ISTITUTO NAZIONALE
DI GEOFISICA E VULCANOLOGIA

Ministero dell'Istruzione
dell'Università e Ricerca

Riunione progetto FISR Sale Operative Integrate e Rete di monitoraggio futuro

WP3 Nuovi Dati e Misure - *Coordinatore: F. Guglielmino (OE)*
TASK 2 - NUOVI MODELLI
Attività: *2.5.1 - Aggiornamento dinamico delle mappe di probabilità di apertura bocche eruttive, probabilità di occorrenza dell'eruzione e pericolosità da flussi piroclastici ai Campi Flegrei, tramite dati di monitoraggio.*
Referente: *A. Neri (PI)*

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Mattia de Michieli Vitturi (PI), Tomaso Esposti Ongaro (PI), Flora Giudicepietro (OV), Roberto Isaia (OV),
Giovanni Macedonio (OV), Stefano Vitale (OV, UNINA).

Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Pisa.

29 Maggio 2019, *Istituto Nazionale di Geofisica e Vulcanologia*, Roma.

Fasi delle attività 2.5.1, WP3, progetto FISR17 - SOIR

FASE 1: aggiornamento dinamico delle mappe di apertura bocca/fessura eruttiva.

FASE 2: modelli stocastici dell'effetto di potenziali precursori sulle stime temporali.

FASE 3: nuovi metodi probabilistici per la simulazione di flussi piroclastici al variare delle condizioni iniziali.

FASE 4: metodi di combinazione probabilistica ed analisi dei dataset di simulazioni pre-generate.

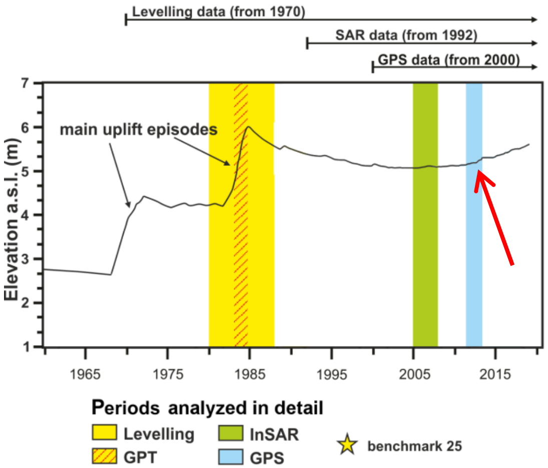
L’elenco completo dei relativi prodotti scientifici è fornito nel seguito, ed include:

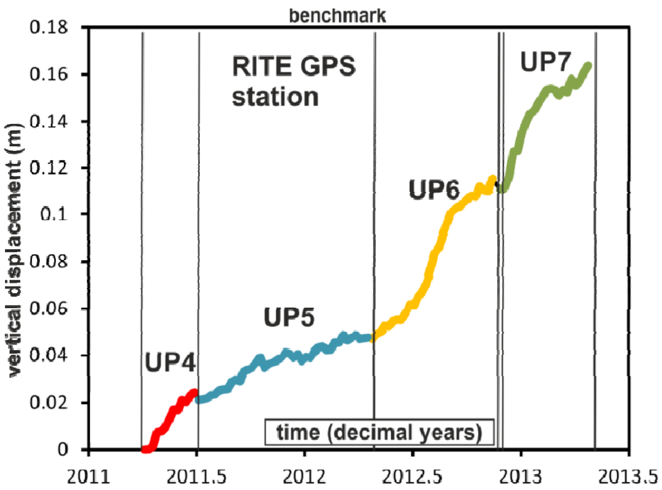
- 3 articoli accettati per la pubblicazione su riviste scientifiche
- 2 studi in revisione in attesa di pubblicazione, ed un rapporto tecnico

- 3 contributi scientifici pubblicati in congressi internazionali svoltisi a partire dall’inizio del progetto
- 3 abstract in congressi internazionali che si svolgeranno nei prossimi mesi, di cui uno su invito.

- **FASE 1:** Aggiornamento dinamico mappe di apertura bocca eruttiva.

Radial interpolation of GPS and leveling data of ground deformation in a resurgent caldera: application to Campi Flegrei (Italy).* [studio in revisione**]

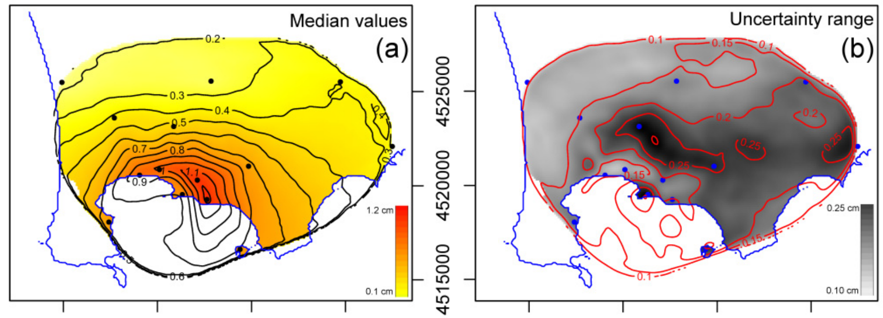




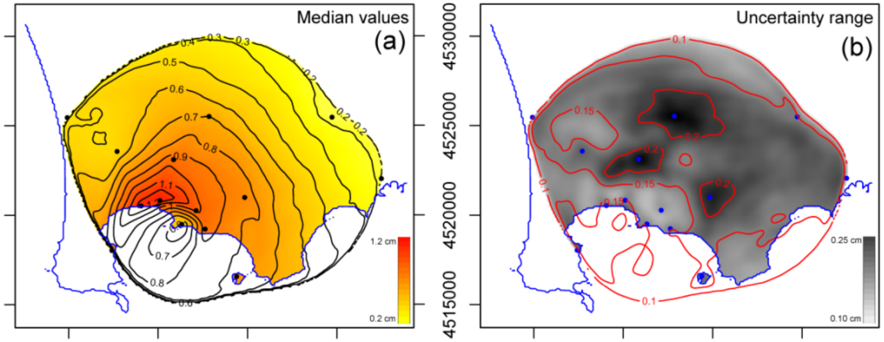
We believe the map of horizontal displacement is a **key tool** in the construction of a vent opening map, under the assumption that the source of the deformation is going to affect the eruption location.

Figure. (a) interpolated maps of horizontal displacement, based on UP4-UP7 GPS data. (b) are uncertainty ranges.

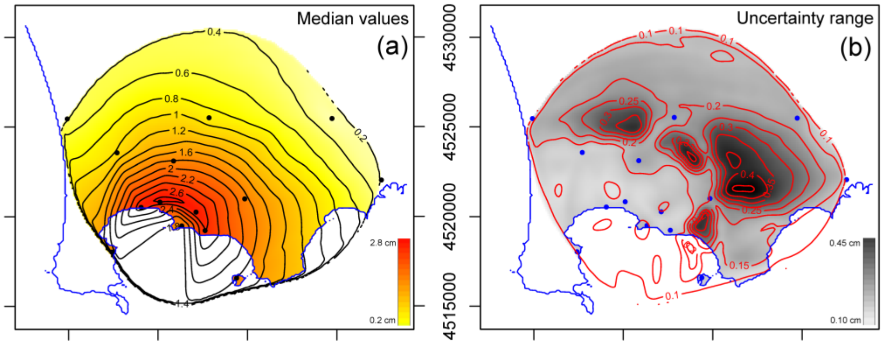
UP4, 4/2011 - 6/2011 Horizontal displacement



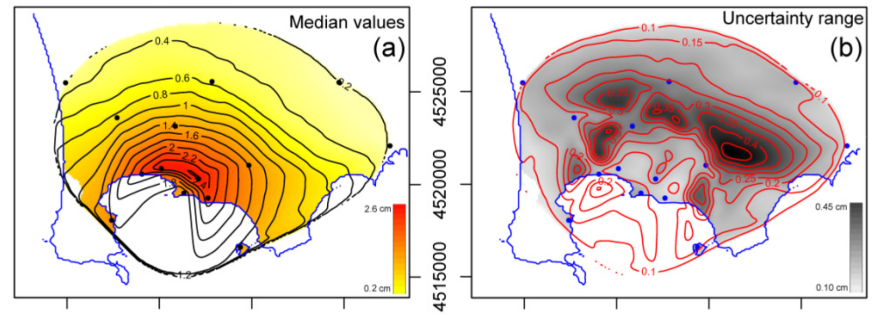
UP5, 7/2011 - 5/2012 Horizontal displacement



UP6, 6/2012 - 10/2012 Horizontal displacement



UP7, 12/2012 - 4/2013 Horizontal displacement



Our method is based on a **multi-polar interpolation**, i.e. we apply a linear interpolation between pairs of vectors, working in polar coordinates with respect to the intersection of the straight lines defined by their horizontal components .

$$\mathbf{v}^{(ij)\lambda} := [\lambda r^{(j)}+(1-\lambda)r^{(i)},\ \lambda\alpha^{(j)},\ \lambda\mathbf{d}^{(j)}+(1-\lambda)\mathbf{d}^{(i)}] \longrightarrow$$

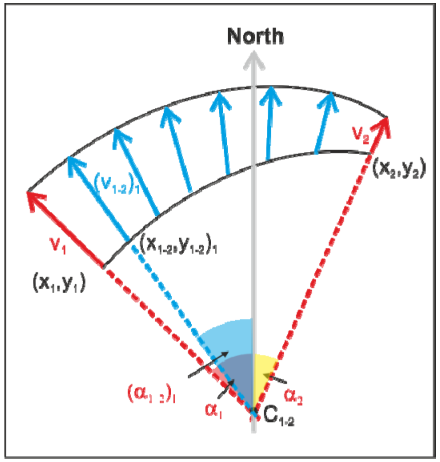
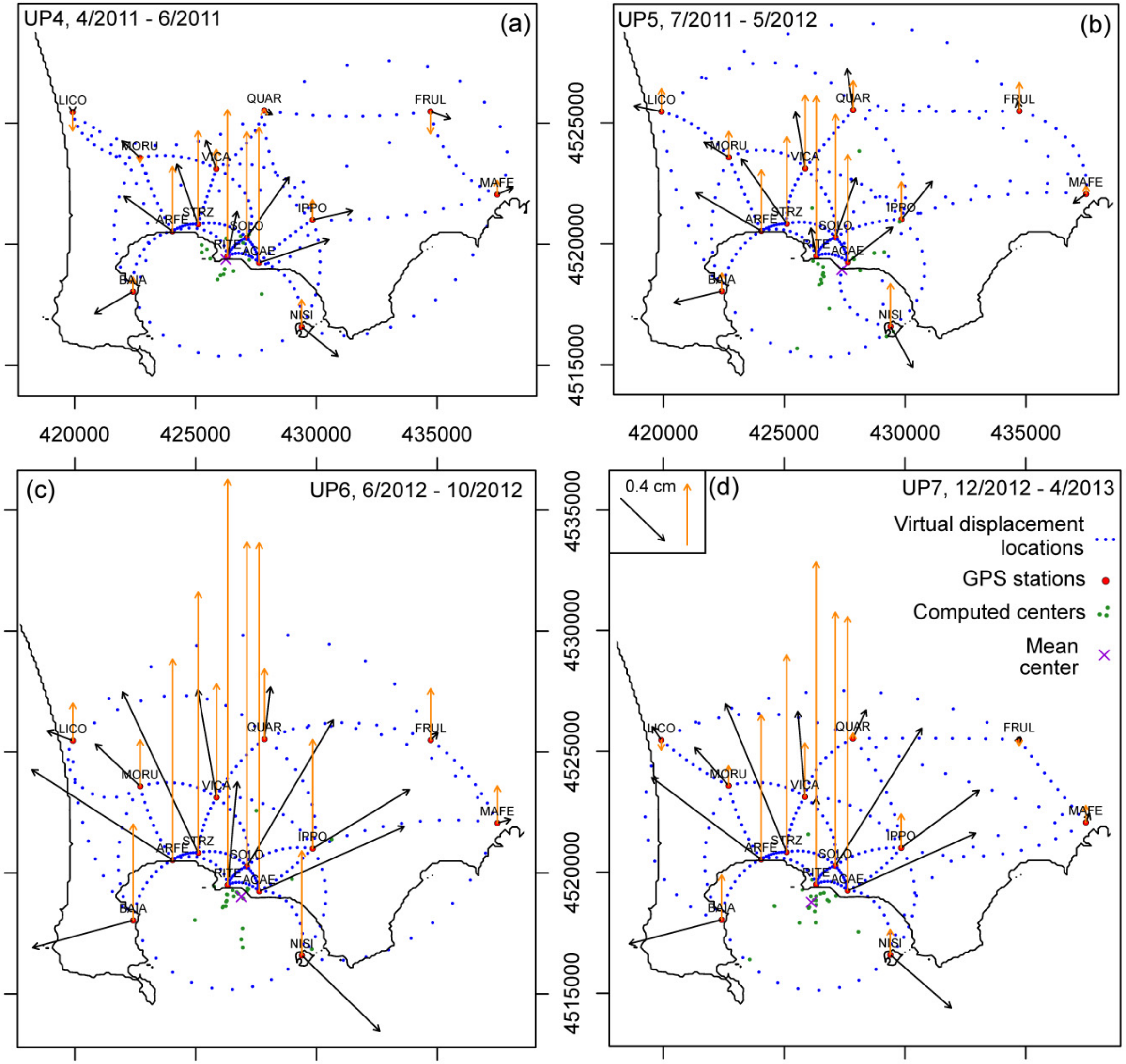


Figure. scheme of the multi-polar interpolation method



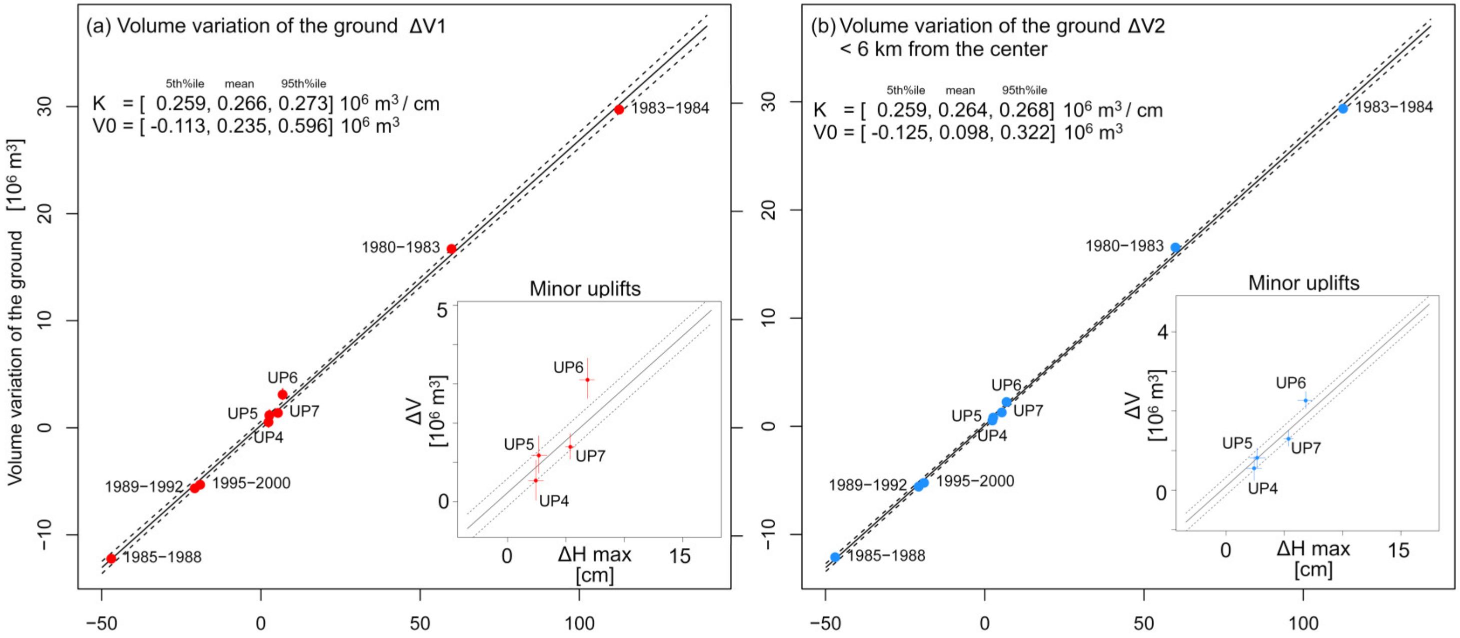
Our results are **not depending** on a priori assumptions about the geometry, location, and physical properties of the source, because they only rely on the **radial symmetry** of the deformation.

Figure. Plots (a-d) display the GPS measurements related to UP4-7. **Blue dots** mark the RIM virtual displacement locations, along elliptic arcs. **Green dots** mark the RIM computed centers for each pair of GPS stations considered (poles of symmetry). A **purple cross** marks the mean of the centers (excluding outliers).

If plotted against the maximum vertical displacement measured Δh_{max}, the volume variation data are significantly aligned. The **Figure** shows the linear regression least square fit:

$$\Delta V = V0 + K\,\Delta h_{max}.$$

We calculate DV as the **sum of the sub-volumes** resulting from the product of the cell areas of the interpolated maps with the corresponding displacement value.

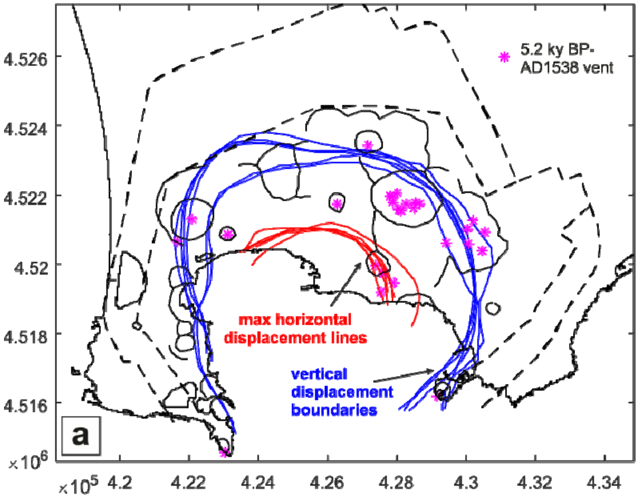


Dashed lines are 5th and 95th percentiles related to the measurement error on Δh_{max} and the RIM uncertainty on ΔV, and to the confidence interval of the least square fit.

ΔV estimates the **ground movement** without considering any dependence on any specific source geometry, physical properties, and location.

The **substantial proportionality** of ΔV and Δh_{max} suggests that the geometry and position of the volcanic source did not change with time, and that the elastic **mechanical behavior of rock held** during the whole period considered.

Figure. **Vertical** displacement boundaries and max **horizontal** displacement lines as resulting from the RIM maps above presented. Past vents locations occurred in the last 5.2 ky BP are reported as **pink stars**.



FASE 2: Modelli stocastici dell'effetto di potenziali precursori sulle stime temporali.

**Probabilistic enhancement of the Failure Forecast Method using a stochastic differential equation and application to volcanic eruption forecasts.* - [Frontiers in Earth Science, May 2019] - Description of the new method.

*Volcanic eruption time forecasting using a stochastic enhancement of the Failure Forecast Method.
[American Geophysical Union Fall Meeting, December 2018, Washington DC.] - A preliminary application to the Campi Flegrei EQ count, 2008-2018.

We enhanced the classical Failure Forecast Method (FFM) of Barry Voight by:

- systematically characterizing the **uncertainty**, including both aleatoric and epistemic sources;
- incorporating a stochastic **noise** in the equations, and a mean-reversion property to constrain it.

We produce **probability forecasts** with the FFM, instead of deterministic predictions.

The FFM differential equations (ODE)

α - convexity parameter
A - slope parameter
t_0 - initial time

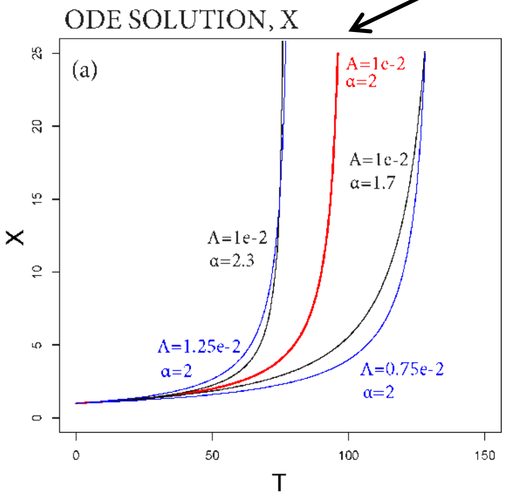
$$dX/dt = AX^{\alpha}$$

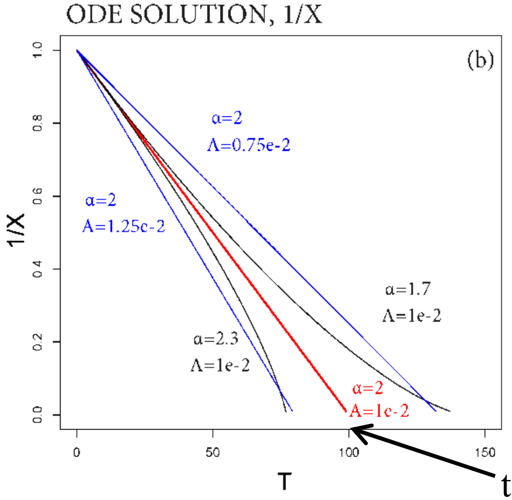
where X is the time rate of signals

$$X(t) = \left[(1-\alpha)A(t-t_0) + X(t_0)^{1-\alpha}\right]^{\frac{1}{1-\alpha}}$$

SOLUTION

t_f - failure time





t_f - failure time

We retrospectively tested the enhanced FFM over four datasets from Voight, 1988.

These refer to:
St. Helens, 1981-82,
Bezymianny, 1960,
Mt. Toc (Vajont), 1963.

$$d\eta_t = \{\underbrace{\gamma\,[(1-\alpha)A(t-t_0)+\eta_{t_0}-\eta_t]}_{\text{mean-reversion terms}} + \underbrace{(1-\alpha)A\}\,dt}_{\text{classical FFM}} + \underbrace{\sigma dW_t}_{\text{noise term}}$$

It makes every perturbation decay with time

γ - mean-reversion parameter
σ - noise parameter
β - initial perturbation

Parameters are based on the residuals in the linearized problem.

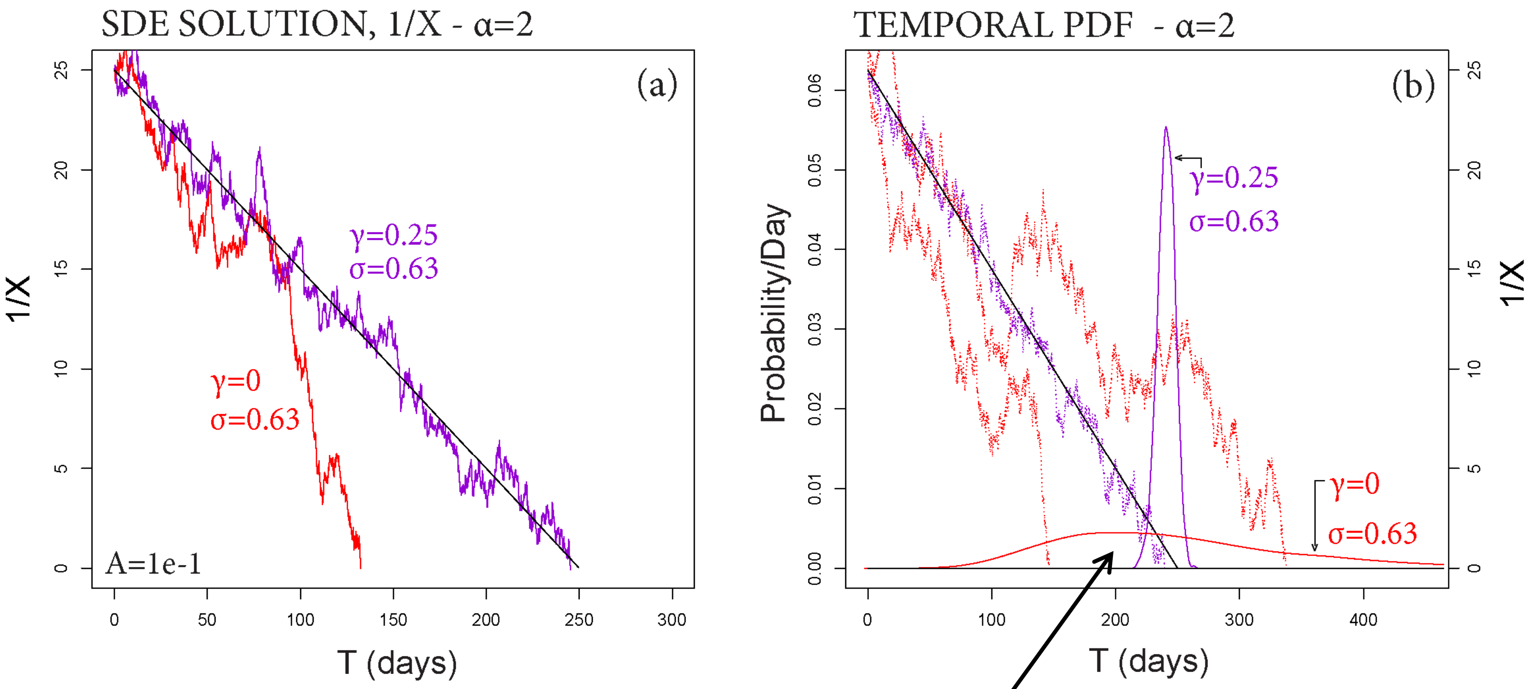


Figure.
SDE solutions,
with $\alpha=2$, $A=0.1$.

The black line is the mean solution.

(a) colored lines are random paths, $\gamma=0$ or $\gamma=0.25$.

(b) also shows g_{tf}. The solution 1/X is reported again.

$$t_f(\omega) = \inf\{t : X^{-1}(\omega,t) = 0\}$$

random variable

$$g_{t_f} : \mathbb{R} \rightarrow \mathbb{R}+, \qquad \int_0^\infty g_{t_f}(x)dx = 1$$

t_f probability density function

We preliminarily applied our enhanced FFM on Campi Flegrei seismic dataset. We remark that the time window is much longer than in the classical applications, and **spans over 40 years**.

t_f is the time when **accelerating signals** as observed in the last 10 years would diverge to infinity. The interpretation of t_f as the onset of a volcanic eruption is **speculative**.

Estimates of t_f are in [2019, 2032] with 90% chance, at the scale of 0.02% probability per day. These are **robust** against the choice of the bin on which the rate is calculated.

Figure. Cumulative number of EQ measured in CF from 1st Jan 2007 to 10th Sep 2018. STH station, Agnano.

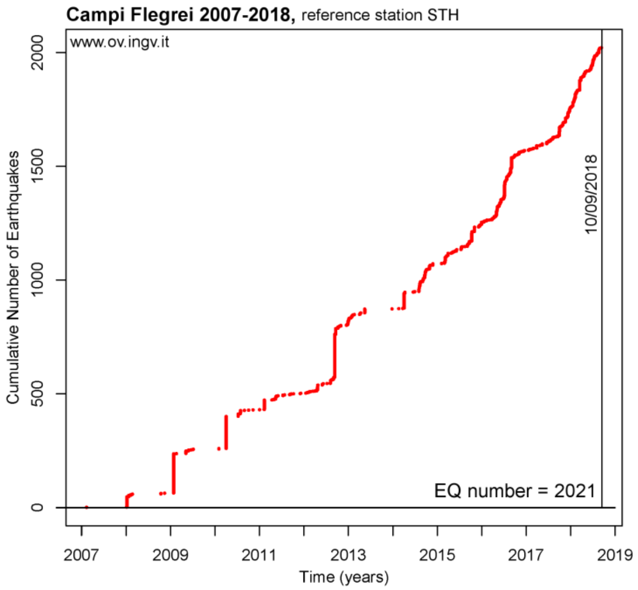
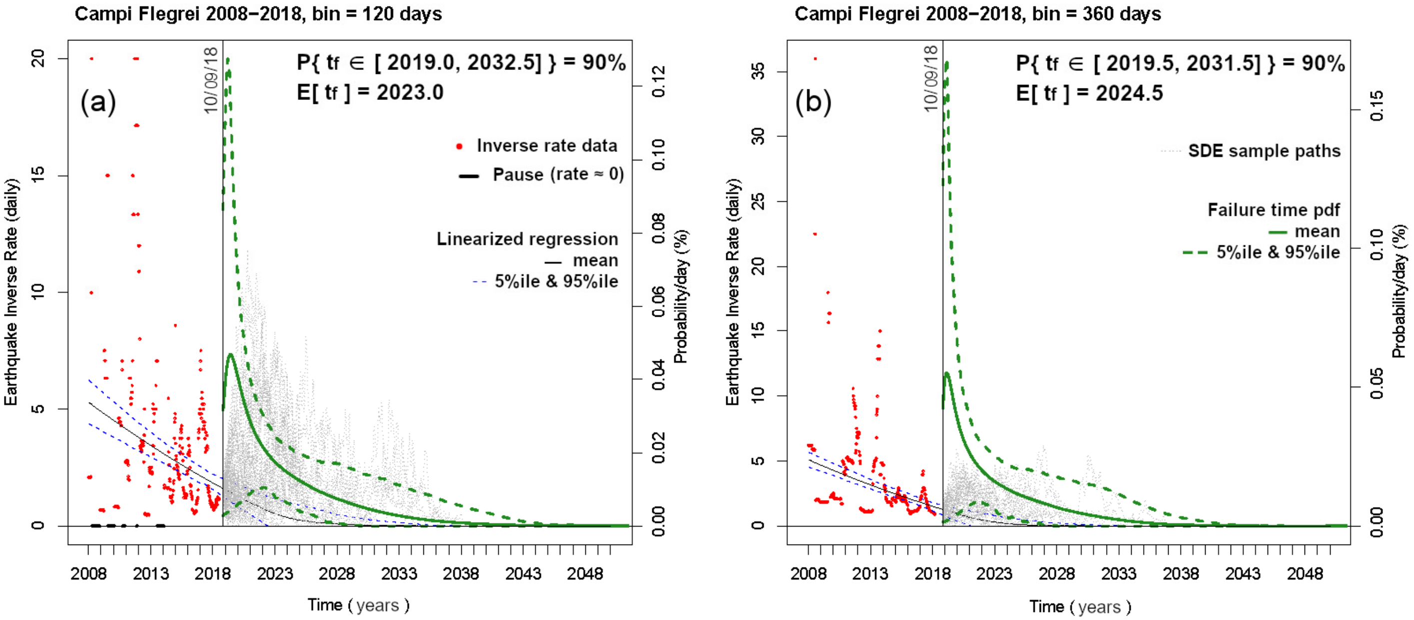


Figure. Probability forecasts of t_f based on FFM, based on the CF data of 2008-2018. In (a) the inverse rate is obtained on 120 days, in (b) on 360 days. **Red points** are inverse rate data.

The **green line** is mean value of g_{tf}, the probability/day scale bar is related to it. **Dashed lines** mark its 5th and 95th percentiles.

Thin blue dashed lines bound the 90% confidence interval of the ODE paths of 1/X, and a thin line is the mean path. **Grey dotted** liner display 50 paths of the SDE.



FASE 3: nuovi metodi probabilistici per la simulazione di flussi piroclastici al variare delle condizioni iniziali.

* *Enhancing the uncertainty quantification of pyroclastic density current dynamics in the Campi Flegrei caldera*.

[**abstract accettato** - FrontUQ, Workshop in Uncertainty Quantification, September 2019, Pisa.]

This is a new effort to improve the UQ of pyroclastic density current dynamics in the Campi Flegrei caldera, thanks to the implementation of a **new 2D depth-averaged granular flow** model in the Monte Carlo simulation of key-controlling variables.

UQ is going to be performed by assuming three different components in the input space: (i) rheology parameters, (ii) volume scale, (iii) source location.

PDC HAZARD IN CAMPI FLEGREI OVER THE NEXT 10 YEARS

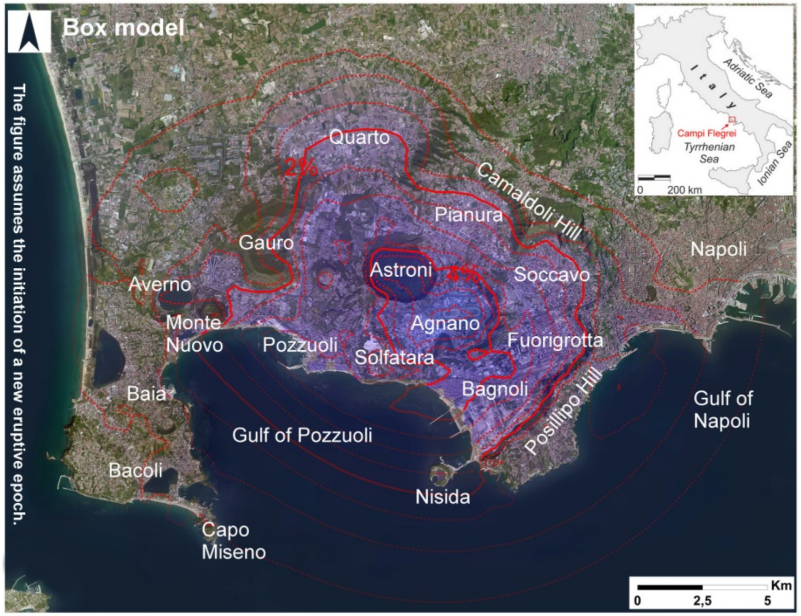
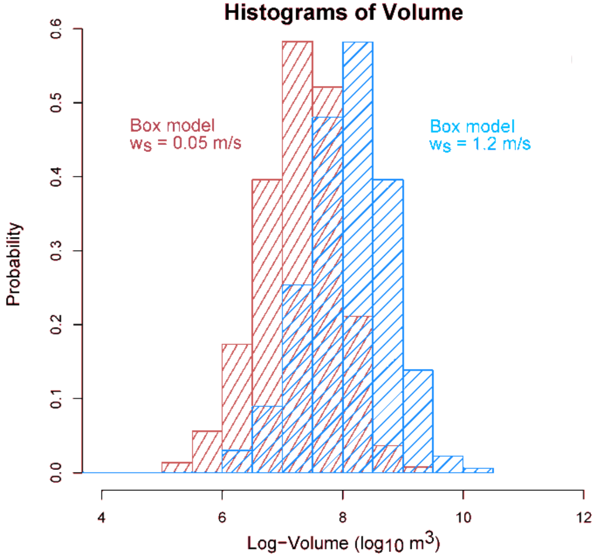


Figure. Temporal PDC invasion hazard map based on the box model integral equations, the vent opening map, long-term* temporal estimates, and invaded areal size distributions already available.

Contours show the probability of PDC invasion in the next 10 years.

***NOT based on new FFM modeling**



A Monte Carlo simulation varies the vent opening location and the value of inundated area, according to the **long-term** probability models already available. A similar statistics is going to be obtained once preliminary short term maps will be fully developed.

Figure. The plot shows the histograms of PDC **log-volume of the multiphase mixture** of solid and gas obtained by probabilistic inversion of the box model integral equations, with initial solid fraction of 1% volume.

Different colors assume different values of **velocity of settling**, 1.2 m/s and 0.05 m/s. These values correspond to particle diameters of about 500 µm and 25 µm, and solid densities of 1000 kg/m^3 and 2000 kg/m^3 respectively.

Fasi delle attività 2.5.1, e relativi prodotti scientifici FISR17 - SOIR

FASE 1: aggiornamento dinamico mappe di apertura bocca eruttiva.

- **Radial interpolation of GPS and leveling data of ground deformation in a resurgent caldera: application to Campi Flegrei (Italy).* - [**studio in revisione**] A. Bevilacqua, S. Vitale, R. Isaia, A. Neri, A. Novellino, F. Tramparulo

**A SDE Framework for Precursors II.*
[**abstract invitato** - International Congress on Industrial and applied Mathematics, July 2019, Valencia.]
A. Bevilacqua
Contributo nel Simposio "Mapping and managing hazards using Precursory Data, and Analysis"
A. Patra, E.B. Pitman, E. Spiller, K. Kyzyurova

FASE 2: modelli stocastici dell'effetto di potenziali precursori sulle stime temporali.

Probabilistic enhancement of the Failure Forecast Method using a stochastic differential equation and application to volcanic eruption forecasts.* - [articolo accettato** su Frontiers in Earth Science, May 2019]
A. Bevilacqua, E.B. Pitman, A. Patra, M. Bursik, A. Neri, B. Voight.

**Volcanic eruption time forecasting using a stochastic enhancement of the Failure Forecast Method*.
[**contributo pubblicato** - American Geophysical Union Fall Meeting, December 2018, Washington DC.]
A. Bevilacqua, A. Patra, E.B. Pitman, M. Bursik, F. Giudicepietro, G. Macedonio, A. Neri, G. Valentine.

*Enhancing the Failure Forecast Method using a noisy mean-reverting process.
[**contributo pubblicato** - Cities on Volcanoes 10, September 2018, Napoli.]
A. Bevilacqua, A. Patra, E.B. Pitman, A. Neri.

Fasi delle attività 2.5.1, e relativi prodotti scientifici FISR17 - SOIR

FASE 3: nuovi metodi probabilistici per la simulazione di flussi piroclastici al variare delle condizioni iniziali.

** Enhancing the uncertainty quantification of pyroclastic density current dynamics in the Campi Flegrei caldera*. [**abstract accettato** - FrontUQ, Workshop in Uncertainty Quantification, September 2019, Pisa.]
A. Bevilacqua, M. de Michieli Vitturi, T. Esposti Ongaro, A. Neri

Refining the input space of plausible future debris flows using noisy data and multiple models of the physics*. [abstract accettato** - FrontUQ 2019.]
A. Bevilacqua, A. Patra, M. Bursik, E.B. Pitman, J.L. Macìas, R. Saucedo, D. Hyman.

** Probabilistic forecasting of plausible debris flows from Nevado de Colima (Mexico) using data from the Atenquique debris flow, 1955*. [**articolo pubblicato** su Natural Hazards Earth System Science, April 2019]
A. Bevilacqua, A. Patra, M. Bursik, E.B. Pitman, J.L. Macìas, R. Saucedo, D. Hyman.

*A prediction-oriented hazard assessment procedure based on the empirical falsification principle, application to the Atenquique debris flow, 1955, México. [**contributo pubblicato** - AGU 2018.]
A. Patra, A. Bevilacqua, M. Bursik, E.B. Pitman, D. Hyman, R. Saucedo, J.L. Macìas.

*PyBox: a Python tool for simulating the kinematics of Pyroclastic density currents with the box-model approach, Reference and User's Guide. [**technical report online**, *Volcano Dynamics Computational Centre*, March 2019]
G. Biagioli, A. Bevilacqua, M. de Michieli Vitturi, T. Esposti Ongaro.

FASE 4: metodi di combinazione probabilistica ed analisi dei dataset di simulazioni pre-generate.

**Statistical theory of probabilistic hazard maps: a probability distribution for the hazard boundary location*
[**articolo accettato** su Natural Hazards Earth System Science, May 2019]
D. Hyman, A. Bevilacqua, M. Bursik.

- **Dynamic probabilistic hazard mapping in the Long Valley Volcanic Region CA: integrating vent opening maps and statistical surrogates of physical models of pyroclastic density currents.* - [**studio in revisione**]
  R. Rutarindwa, E. Spiller, A. Bevilacqua, M. Bursik, A. Patra.