Task 6.1 – Volcanic Hazard Assessment at Campi Flegrei

Developing long-term probability time models for the episodic volcanism of Campi Flegrei caldera (Italy)

Andrea Bevilacqua(1, 2), Franco Flandoli(3), Augusto Neri(1),
Roberto Isaia(4), Stefano Vitale (5)

(1) Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Pisa, Pisa
(2) Scuola Normale Superiore, Pisa
(3) Università di Pisa, Dip.to di Matematica, Pisa
(4) Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Vesuviano, Napoli
(5) Università di Napoli "Federico II", Dip.to di Scienze della Terra, dell'Ambiente e delle Risorse, Napoli

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Research objective

To produce a **long-term probabilistic temporal model for vent opening** at Campi Flegrei based on available information concerning past activity, quantifying its uncertainty and developing a probability function to represent the main features of its eruptive record.

The study is aimed at further developing the results of Bevilacqua et al. [2015] and Neri et al. [2015], by **including temporal scales** into the spatial hazard assessments produced.

Conditional hazard map

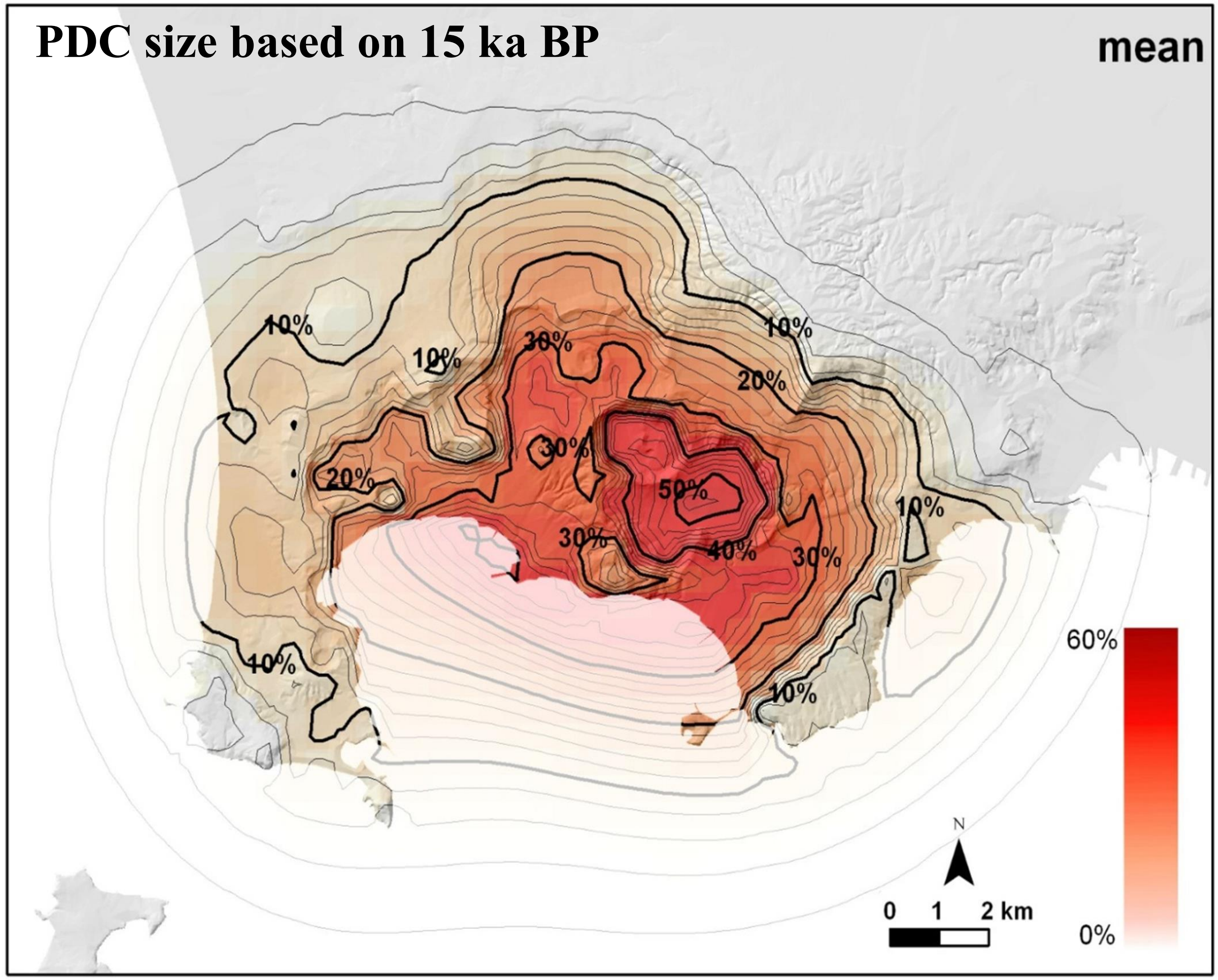


Fig 1. Mean probability map of **PDC invasion hazard**, modified from Neri et al. [2015]. Contours and colours indicate the percentage probability of PDC invasion **conditional on the occurrence** of an explosive eruption with vent located onland**.**

Simplified eruption history of Campi flegrei caldera

• Campi Flegrei caldera was created by **two ancient large eruptions**: the Campanian Ignimbrite (CI - 40 ka BP) and the Neapolitan Yellow Tuff (NYT - 15 ka BP).

• In the last 15 ka the **eruption vents were sparse** in the caldera and most of the eruptions were explosive.

• There were **3 eruptive epochs** of volcanic activity, alternated to long periods of quiescence.

	Start	Duration
Epoch I	[15 ka BP	~4.5 ka]
Epoch II	[9.6 ka BP	~0.5 ka]
Epoch III	[5.5 ka BP	~2 ka]

• The most recent 'Monte Nuovo' eruption was in AD 1538, after ~3-3.5 ka of quiescience.

We partitioned the caldera in 16 zones $(A_l)_{l=1,\dots,N}$ with different features and history of activity.

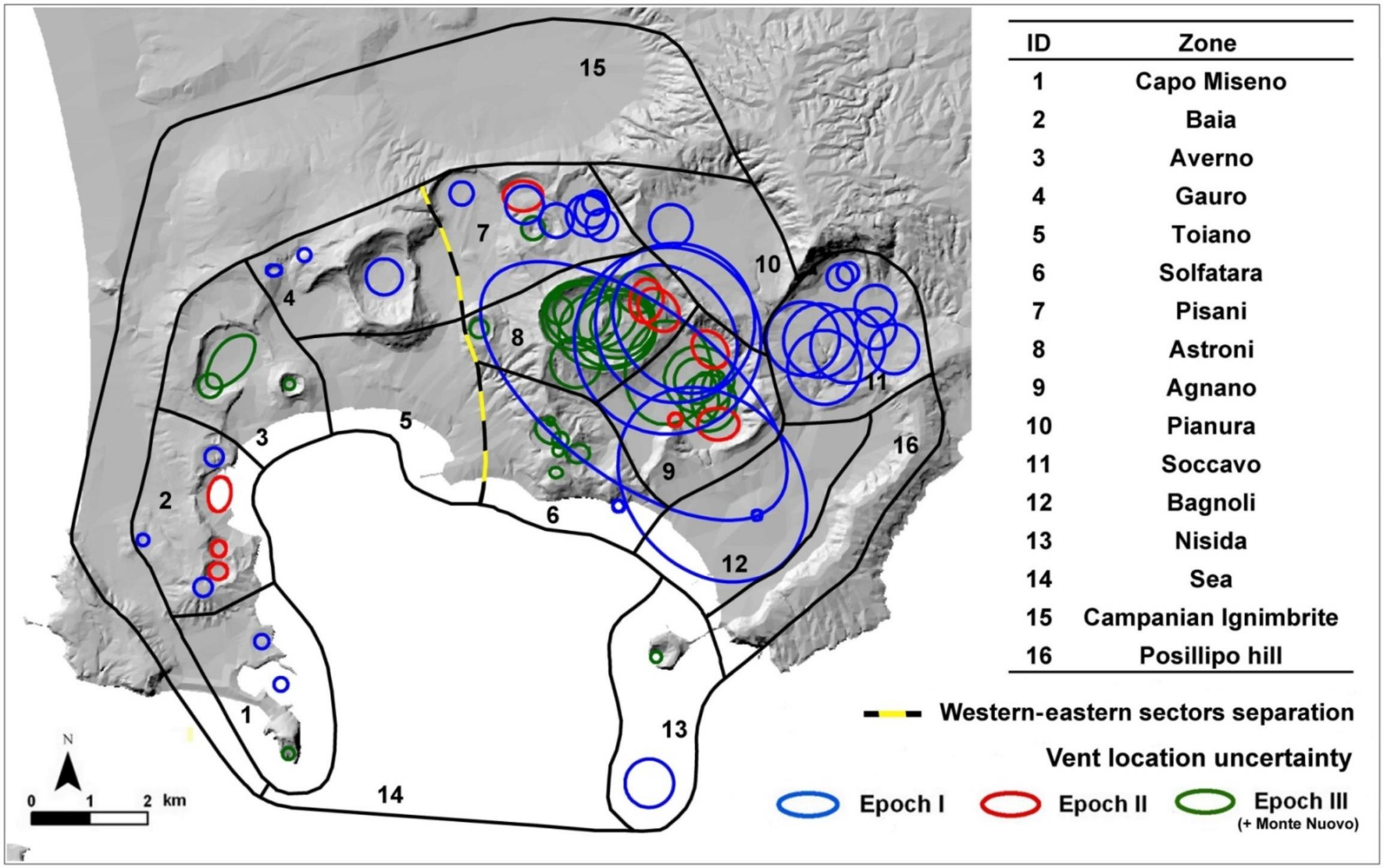


Fig 2. Caldera partitioning in 16 zones. The colours of the ellipses, representing the uncertainty areas of vent location, correspond to the epoch of activity. The yellow dashed line separates eastern and western sectors. The first 13 zones have the same extent. See Bevilacqua et al. [2015].

Approach

The volcano was assumed as a **random system** that had to be assessed with incomplete and **uncertain information**.

Uncertainty quantification assumed a great importance, and we distinguished:

I. the **physical variability,** i.e. the intrinsic randomness of the system under study,

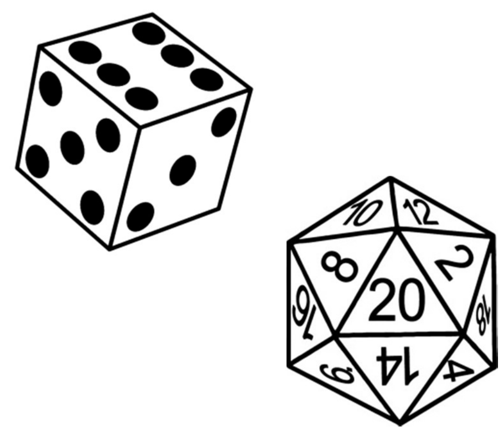
II. the **epistemic uncertainty** due to the imperfect knowledge of the system.

Adopting a **doubly stochastic approach,** the ill-constrained parameters of the probability models were themselves represented as additional random variables.

As a consequence of this approach, all the probability estimates have their own confidence intervals.

Example: define X as the random result of an unknown dice, which could have 6 or 20 faces with equal chances.

Following a doubly stochastic approach, we will say that the probability P of the event {X>3} is 67.5% in mean, with an uncertainty range from 50% to 85%.



Methodology

In particular, the study included two phases:
1) A probability model for epistemic uncertainty on past record, concerning the **uncertainty estimation** on the sequence of times, the location and the erupted volume of past events.

2) A probability model for the **representation and replication** of the main eruptive activity features in time-space, such as the vent clustering, and incorporating the effects of the sources of epistemic uncertainty considered.

The two models are linked through a nested Monte Carlo simulation by assuming to calculate the parameters of model (2) that **maximize the likelihood** of each sample of model (1).

The approach followed relies on the **mathematical modeling** of the past record without assuming any physical model describing the deep-crustal processes.

Epistemic uncertainty on past record

We based on the data available in Smith et al. 2011, including some updates.

In the eruption record there are 3 classes of events:

A) with **datation only**;

B) with **sequence order only**;

C) with **both order and date**;

Events in (A) and (C) were sampled with **symmetrical triangular distributions** with the assumed percentiles.

Events in (B) were sampled **uniformly and independently** inside intervals consistent with the sequence.

Uncertainty affecting the estimated volumes is assumed equal to ±50%, consistently with recent literature (e.g. Klawonn et al. 2014).

Tab 1. Record of times, erupted volumes and locations (eastern or western sectors and partition zones) of the events at Campi Flegrei during Epoch III.

EPOCH III

ID	Name	Time [a]		VDRE [km^3]			E/W	Zone
		2.5%ile	97.5%ile	5%ile		95%ile		
1	Agnano 1	5266	5628	0.01	0.02	0.03	E	9
2	Agnano 2	-	-	0.01	0.01	0.02	E	9
3	Averno 1	5064	5431	0.01	-	0.10	W	3
4	Agnano 3	-	-	0.10	0.19	0.29	E	9
5	Cigliano	*	*	0.03	0.05	0.08	E	8
6	Pigniatiello 2	*	*	0.01	0.02	0.03	E	9
7	Capo Miseno	3259	4286	0.01	0.02	0.03	W	1
8	Monte Sant'Angelo	4832	5010	0.10	-	0.30	E	9
9	Paleoastroni 1	4745	4834	0.03	0.05	0.08	E	8
10	Paleoastroni 2	4712	4757	0.10	-	0.30	E	8
11	Agnano Monte Spina	4482	4625	0.43	0.85	1.28	E	8 - 9
12	St. Maria delle Grazie	4382	4509	0.01	-	0.10	E	6
13	Olibano lava dome	*	*	0.00	-	0.01	E	6
14	Paleoastroni 3	-	-	0.01	0.02	0.03	E	8
15	Solfatara lava dome	*	*	0.00	-	0.01	E	6
16	Olibano tephra	*	*	0.01	-	0.10	E	6
17	Accademia lava dome	-	-	0.00	-	0.01	E	6
18	Solfatara	4181	4386	0.02	0.03	0.05	E	6
19	Averno 2	**	**	0.04	0.07	0.11	W	3
20	Astroni 1	4153	4345	0.03	0.06	0.09	E	8
21	Astroni 2	-	-	0.01	0.02	0.03	E	8
22	Astroni 3	-	-	0.08	0.16	0.24	E	8
23	Astroni 4	-	-	0.07	0.14	0.21	E	8
24	Astroni 5	-	-	0.05	0.10	0.15	E	8
25	Astroni 6	-	-	0.06	0.12	0.18	E	8
26	Astroni 7	4098	4297	0.04	0.07	0.11	E	8
27	Fossa Lupara	3978	4192	0.01	0.02	0.03	E	7
28	Nisida	3213	4188	0.01	0.02	0.03	E	13

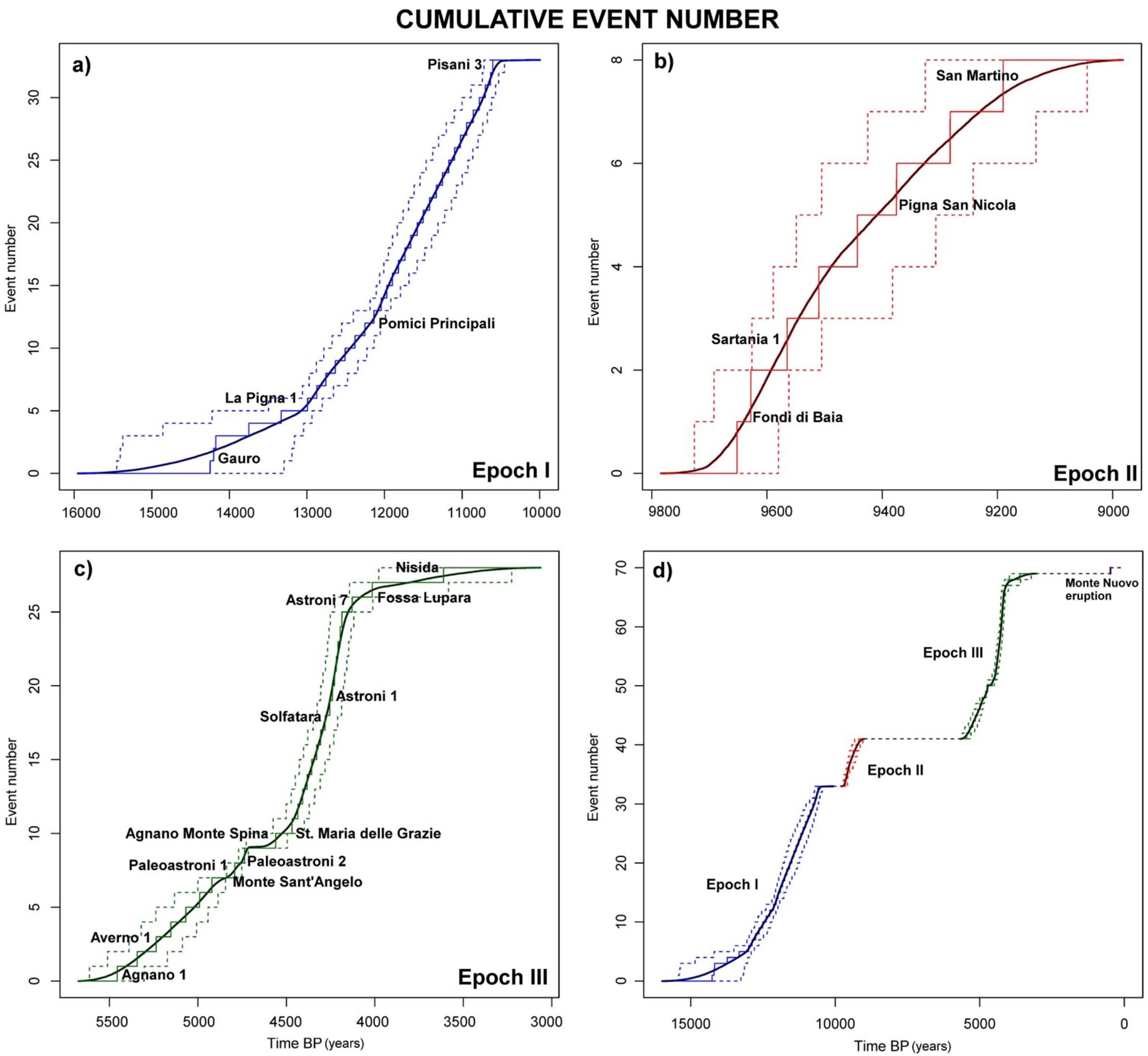


Fig 3. Event number as a function of time during Epoch I (a), Epoch II (b), Epoch III (c) and then during the entire record considered (d) (including Monte Nuovo).

Bold line is the mean value, narrow line is the 50th percentile and dashed lines are 5th and 95th uncertainty percentiles.

The labels correspond to the eruptions with both datation bounds and sequence place.

Intensification of the activity rate is quite evident after about ten events from the beginning of Epochs I and III.

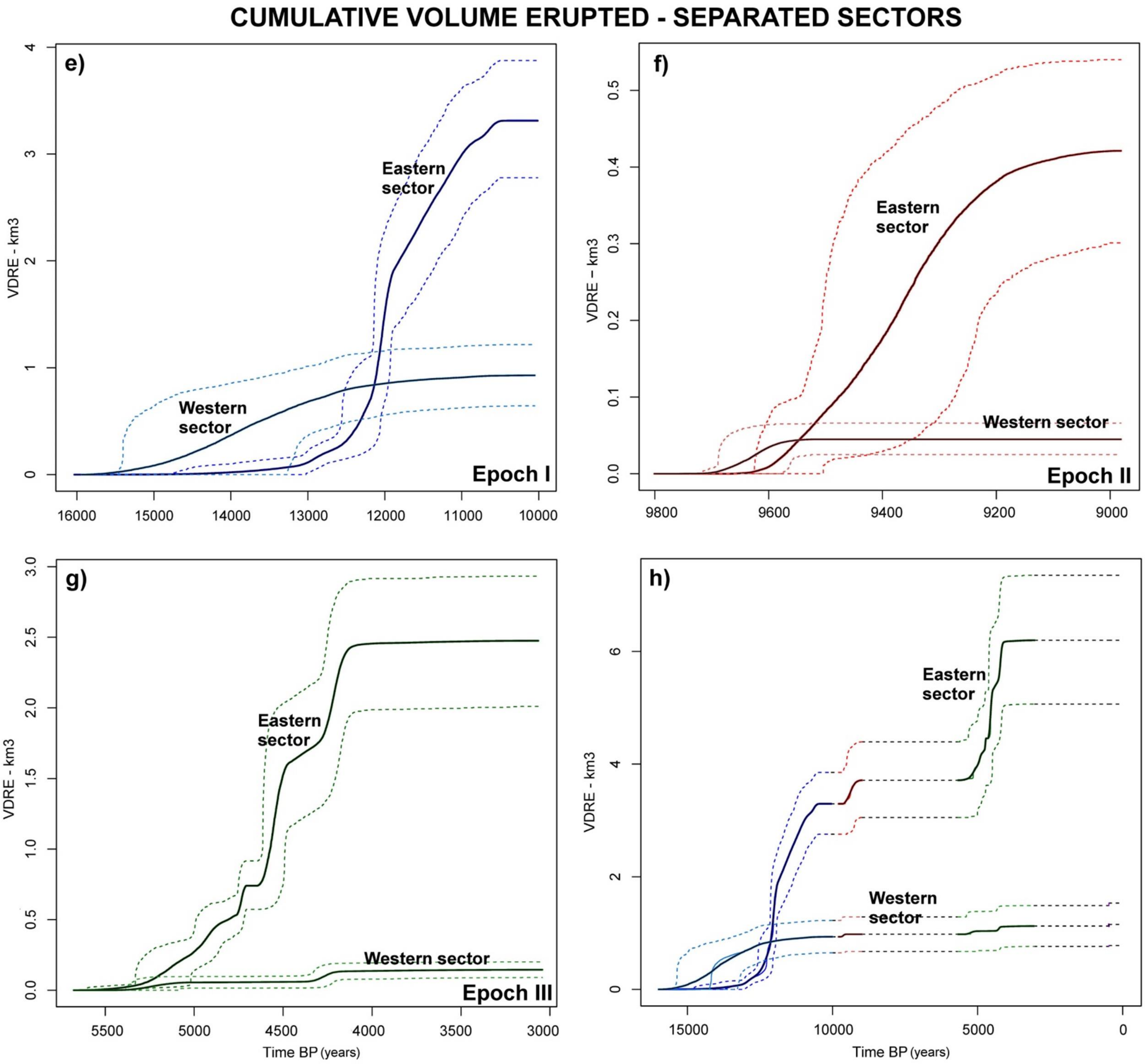


Fig 4. Cumulative volume erupted as a function of time during Epoch I (a), Epoch II (b), Epoch III (c) and then during the entire record considered (including Monte Nuovo) (d).

The cumulative volumes erupted by the western part of the caldera, are remarkably **smaller** than by the eastern.

Activity in the western sector seems mainly associated to the **initial phases** of the eruptive epochs, compatible with considering the Monte Nuovo eruption as the **first event** of a new Epoch.

Probability model for the for the representation of the eruptive pattern

The stochastic process Z which has been chosen for representing the eruptive events as a function of time belongs to the class of **Cox-Hawkes multivariate counting processes**.

Each component Z^l counts the number of events occurred in zone A_l of the caldera partition.

Cox-Hawkes generalize the class of **Poisson processes**, which sample the waiting times between events as independent identically distributed exponential random variables.

In general the intensity function λ of a counting process has the meaning of the **average density** of new events occurring with respect to time. Indeed the integral $\int \lambda dt$ gives the average number of events in the selected time interval.

The **Cox processes** assume their intensity function λ affected by uncertainty. They are doubly stochastic (e.g. Jaquet et al. 2000; Jaquet et al. 2008).

Hawkes processes assume that their intensity function increases with a jump whenever an event occurs and decreases as time passes without any event occurring. They naturally **generate clusters** (e.g. Bebbington and Cronin 2011).

The **Cox-Hawkes processes** are both doubly-stochastic and self-exciting.

With multivariate Cox-Hawkes processes we assumed that each new eruption **self-excites** its zone, increasing the probability of additional eruptions in it. Including the effects of **epistemic uncertainty** in the model.

The Cox- Hawkes processes

For the Cox-Hawkes processes we have:

$$\lambda^l(t,\omega) = \lambda_0^l(e) + \sum_{t_i^l(w)<t} [\varphi(e)](t - t_i^l(\omega))$$

Random intensity $\lambda^l(t,\omega)$ is the sum of a **constant term** $\boldsymbol{\lambda_0}$ (base rate) and of a time dependent random term that represents an **additional intensity** produced by each previous event.

The base rate represents the average density of new clusters (even of one point), while their additional intensity generates the offspring points.

φ is a positive decreasing function, representing self-excitement decay. It was assumed **exponential** and depending on two parameters.

$$[\varphi(e)](s) = h(e)\exp(-k(e)s)$$

The parameters $\lambda^l{}_0(e)$, $k(e)$ and $h(e)$ are **conditional on the epistemic assumptions**, represented by e. We estimated them by a maximum likelihood procedure.

Indeed it is possible to calculate an **expression for the likelihood** of an eruption sequence in zone *l,* before time *t*.

$$L_l\left((t_i^l)_{i=1,\ldots,n^l}, t\right) = \left(\prod_{i=1}^{n^l} \lambda^l(t_i^l)\right) \exp\left(-\int_0^t \lambda^l(s)ds\right)$$

This was implemented in a nested **Monte Carlo simulation** and repeated for each sample of the uncertainty.

Base return time, self-excitement duration, mean offspring

COX-HAWKES PROCESS PARAMETERS

	Eruption record/Statistics	Base return time 1/λ0 - years			Self excitement duration T - years			Mean offspring μ		
		5th %ile	mean	95th %ile	5th %ile	mean	95th %ile	5th %ile	mean	95th %ile
1	Epoch I	98	**148**	237	60	**658**	1320	0.14	**0.30**	0.43
2	Epoch II	43	**63**	94	3	**101**	304	0.13	**0.23**	0.36
3	Epoch III	80	**106**	142	11	**96**	196	0.30	**0.42**	0.50
4	Epochs I x II x III	82	**105**	140	48	**189**	435	0.26	**0.41**	0.59
5	Epochs Ia x II x IIIa	92	**124**	176	38	**452**	919	0.15	**0.38**	0.61
6	Epochs IW x IIW x IIIW	357	**468**	697	0	**68**	175	0.00	**0.14**	0.23
7	Epochs IE x IIE x IIIE	99	**140**	207	62	**352**	755	0.38	**0.59**	0.76
8	Epoch I*II*III*MN	303	**352**	404	152	**337**	480	0.38	**0.45**	0.51
9	Epochs IW*IIW*IIIW*MN	983	**1090**	1205	12	**112**	265	0.14	**0.19**	0.24

Tab 2. Base return time 1/λ0, duration of the self-excitement T, and mean offspring of each event μ as computed by the probability temporal model. Mean values, 5th and 95th percentiles are reported for each parameter.

Rows 1st – 3rd are obtained from the maximum likelihood **parameters** on the three eruptive epochs.

Assuming the three epochs past record as independent samples and then maximizing the product of their likelihoods, are obtained **global results** consistent with the Epoch III activity except for a longer self-excitement (row 4th).

Considering only the events occurred in **the first parts of the epochs** before the climatic eruptions, gives slightly longer base return times and much longer durations of the self-excitement decay (row 5th).

Considering the **western record** only, the base return time significantly increases and the self-excitement behavior was weakened (row 6th). This is not true for the **eastern record** (row 7th).

Fitting the model on the **whole eruptive record** including even the periods of quiescence produce longer base return time and longer duration of the self-excitement decay (row 8th). However, this is in contrast with the existence of epochs.

This assumption seems better fitting on the western record separated, in this case producing a very long base return time of ~1 ka, more compatible with the length of the **periods of quiescence** (row 9th).

Probability forecasts of the next eruption time

A probability density function for the **remaining time** before the next eruption has been calculated.

We assumed a process Z_{mn} starting without excitement except for the residual additional intensity from Monte Nuovo event.

Again the different volcanological assumptions can change the results.

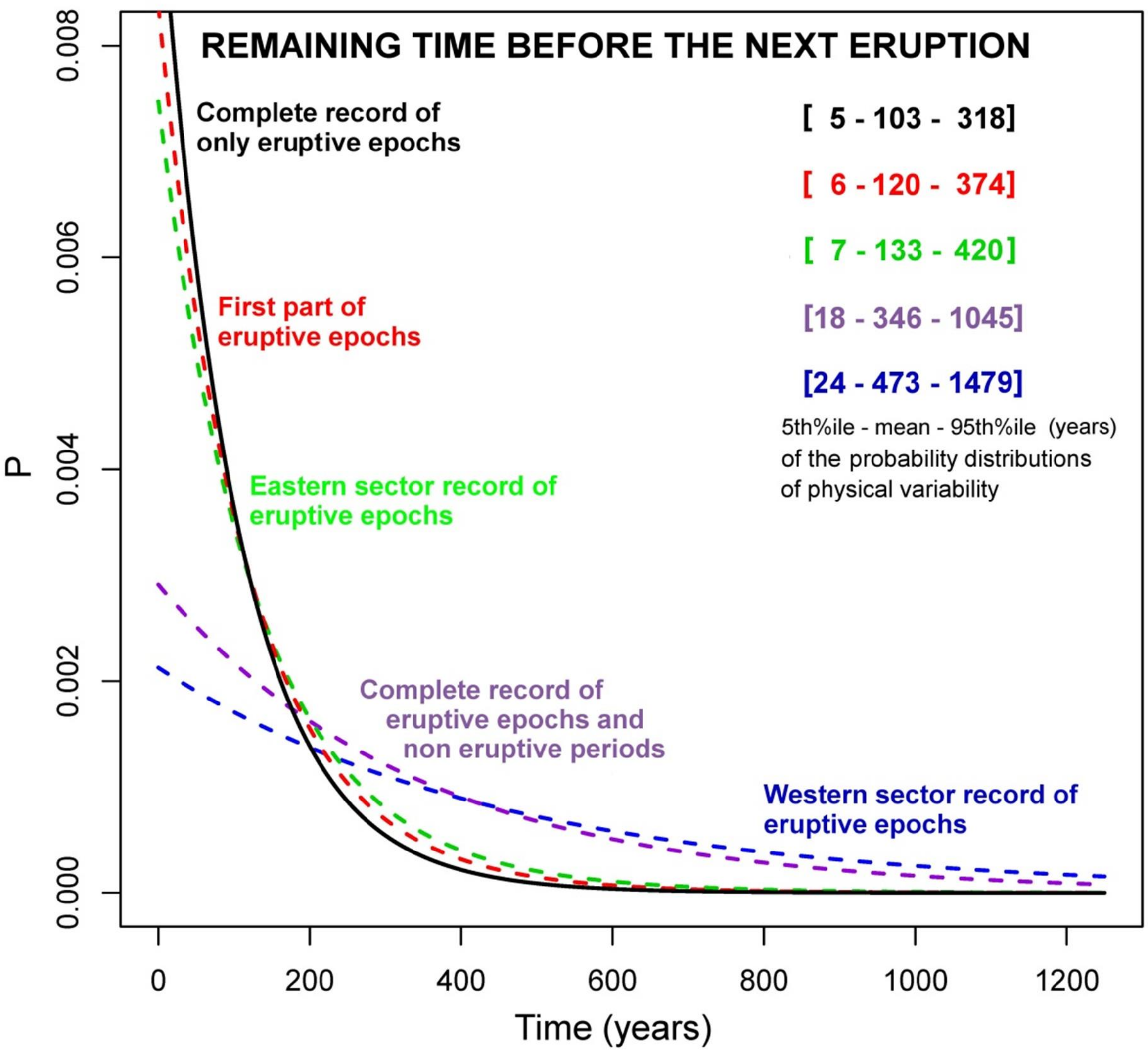


Fig 5. Mean probability density functions for the remaining time before the next eruption, assuming maximum likelihood exponential distributions.

Different colours correspond to alternative geological assumptions.

The values reported refer to the 5^{th} percentile, the mean value and the 95^{th} percentile of the physical variability.

The mean with respect epistemic uncertainty affecting eruptive record was assumed.

Probability forecasts of the next eruption time with uncertainty quantification

The mean and **uncertainty percentiles** of each probability density values can be reported, as a function of the considered epistemic uncertainty affecting the stratigraphic record.

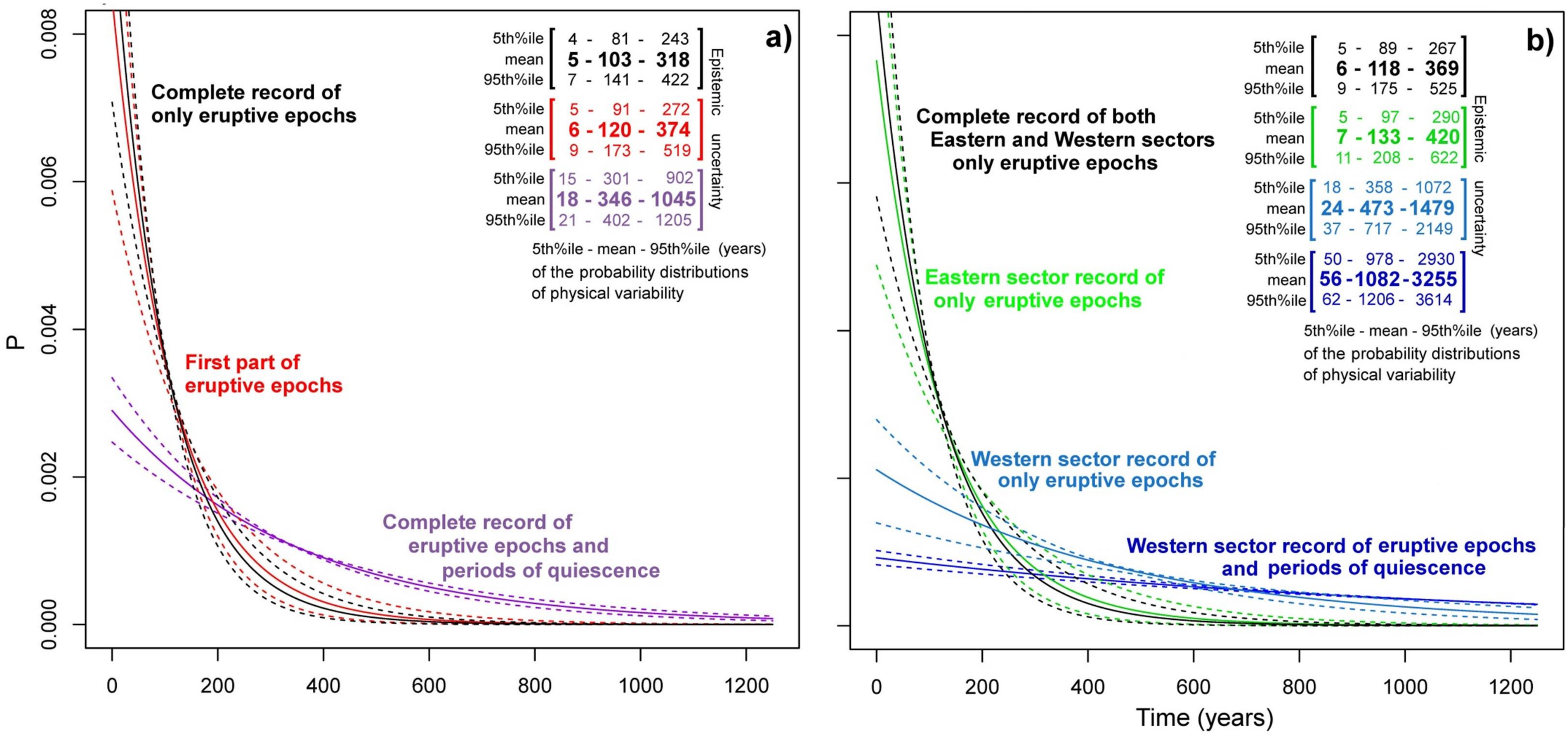


Fig 6. The bold lines indicate the mean probability density functions per year, and the dashed lines are composed of the 5*th* and 95*th* *e*pistemic uncertainty percentiles of the values of such functions.

The values reported are the 5*th* percentile, the mean and the 95*th* percentile with respect to epistemic uncertainty (from above to below), of the 5*th* percentile, the mean value and the 95*th* percentile of the physical variability (from left to right).

Preliminary hazard maps with temporal scale - 50 years

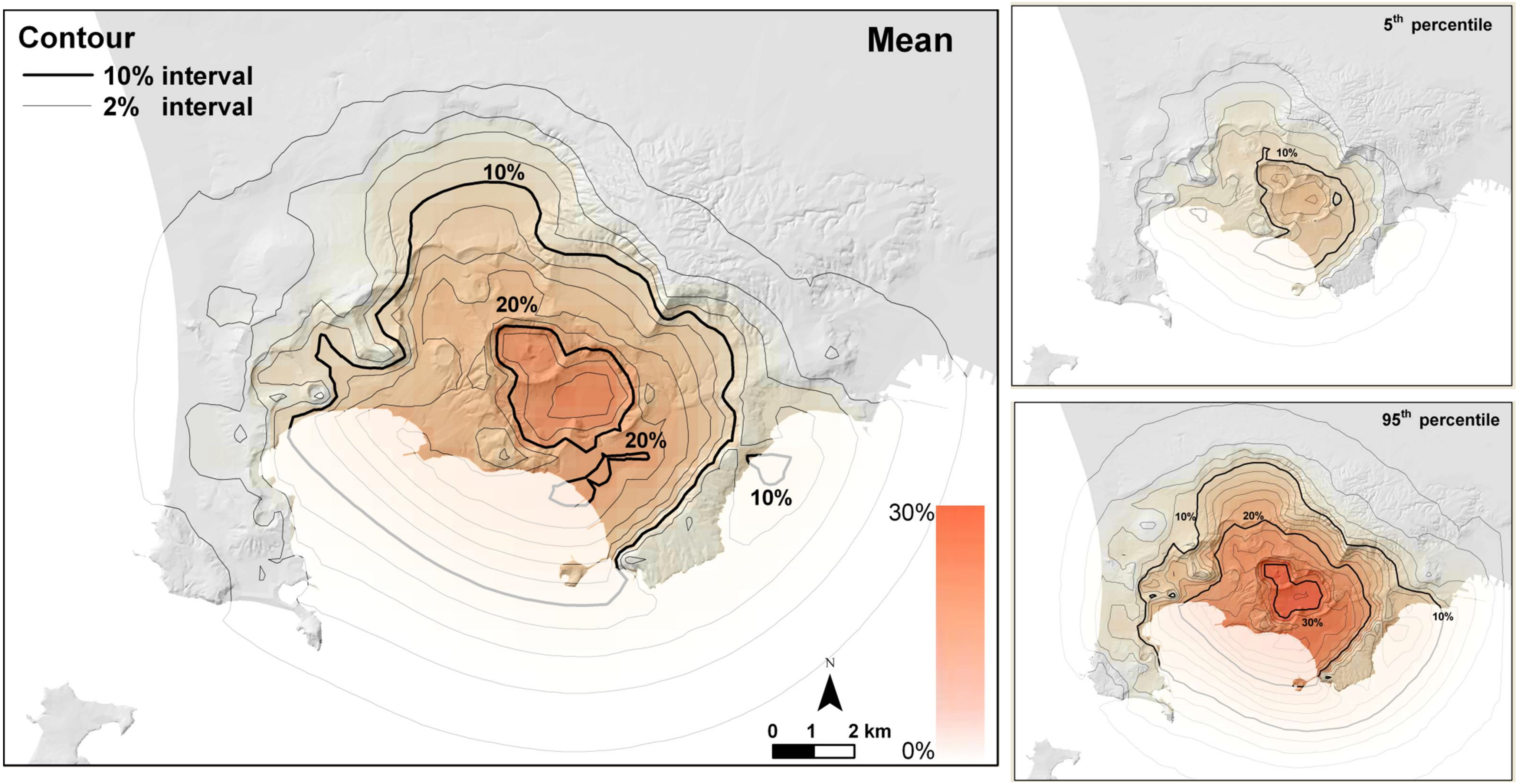


Fig 7. PDC invasion probability maps on a **50 years time window**, vents located in the on-land part of the caldera. Invasion areas scale and temporal model based treating separately the eastern and western sectors of the caldera. Contours and colours indicate the percentage probability of PDC invasion by explosive eruptions in the next 50 years.

Vent opening maps based on Bevilacqua et al. [2015], hazard maps based on Neri et al. [2015], Cox-Hawkes temporal model from Bevilacqua [2016] - PhD Thesis. Figure from Bevilacqua et. al [2016] - EGU2016 General Assembly, oral presentation.

Concluding remarks

- **Doubly stochastic models** are a general tool for assessing random systems that depend on uncertain information, as in the case of volcanic processes.

- **Cox and Hawkes processes** allow to consider data uncertainty and to reproduce spatial and temporal clustering of eruptive events. In the study developed both these features were considered together for the first time.

- Activity in the **western sector** involved significantly **smaller volumes**, but it was the first to appear in the **initial stages** of Epochs I and II, whereas no clear indication can be obtained from the data of Epoch III. This observation is compatible with the assumption that the Monte Nuovo eruption represents the start of a new epoch of activity.

- By assuming that Monte Nuovo represents the start of a new epoch of activity, and by considering the caldera as a whole, the **average time to the next eruptive event** is of the order of ~100-120 years, with the 5^{th} and 95^{th} percentiles of physical variability corresponding to ~5 and ~350 years, respectively. Epistemic uncertainty was quantified as ±25-35%.

- However, distinction between the **western and eastern sectors** of the caldera provides remarkably different average return times for the events (as well as clustering properness). As a consequence, time and scale separate analyses of the two sectors of the caldera would be more appropriate for hazard assessment purposes.

Publications

Quantifying volcanic hazard at Campi Flegrei caldera (Italy) with uncertainty assessment: I. Vent opening maps, *A. Bevilacqua , R. Isaia, A. Neri, S. Vitale , W. P. Aspinall, M. Bisson, F. Flandoli, P. J. Baxter, A. Bertagnini, T. Esposti Ongaro, E. Iannuzzi, S. Orsucci, M. Pistolesi, M. Rosi,* J Geophys Res, 120 (4), 2309-2329.

Quantifying volcanic hazard at Campi Flegrei caldera (Italy) with uncertainty assessment: II. Pyroclastic density current invasion maps, *A. Neri, A. Bevilacqua, T. Esposti Ongaro, R. Isaia, W. P. Aspinall, M. Bisson, F. Flandoli, P. J. Baxter, A. Bertagnini, E. Iannuzzi, S. Orsucci, M. Pistolesi, M. Rosi, S. Vitale*, J Geophys Res, 120 (4), 2330-2349.

Doubly Stochastic Models for Volcanic Hazard Assessment at Campi Flegrei Caldera, *A. Bevilacqua*, "PhD Thesis", Edizioni della Normale, Birkhäuser/Springer, (accepted).

Acknowlegments

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- **Project MED-SUV** "*Mediterranean Supersite Volcanoes*", European Union, 2013-2016.
- **Project DPC-V1** "*Valutazione della pericolosità vulcanica in termini probabilistici*", Dipartimento della Protezione Civile (Italy), 2012-2015.
- **Project EJN** "*Expert Judgment Network*", COST Action, European Union, 2013-2017.

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