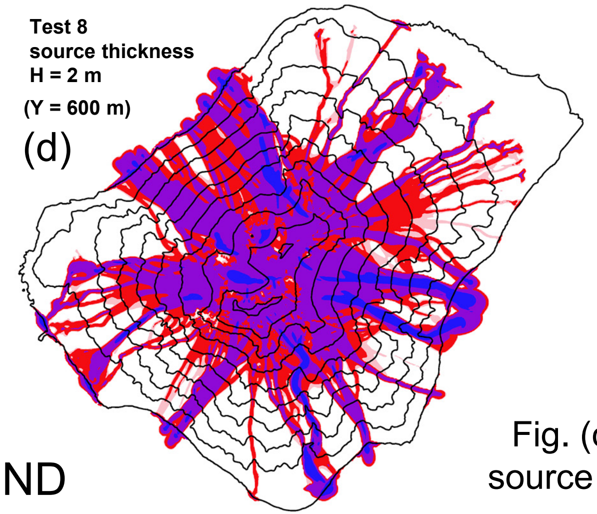




Fig. (c, d) vary the source thickness H.

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

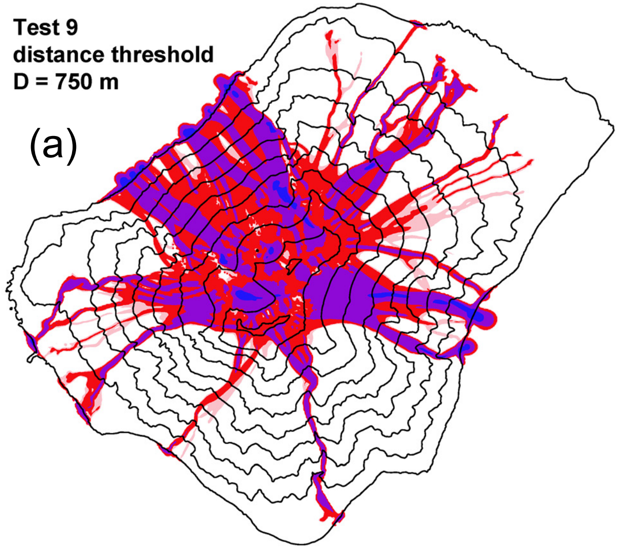
Fig. (a-d) are all related to maximum flow thickness.

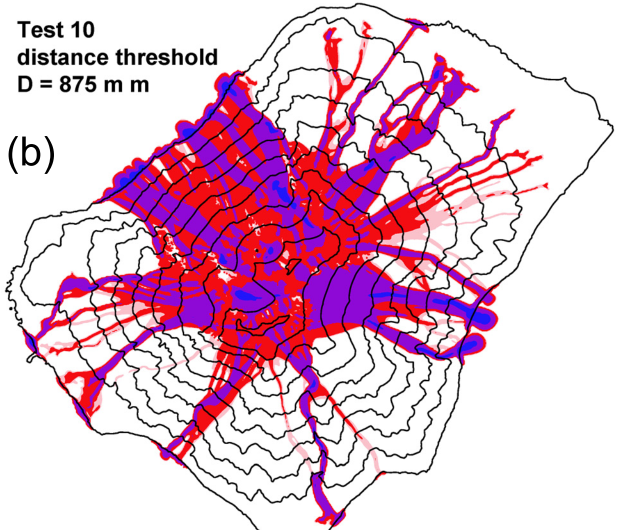
The uncertainty affecting **source volume variables has greatest effects**, with significant differences both on the affected basins and the runout.

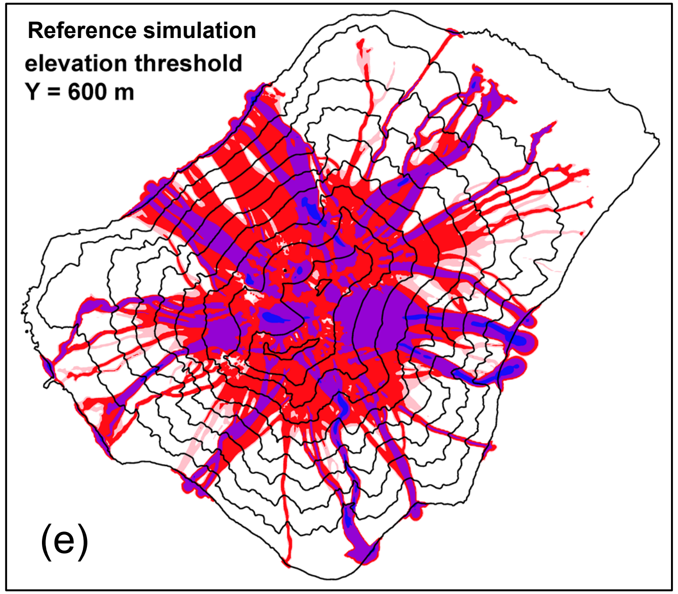
# Sensitivity to the distance threshold

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

Fig. (e) is based on the elevation threshold Y and included by comparison.

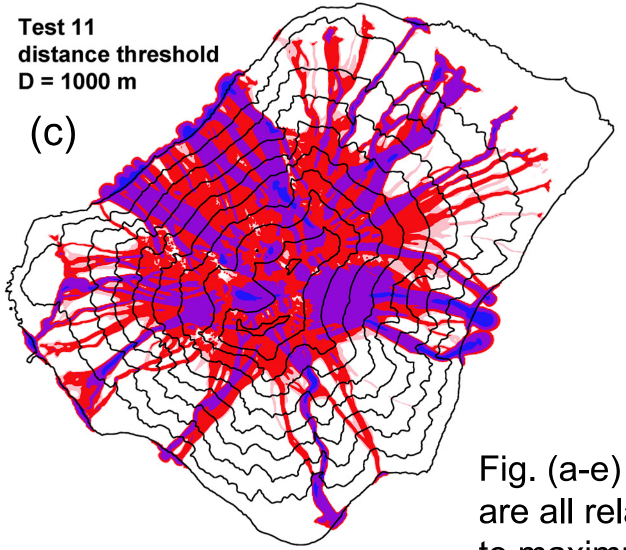



The hazard to the South is reduced, especially in (a) and (b).

In contrast, the hazard to the North is increased.



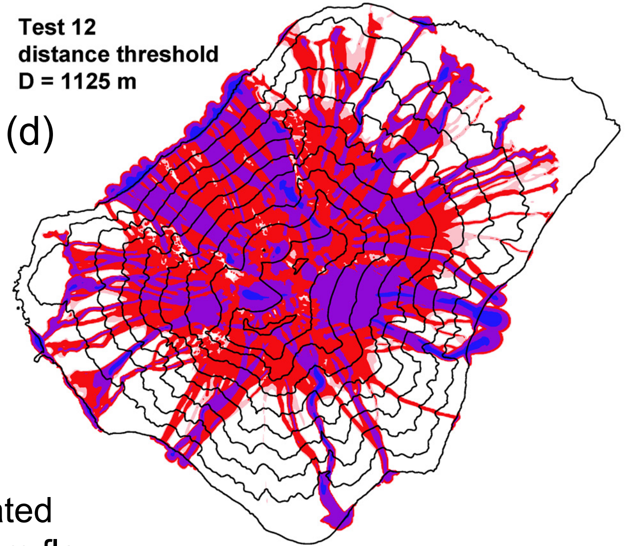




Fig. (a-e) are all related to maximum flow thickness.

LEGEND

flow thickness

**blue** > 5m

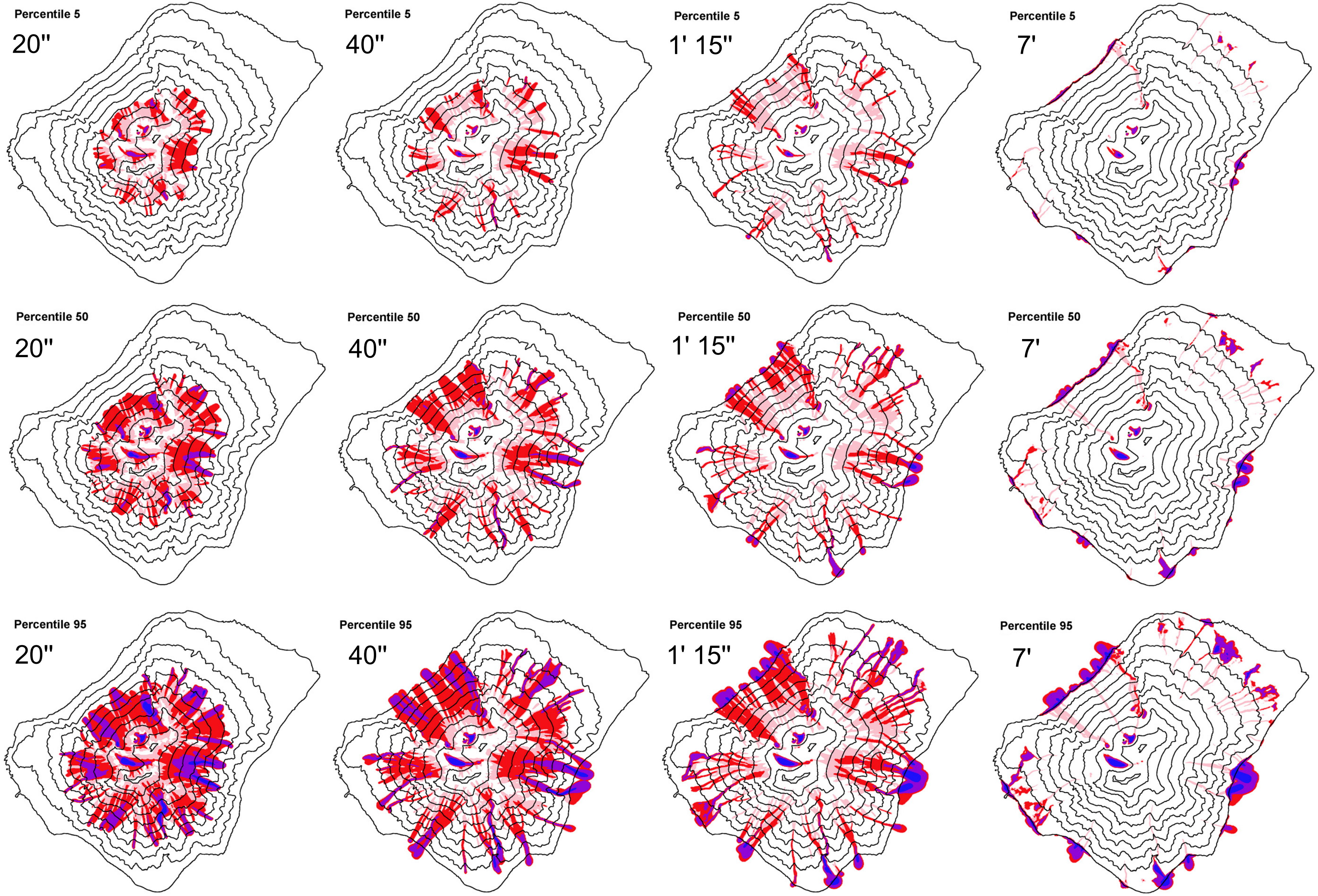
**violet** > 1 m

**red** > 0.1 m

**pink** > 0.02 m

# Monte Carlo results - percentile values $5^{th}$, $50^{th}$, $95^{th}$

This example is based on the elevation threshold.




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

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

The partitioning of source area is required to quantify the hazard conditional on the occurrence of a PDC.

LEGEND

flow thickness

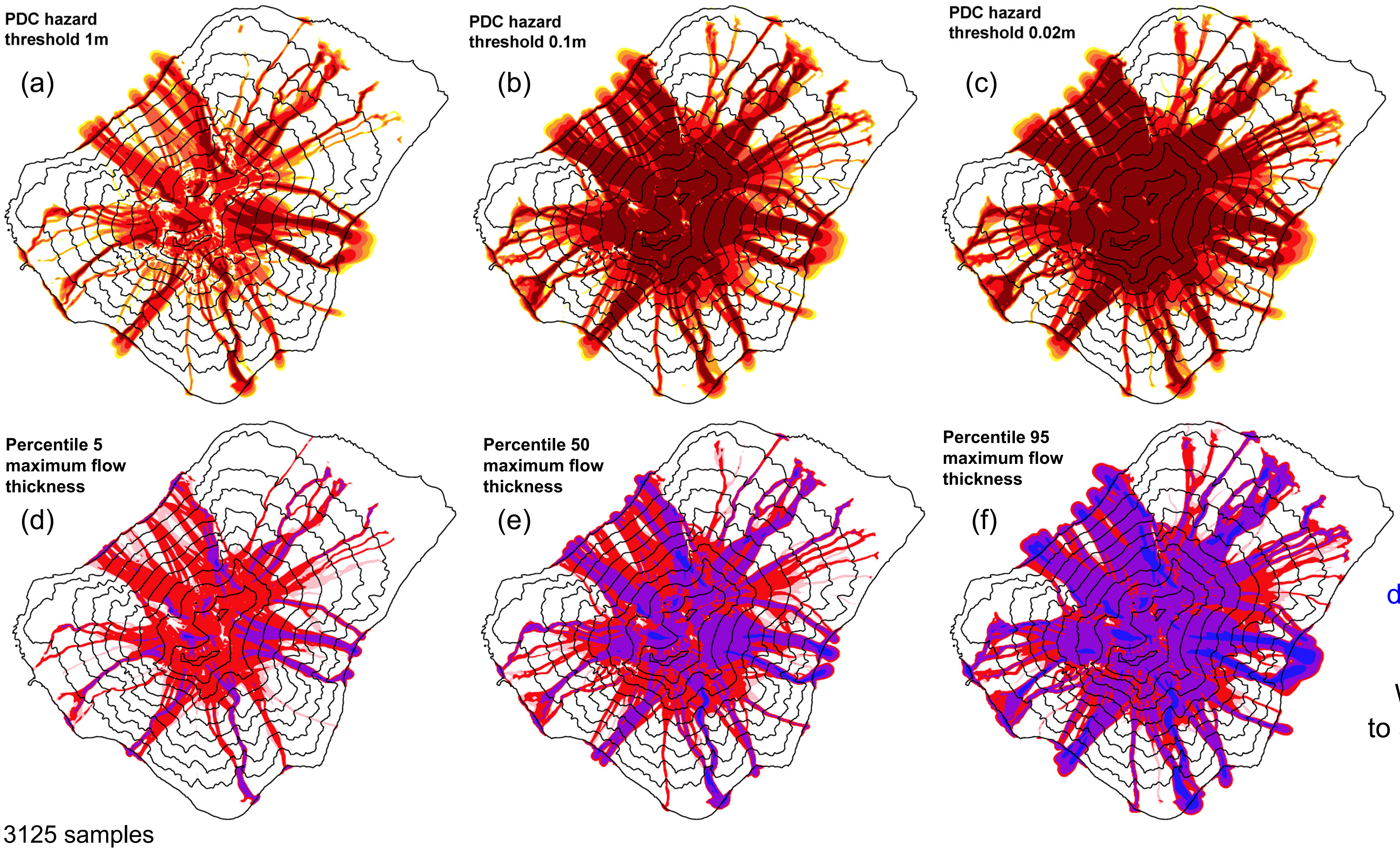
**blue** > 5m

**violet** > 1 m

**red** > 0.1 m

**pink** > 0.02 m

# Preliminary hazard maps - source area based on the elevation threshold




LEGEND

PDC hazard

brown > 95%

red > 50%

tomato > 25%

orange > 10%

yellow > 5%

flow thickness

blue > 5m

violet > 1 m

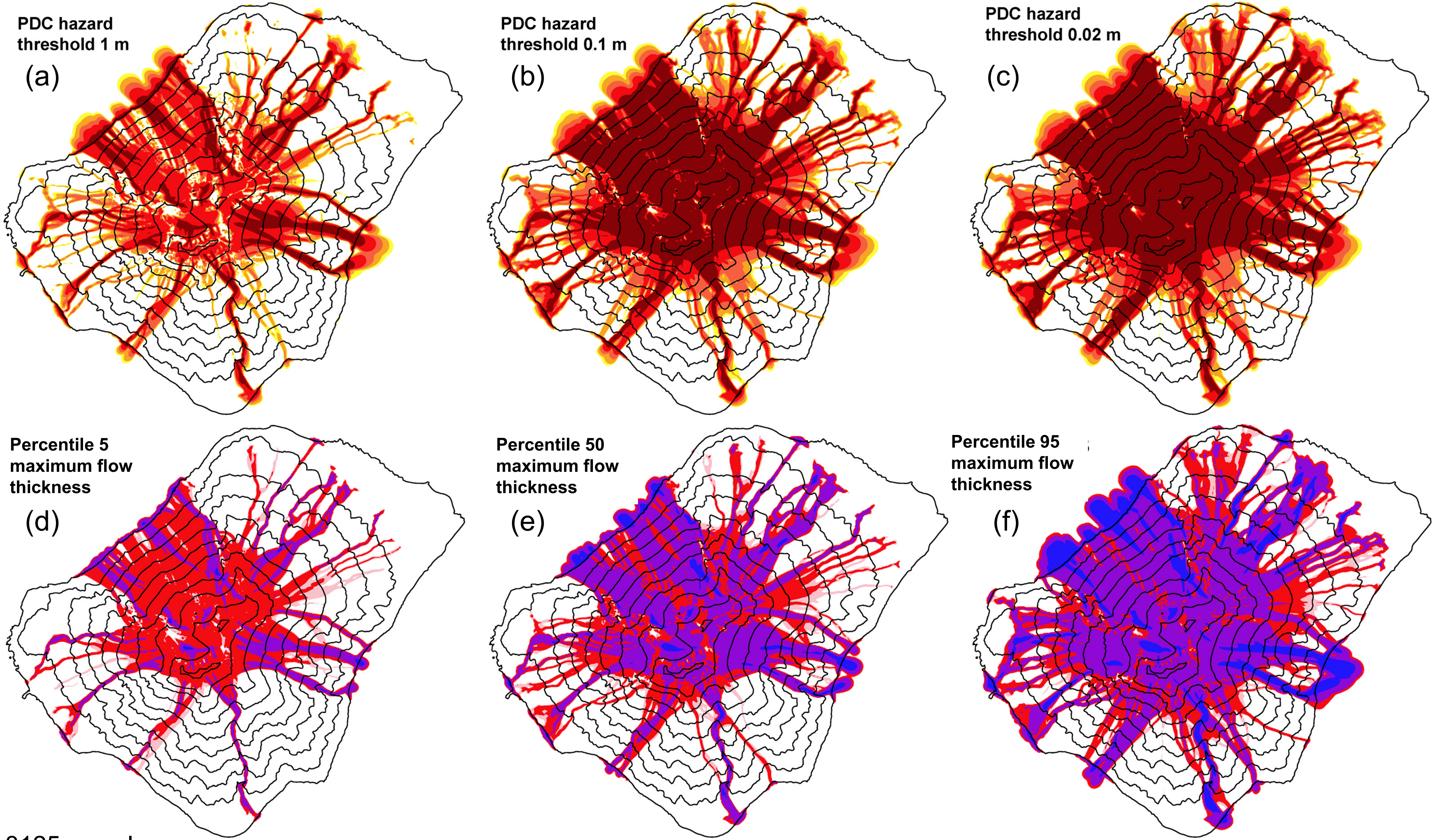
red > 0.1 m

pink > 0.02 m

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

We are considering to add a buffer for the more dilute and dominantly-inertial part of these flows.

# Preliminary hazard maps - source area based on the distance threshold




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

Compared to the results based on the elevation threshold, the hazard levels increase to the North and decrease to the South.

# Main results

- We have run Monte Carlo **pyroclastic avalanches simulations** of secondary PDCs at Stromboli, testing an input space made of two parameters related to the flow friction modeling and four related to the source volume.

- Our tests of sensitivity highlighted that:
  - friction parameters have relatively small effects within the range investigated: **affected basins do not change** and PDCs reach the coastline regardless.
  - source volume parameters produce greatest effects both on the **affected basins and the runout**.

- We partitioned the source area in **six zones** related to the watershed basins draining towards different sectors of the coast.

- Source maps based on the elevation can significantly differ from those based on the crater distance, depending on the basin. A source area formulation based on the distance from the craters produces a **shift towards NW**. According to that, the preliminary hazard to the South and SE is reduced; in contrast, to the North and NW it increases.

Future work will explore:
- the **refinement or extension** of the input spaces adopted, for a more strict connection to the **past erupted distributions**,
- the formulation of the **probability of occurrence** of such PDCs after a paroxysm, in each zone, based on all historical accounts,
- **risk assessments** for the impact of the flows, and hazard zonation of the **mass reaching the coastline** in the various sectors.

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The talk does not necessarily represent official views and policies of DPC. The research is also supported by INGV project "*Reti Multiparametriche, Vulcani A7*".