IAEA ANSN / ISSC - REGIONAL WORKSHOP ON
"Volcanic, Seismic, and Tsunami Hazard Assessment Related to NPP Siting Activities and Requirements"
Jakarta, Indonesia, 13-17 June 2011

"Tephra fallout hazard maps: Application to the Neapolitan volcanoes"

(Antonio Costa)
INTERNATIONAL SEISMIC SAFETY CENTRE, NSNI/IAEA

IAEA
International Atomic Energy Agency

Lecture 12

IAEA

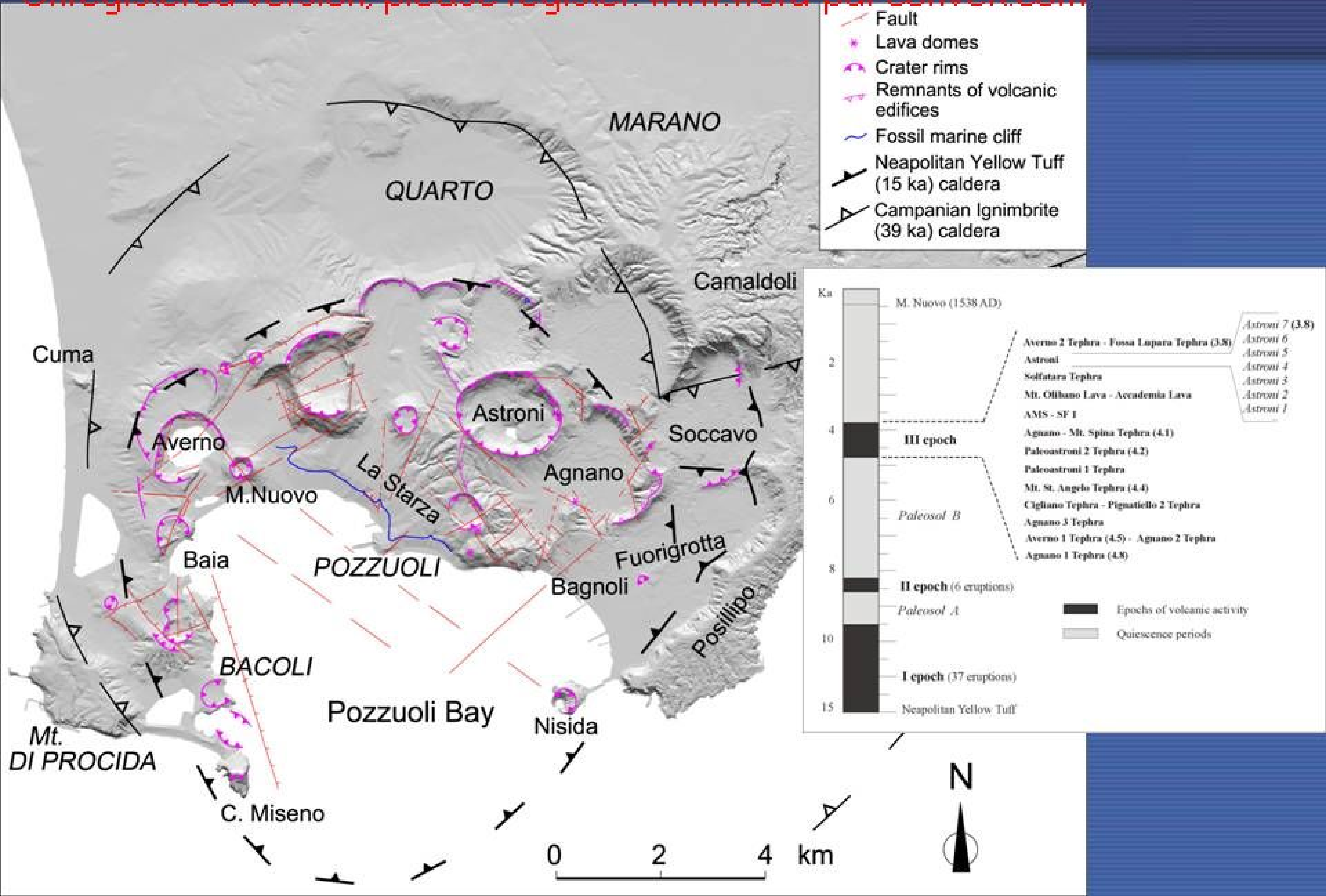
1 – Methodology for constructing tephra hazard maps for Campi Flegrei caldera, Naples, Italy

2 – Building in uncertainties (e.g. vent locations)

3 – Deterministic approach to forecast ash fallout from Vesuvius volcano, Naples, Italy

4 – Conclusion

Campi Flegrei Caldera



Campi Flegrei eruptions past 5ka

Table 1
Measured physical parameters for the explosive eruptions of the past 5 ka at Campi Flegrei caldera.

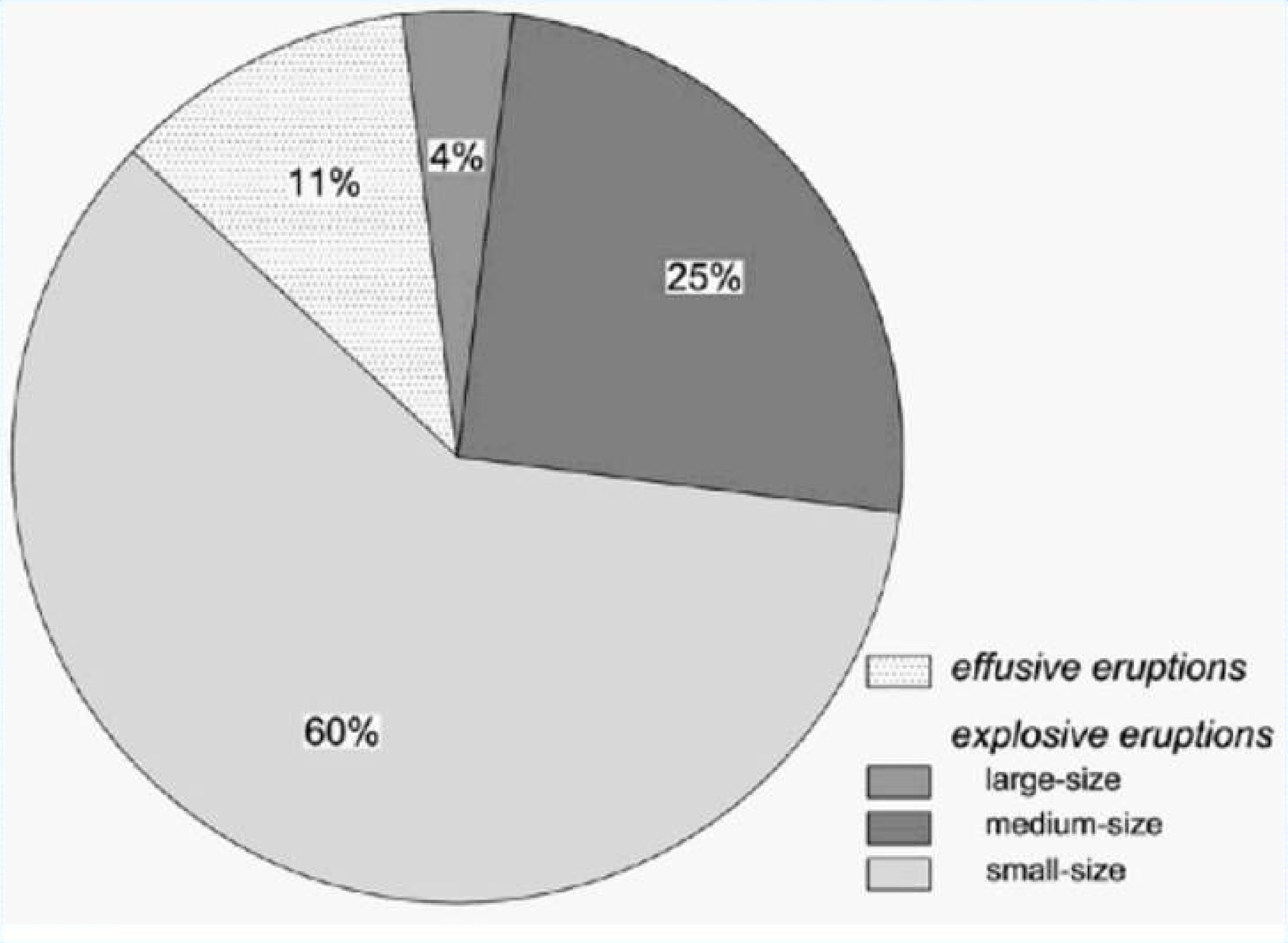
Eruption	Age (ka bp)	$Area_{1cm}$ (km^2)	$Area_{10cm}$ (km^2)	Volume Tephra (km^3)	Volume DRE (km^3)	Density (kg/m^3)	Total Erupted Mass ($kg*10^{11}$)	Magnitude	Mass Discharge Rate (kg/sec)
Agnano 1	4.80[a]	107	56	0.033	0.018	1400	0.46	3.66	
Averno 1	4.70[b]	262	103	0.095	0.053	1400	1.33	4.12	
Agnano 2	4.60[b]	58	19	0.025	0.014	1400	0.35	3.54	
Agnano 3	4.55[b]	872	414	0.333	0.186	1400	4.66	4.67	
Cigliano	4.50[b]	91	54	0.093	0.052	1400	1.30	4.11	
Pignatiello 2	4.45[b]	29	18	0.028	0.016	1400	0.39	3.59	
Monte S. Angelo	4.40[a]	230	121	0.125	0.070	1400	1.75	4.24	
Paleo Astroni 1	4.30[b]	159	82	0.090	0.050	1400	1.26	4.10	
Paleo Astroni 2	4.20[a]	648	218	0.178	0.010	1400	2.49	4.40	
Agnano–Monte Spina	4.10[a]	2,237	882	1.940	0.854	1100	21.30	5.33	$1.2*10^8$
Paleo Astroni 3	3.95[b]	45	29	0.033	0.018	1400	0.46	3.66	
Solfatara	3.90[b]	78	31	0.046	0.026	1400	0.64	3.81	
Astroni 1	3.88[b]	223	127	0.108	0.060	1400	1.51	4.18	
Astroni 2	3.87[b]	78	46	0.035	0.020	1400	0.49	3.69	
Astroni 3	3.86[b]	593	274	0.281	0.157	1400	3.93	4.59	
Astroni 4	3.85[b]	710	226	0.242	0.135	1400	3.39	4.53	
Astroni 5	3.84[b]	817	427	0.184	0.103	1400	2.58	4.41	
Astroni 6	3.83[a]	893	365	0.233	0.121	1300	3.03	4.48	$7.4*10^6$
Astroni 7	3.82[a]	110	50	0.116	0.065	1400	1.62	4.21	
Averno 2	3.80[b]	85	45	0.139	0.067	1200	1.67	4.22	$3.2*10^6$
Fossa Lupara	3.75[b]	24	11	0.041	0.016	1000	0.41	3.61	
Monte Nuovo	0.50	28	17	0.052	0.029	1400	0.73	3.86	$2.0*10^6$

[a] Measured and [b] inferred ages from Di Vito et al. (1999) and Orsi et al. (2004).

(After Orsi et al., 2009)

IAEA

Probability of eruption styles (last 5000 yrs, ~25 eruptions)



IAEA

(Orsi et al., 2009)

Expected eruption scenarios at Campi Flegrei

Scale	Mass flow-rate (kg/s)	Total Mass (kg)	Composition
Low	$10^5 – 10^6$	$\sim 10^{10}$	Independent from the scale
Medium	$10^6 – 10^7$	$\sim 10^{11}$	Independent from the scale
High	$> 10^7$	$>5X10^{11}$	Independent from the scale

IAEA

Probability of scenarios at Campi Flegrei

Size	A_{1cm} (km^2)	V_{Tephra} (km^3)	V_{DRE} (km^3)	TEM ($kg*10^{11}$)	Magnitude	Type esruption(s)
Large	>500	>0.40	>0.3	>5	>5	Agnano–Monte Spina
Medium	500–1000	0.15–0.40	0.1–0.3	2–5	4.3–5	Astroni 6
Small	0–500	0–0.15	0–0.1	0–2	<4.3	Monte Nuovo; Averno2

Total mass

Eruption size class	Average best guess probability	Confidence intervals (epistemic uncertainty)		
		10th perc	50th perc	90th perc
Large explosive	3.73×10^{-2}	5.78×10^{-3}	2.67×10^{-2}	7.50×10^{-2}
Medium explosive	2.50×10^{-1}	1.49×10^{-1}	2.36×10^{-1}	3.55×10^{-1}
Small explosive	6.06×10^{-1}	4.99×10^{-1}	6.14×10^{-1}	7.22×10^{-1}
Effusive	1.07×10^{-1}	3.89×10^{-2}	9.84×10^{-2}	1.86×10^{-1}

IAEA

(Orsi et al., 2009)

Characterization of Reference Scenarios

As a HM scenario we consider an eruption with parameters similar to the **AMS** (4.1 ka BP) ash fallout phases **B1** and **D1** with a mass equal to the total **B1+D1** masses and average parameters.

As a MM scenario we consider an eruption with parameters similar to the ASTRONI (3.8 ka BP) ash fallout phase U6. Mass was cautiously overestimated in order to take into account the distal massive fine ash deposits associated to the pyroclastic currents of U6 dispersed on an area larger than the basal pumice fallout deposit with an impact on the ground mostly related to their loading.

The LM scenario is represented by the A2 fallout layer of the Averno 2 eruption (3.8 ka BP)

Adopted ash dispersal models

- **HAZMAP** (Macedonio et al., 2005): Based on an analytical solution of the advection-diffusion-sedimentation equation for ash dispersal. Other models based on the same approach are TEPHRA2 (Bonadonna et al 2005) and ASHFALL (Hurst and Turner, 1999).
  Principal assumption: constant horizontal wind, negligible vertical diffusion.
  MOSTLY USED FOR SMALL DOMAIN AND STATISTICAL ANALYSIS.

- **FALL3D** (Costa et al., 2006; Folch et al., 2008): Full 3D time-dependent Eulerian model that solve numerically the advection-diffusion-sedimentation equation for ash dispersal.
  MOSTLY USED FOR LARGE DOMAIN AND REAL-TIME ANALYSIS.

IAEA

The computational model HAZMAP

Based on a semi-analytical solution of the ADS equation:

$$\partial C/\partial t + \mathbf{U}\cdot\nabla C - \partial(V_{sj}C)/\partial z = \nabla\cdot(K\nabla C) + S$$

Deposit: sum of Gaussian deposits generated by point sources

Wind field: constant in time; uniform in x,y; variable in z (layers)

Diffusion coefficients: constant

Settling velocity: many classes; variable in z

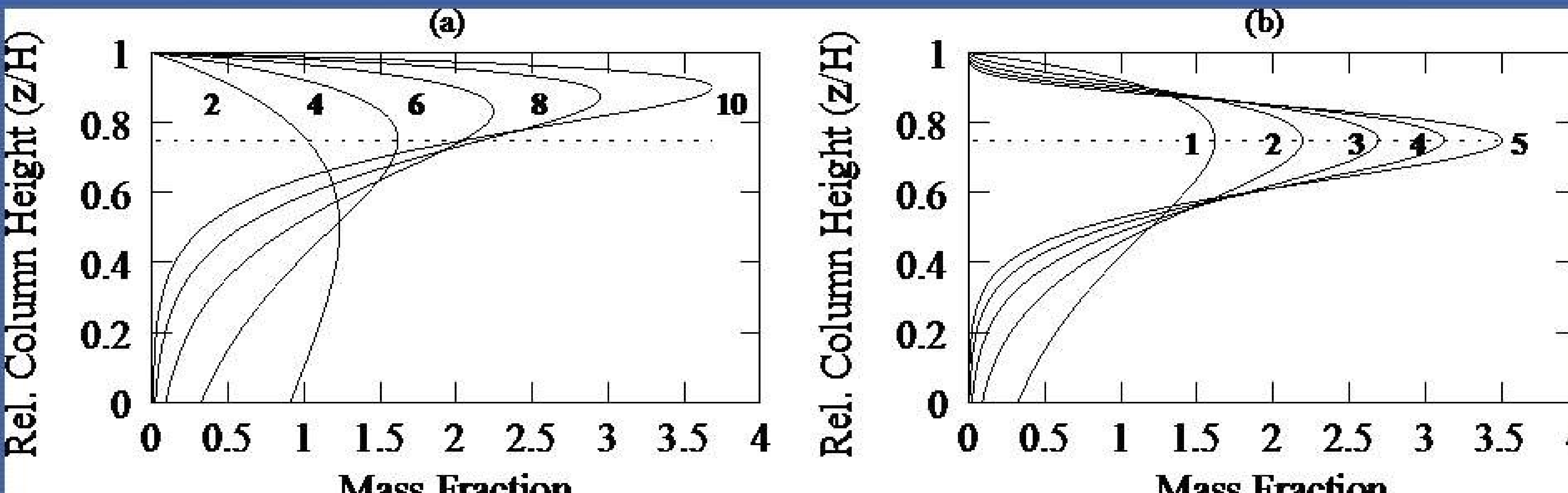
Input: mass, column height and shape, settling velocity distribution, wind profile

Output: mass loading on the ground (one wind profile), or probability of a loading greater than a threshold (many wind profiles)

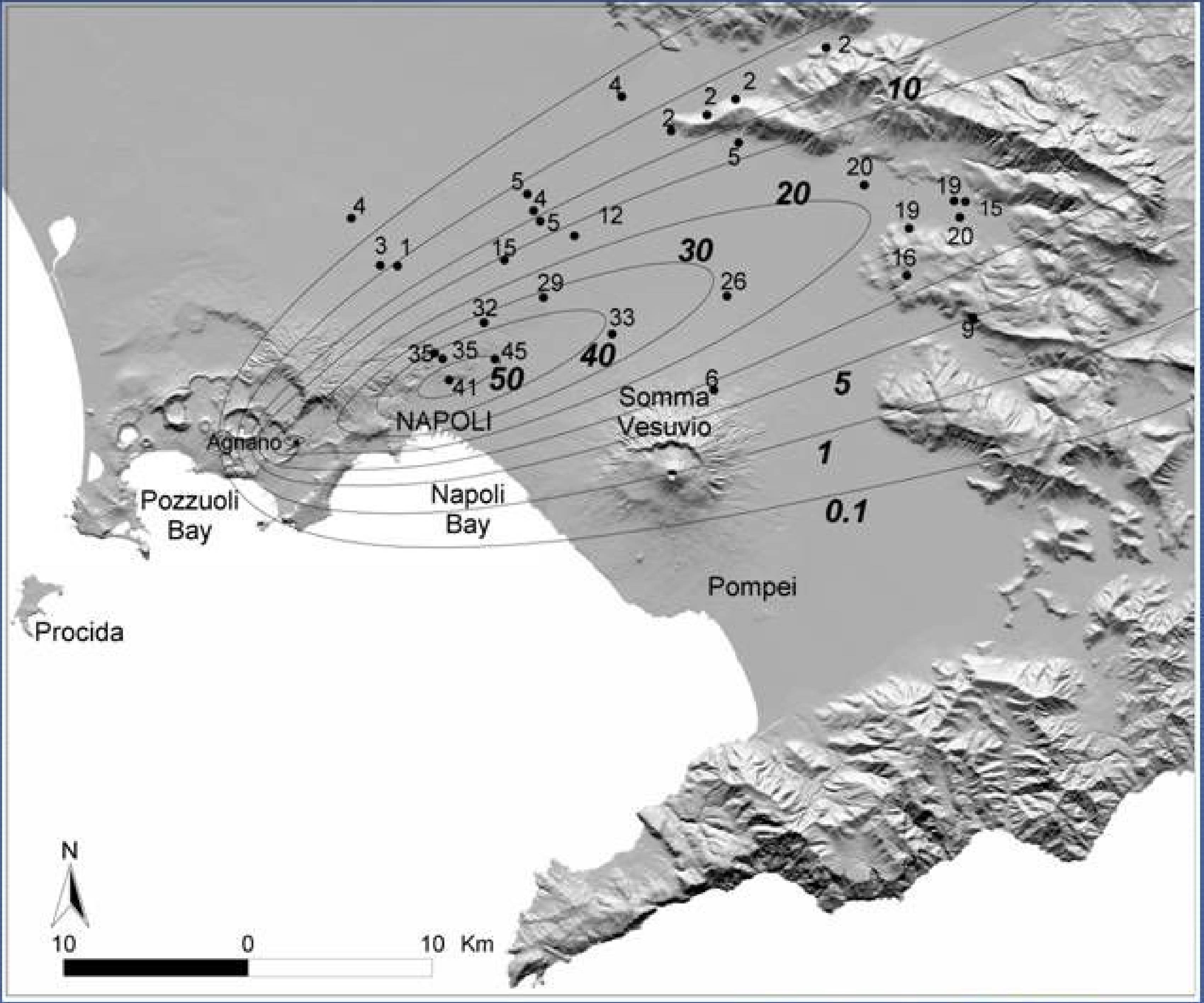
IAEA

Input parameters

- Total Mass;
- Bulk Granulometry;
- Wind and Turbulence Coefficient;
- Column Height; and
- Mass Distribution Parameters ($S(z)=S_0\exp\{1-z/H[A(z/H-1)]\}^{l}$).



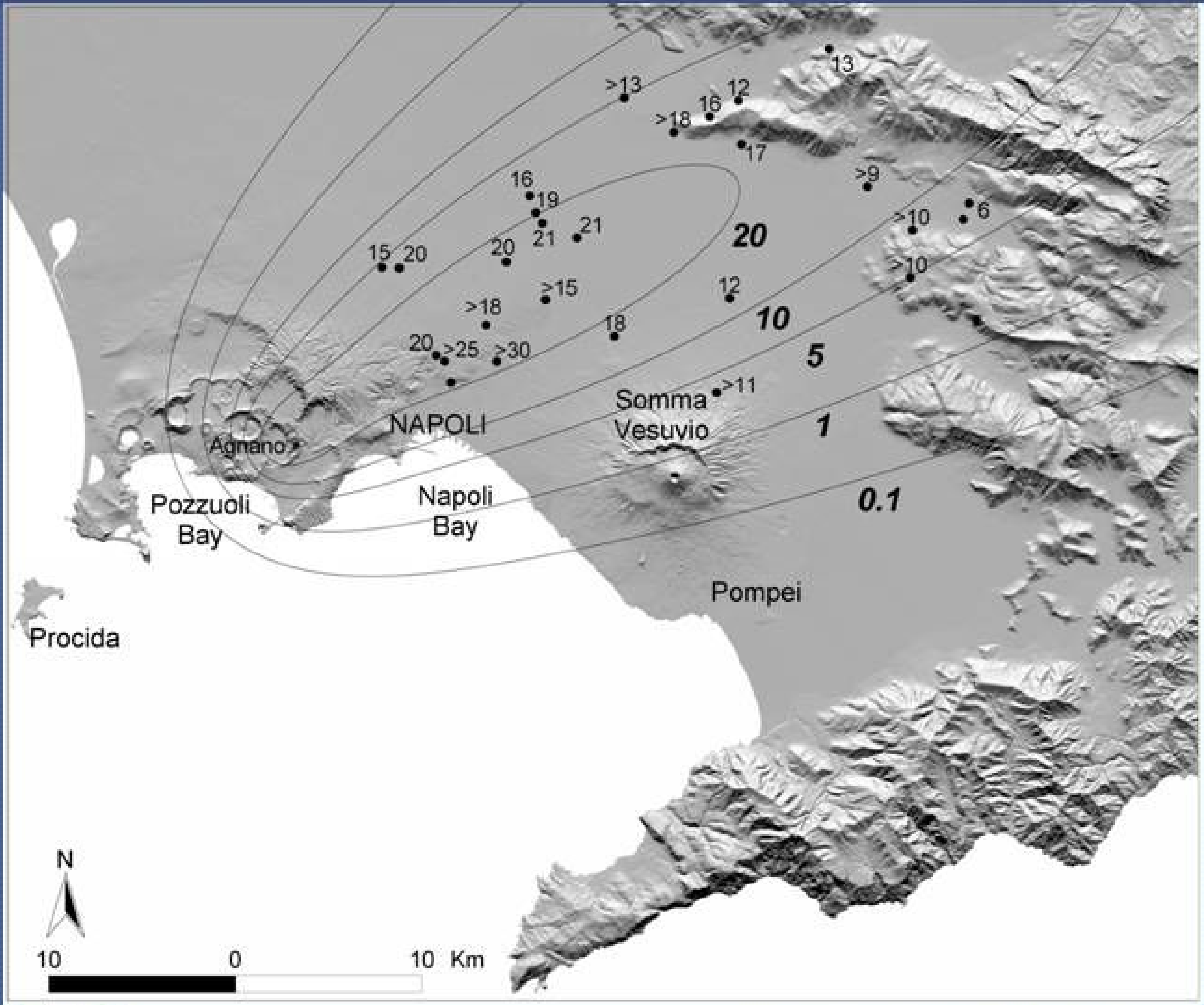
Reconstructed AMS (B1) isopachs



(Costa et al., 2009)

IAEA

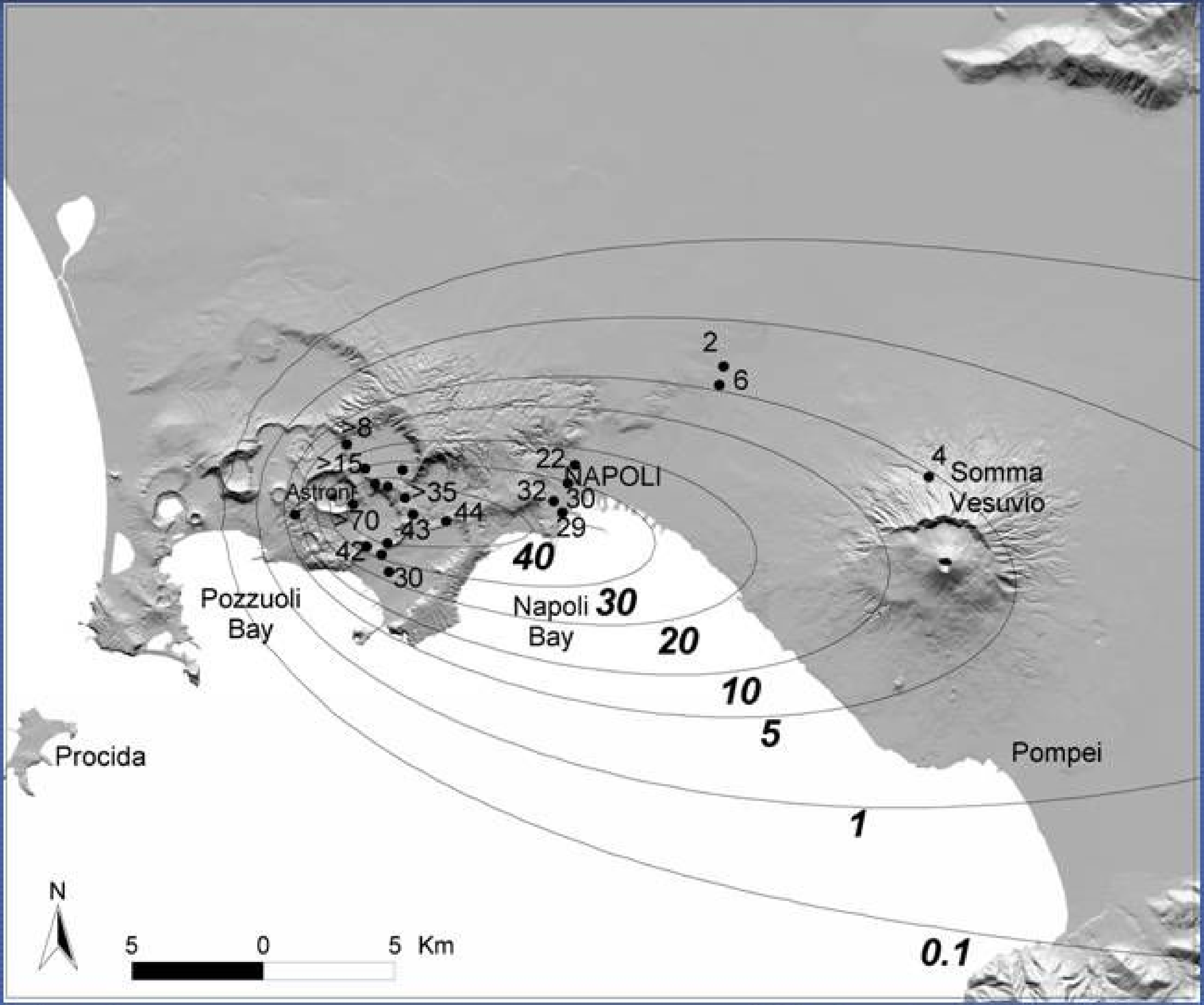
Reconstructed AMS (D1) isopachs



IAEA

(Costa et al., 2009)

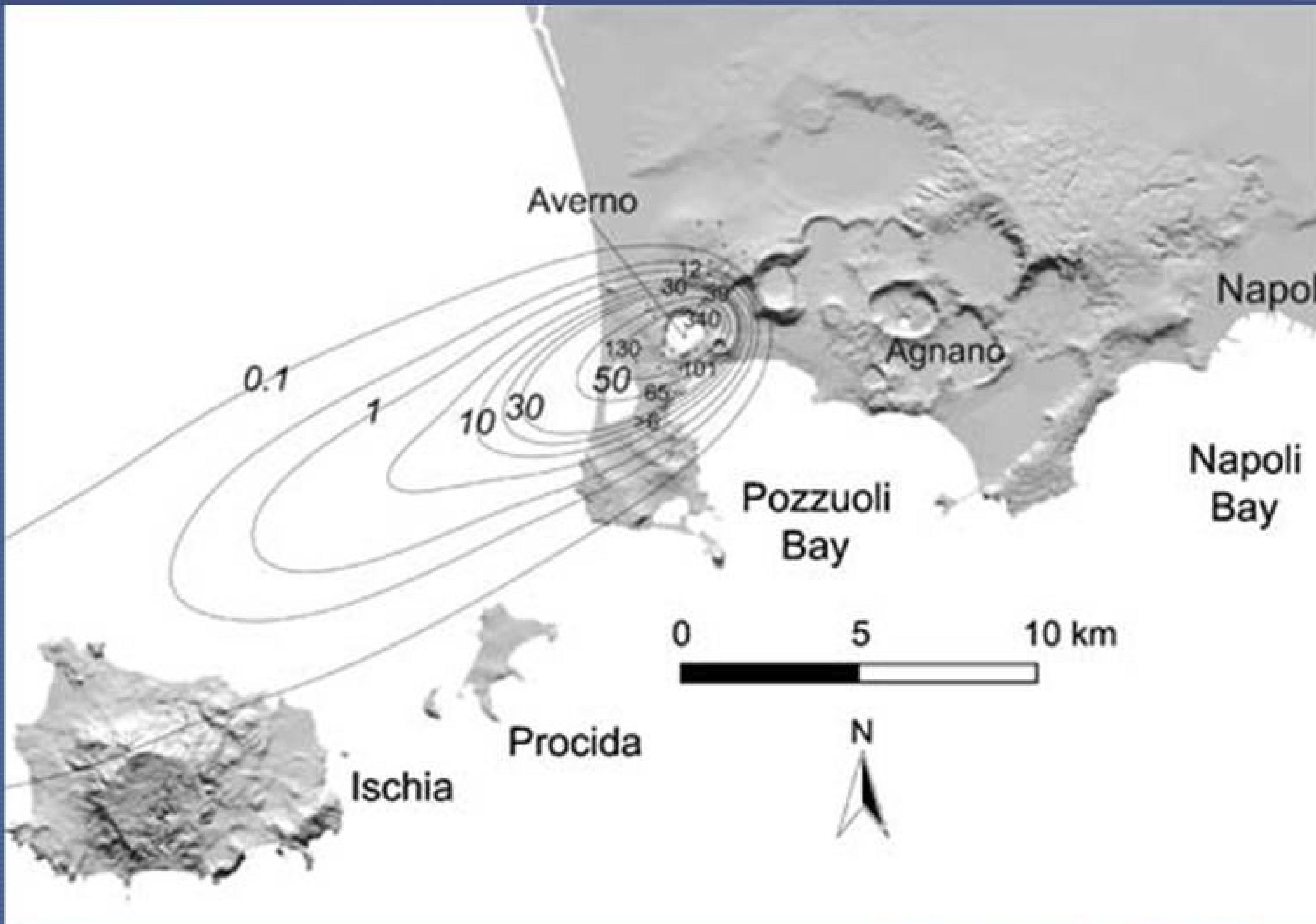
Reconstructed Astroni (U6) isopachs



IAEA

(Costa et al., 2009)

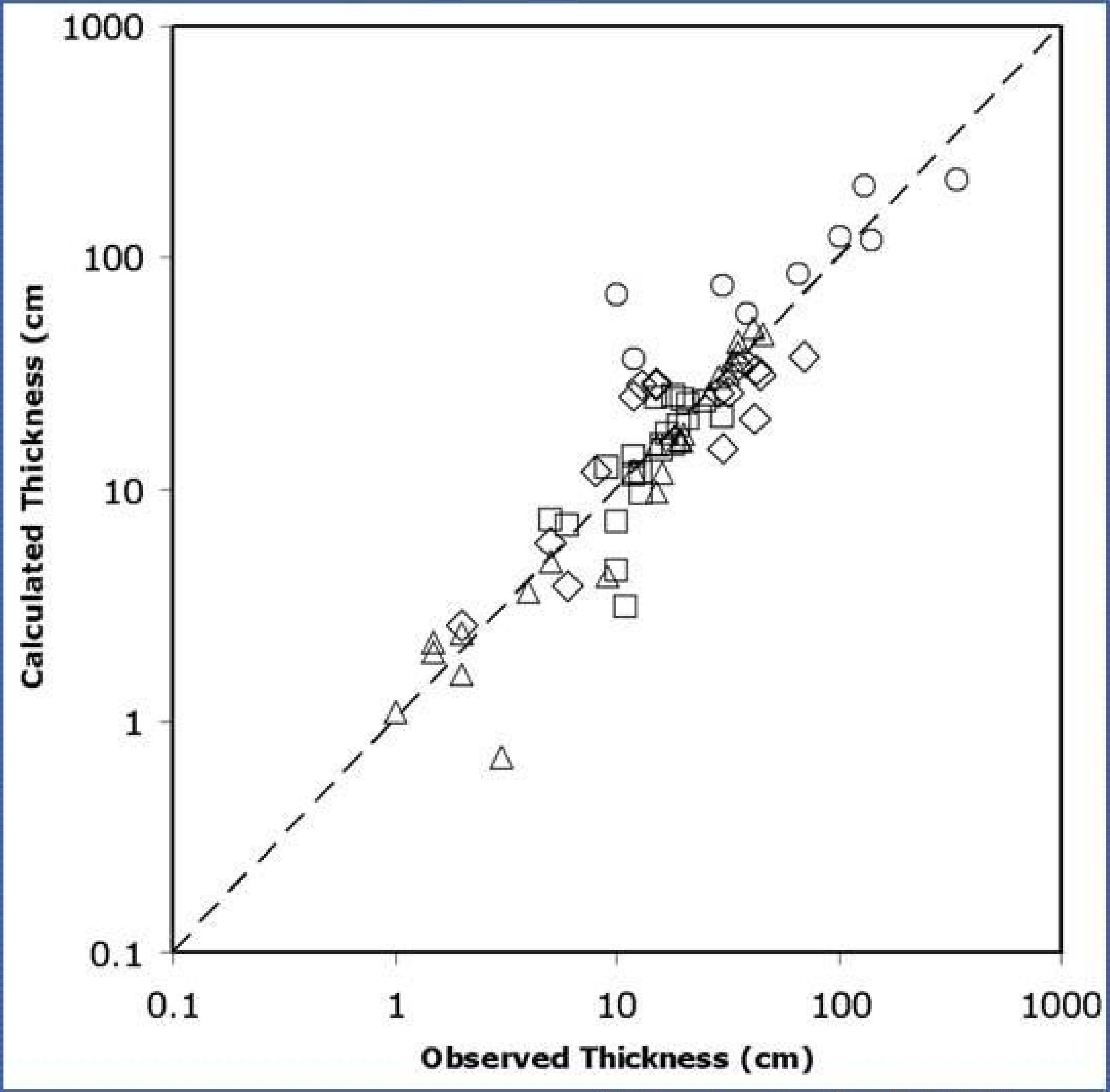
Reconstructed Averno (Af2) isopachs



(Costa et al., 2009)

IAEA

Validation



(Costa et al., 2009)

IAEA

Input parameters fallout hazard maps at Campi Flegrei

Table 1 Input parameters used for probability maps construction

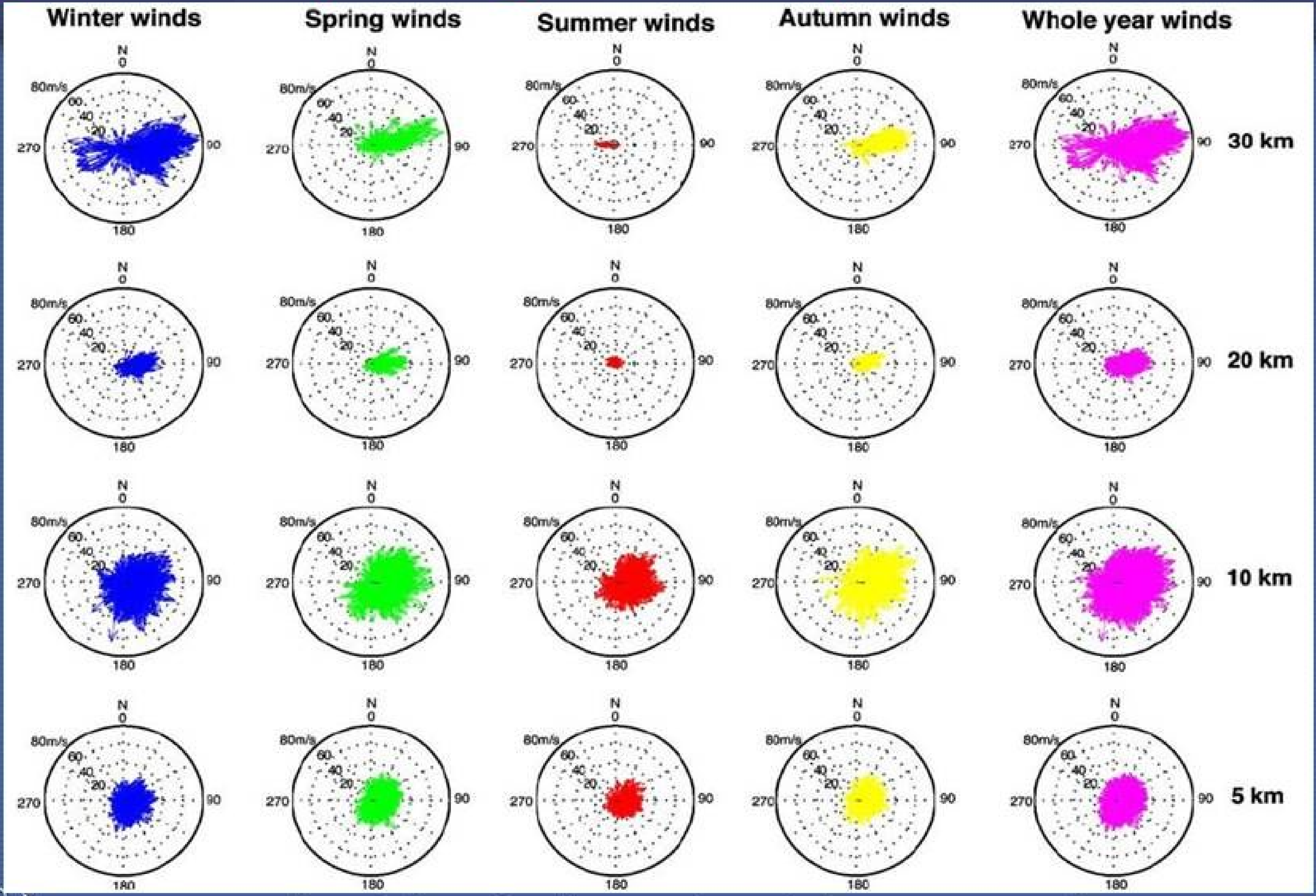
Model parameters	Scenario type		
	High-magnitude (Plinian) "AMS (B1+D1)"	Medium-magnitude (sub-Plinian) "ASTRONI (U6)"	Low-magnitude (violent Strombolian) "Af2"
Total mass	5.2×10^{11} kg	1.2×10^{11} kg[a]	2.3×10^{10} kg
Column height	26 km	12 km	7 km
Column shape coefficients: A/λ	4/1	4/1	3/1
Number of V_{sett}-classes	6	6	6
Bulk settling velocity distribution: V_{sett} (Wt%)	0.5 m/s (18); 2.5 m/s (52); 4.5 m/s (18); 6.5 m/s (6); 8.5 m/s (3); 10.5 m/s (3)	0.5 m/s (12); 2.5 m/s (28); 4.5 m/s (36); 6.5 m/s (17); 8.5 m/s (5); 10.5 m/s (2)	0.5 m/s (10); 2.5 m/s (16); 4.5 m/s (29); 6.5 m/s (26); 8.5 m/s (12); 10.5 m/s (7)
Diffusion coefficient K	5000 m^2/s	5000 m^2/s	1000 m^2/s
Mass eruption rate	$\lesssim10^8$ kg/s	$\lesssim10^7$ kg/s	$\lesssim10^6$ kg/s
Daily wind profiles (period 1968–2003)	NOAA (lat 40°; long 15°)	NOAA (lat 40°; long 15°)	NOAA (lat 40°; long 15°)
References	Pfeiffer and Costa (2004a)	Pfeiffer and Costa (2004b)	Di Vito et al. (2004)
Total mass using Pyle (1989)	3.6×10^{11} kg (B1) 5.1×10^{11} kg (D1)	1.0×10^{11} kg[a]	3.9×10^{10} kg
Max column height using Carey and Sparks (1986)	23 km (B1); 27 km (D1)	14 km	10 km

Mass eruption rates, given by buoyant plume theory, total mass, calculated using Pyle (1989), and column height, estimated according to Carey and Sparks (1986), are also reported for completeness.
[a] Including fine ashes (see text for details)

(Costa et al., 2009)

IAEA

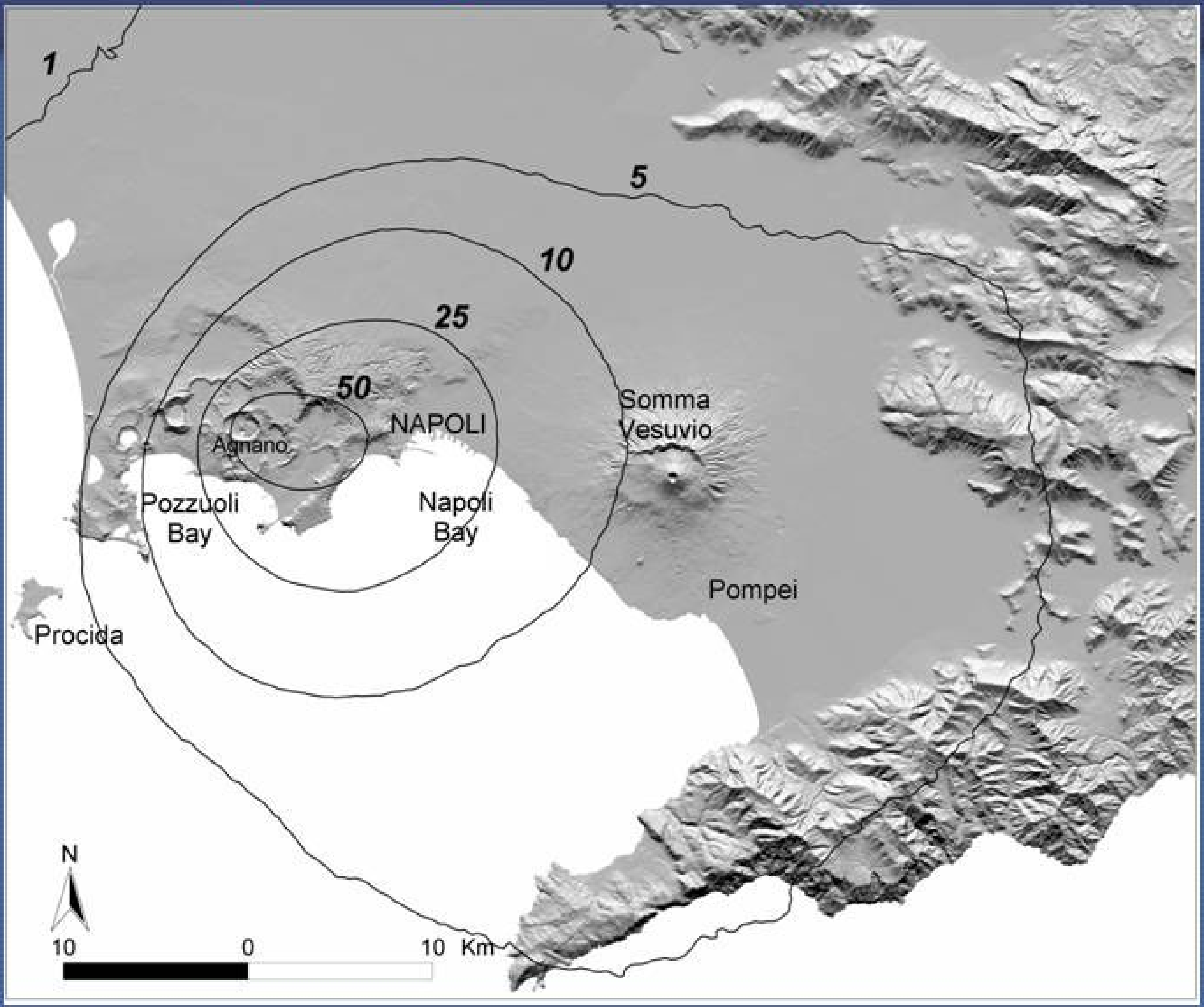
Wind profiles for probability maps



Daily Wind Profiles(#>13000): Period 1968-2003; At lat=40°, long=15° (from NOAA)

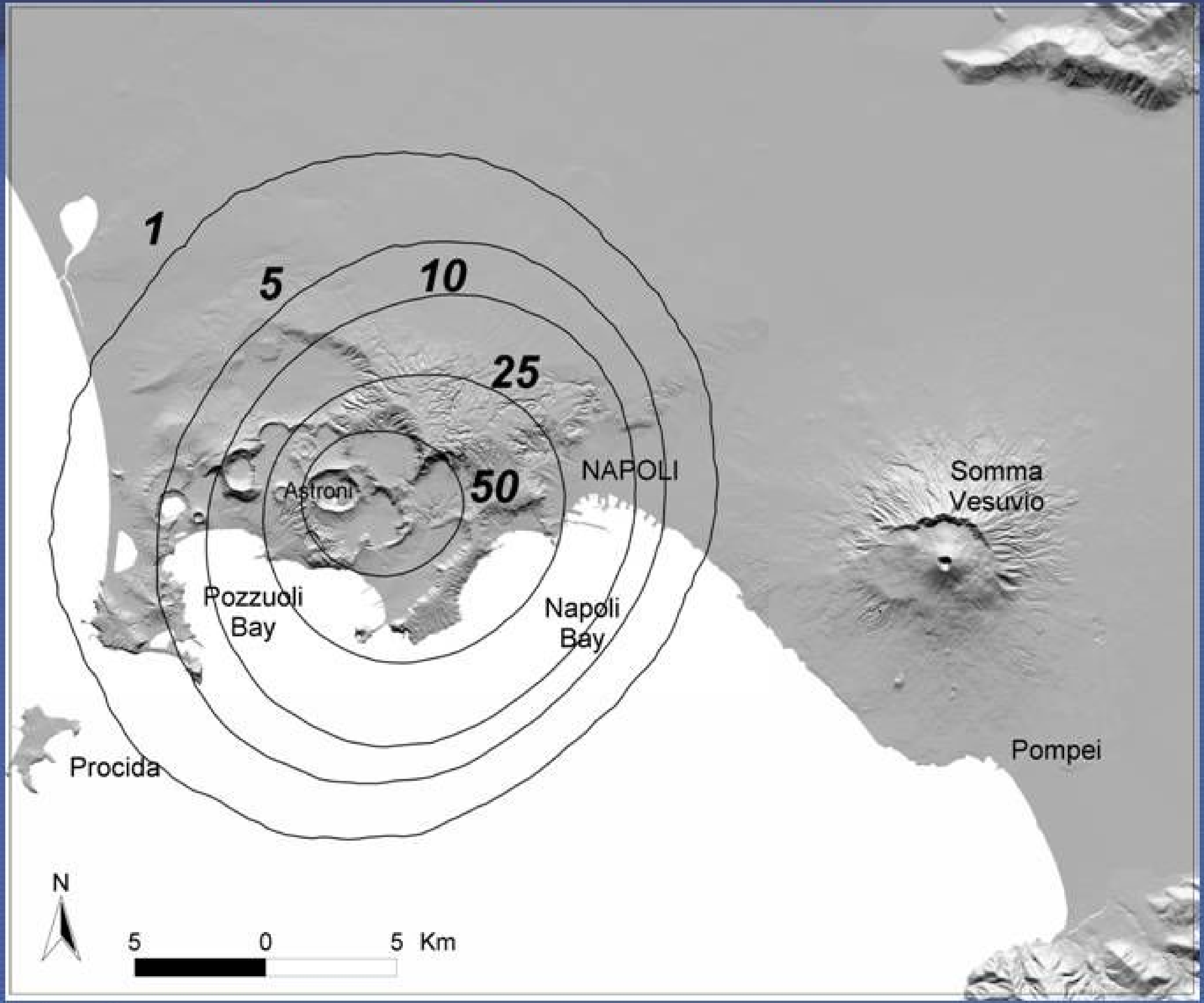
IAEA

HM Scenario: Probability Maps for Ash Fallout (300 kg/m^2)



IAEA

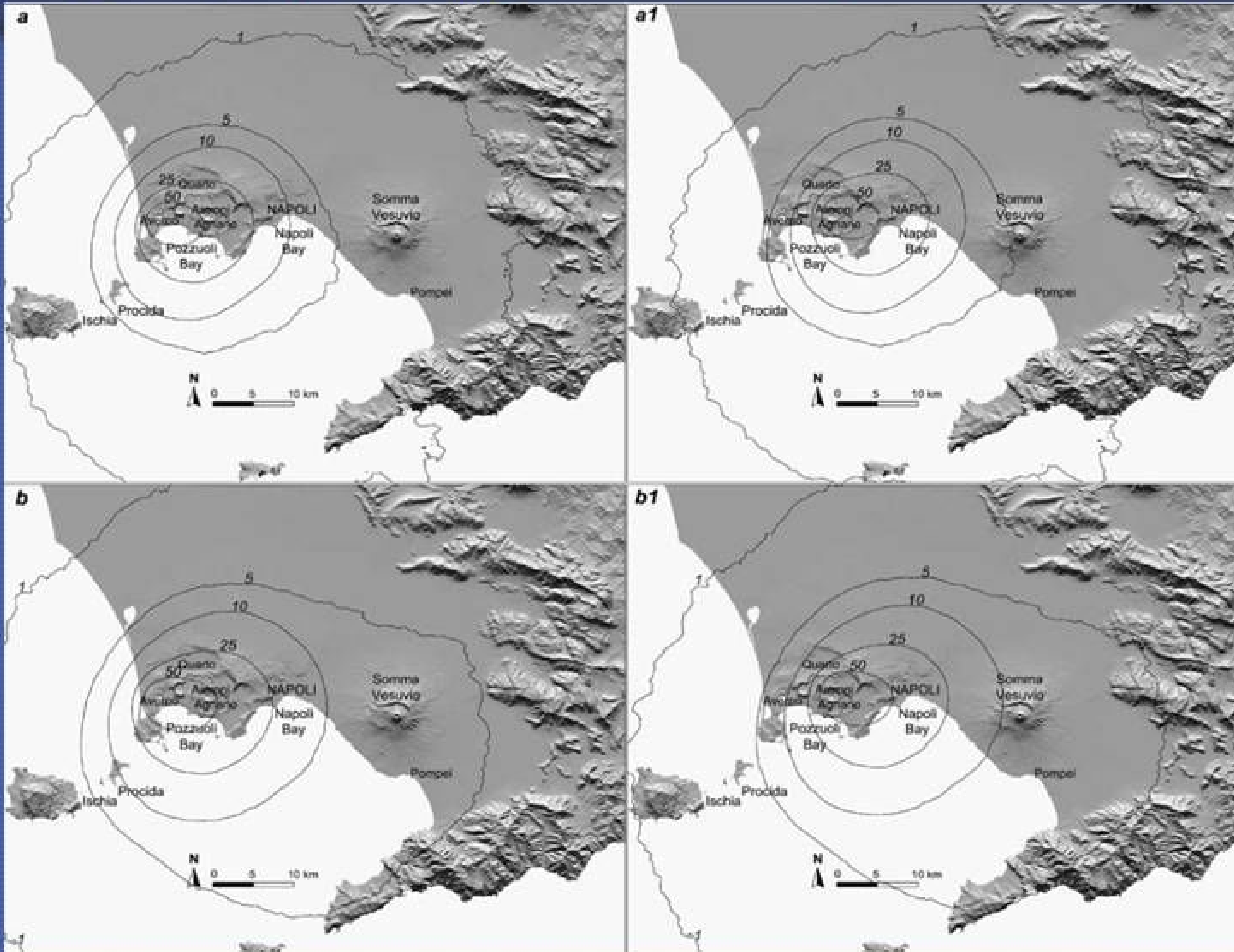
MM Scenario: Probability Maps for Ash Fallout (300 kg/m^2)



IAEA

Ash loading probability map for a Plinian eruption at Campi Flegrei

(different loading thresholds and vent locations)



400 kg/m²

300 kg/m²

IAEA

Vent at Averno-Monte Nuovo

Vent at Agnano-San Vito

BET Structure & Probability

BET_EF
short to long-term

BET_VH
long-term

Node 1	Node 2	Node 3	Node 4	Node 5	Node 6	Node 7	Node 8
unrest	magma	eruption	vent	size	outcome	reaching area (1 to M)	Overcoming threshold
Yes	Yes	Yes	ALL LOCs	ALL SIZEs	Tephra fall	Yes	Yes
No	No	No	LOC 1	SIZE 1	Pyroclastic flows	No	No
			…	…	Lava Flows		
			LOC N	SIZE M	…		

The probability π of the SELECTED PATH is the product of conditional probability θ_i at ALL SELECTED BRANCHES:

$$[\pi] = [\theta_1] \bullet [\theta_2] \bullet [\theta_3] \bullet [\theta_4] \bullet [\theta_5] \bullet \ldots$$

BET_VH

- BET_VH evaluates long-term probability (and uncertainty) of:
  - Node 6: outcome producing
  - Node 7: outcome reaching a certain area
  - Node 8: outcome overcoming a given threshold in the area
- BET_VH allows to produce:
  - One or few single scenario/s (i.e. Agnano Monte Spina)
  - Multiple joint-scenario with ALL possible:
    VENT positions; and
    SIZE of the eruptions

Bull Volcanol
DOI 10.1007/s00445-010-0358-7

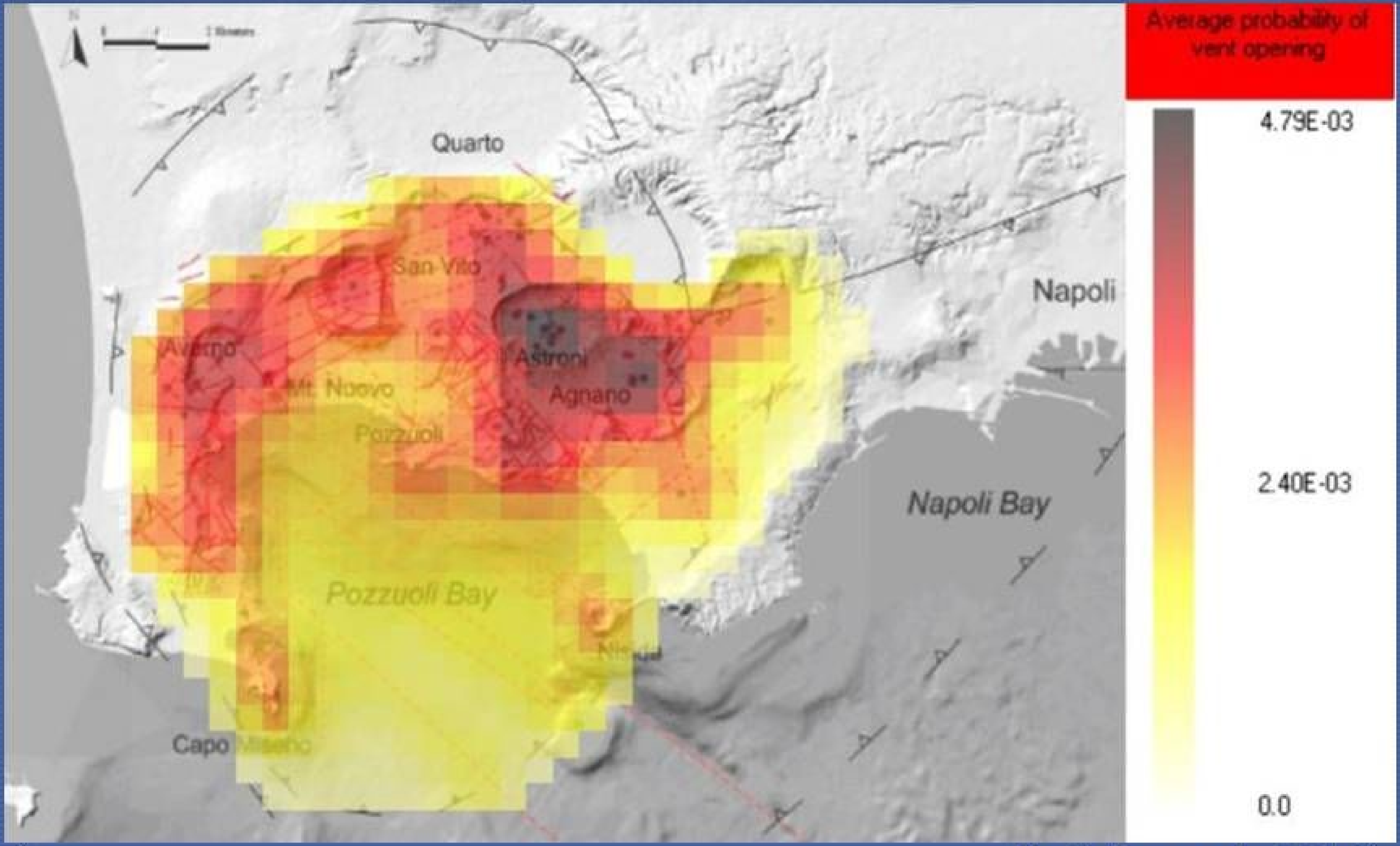
RESEARCH ARTICLE

BET_VH: exploring the influence of natural uncertainties on long-term hazard from tephra fallout at Campi Flegrei (Italy)

Jacopo Selva · Antonio Costa · Warner Marzocchi · Laura Sandri

IAEA

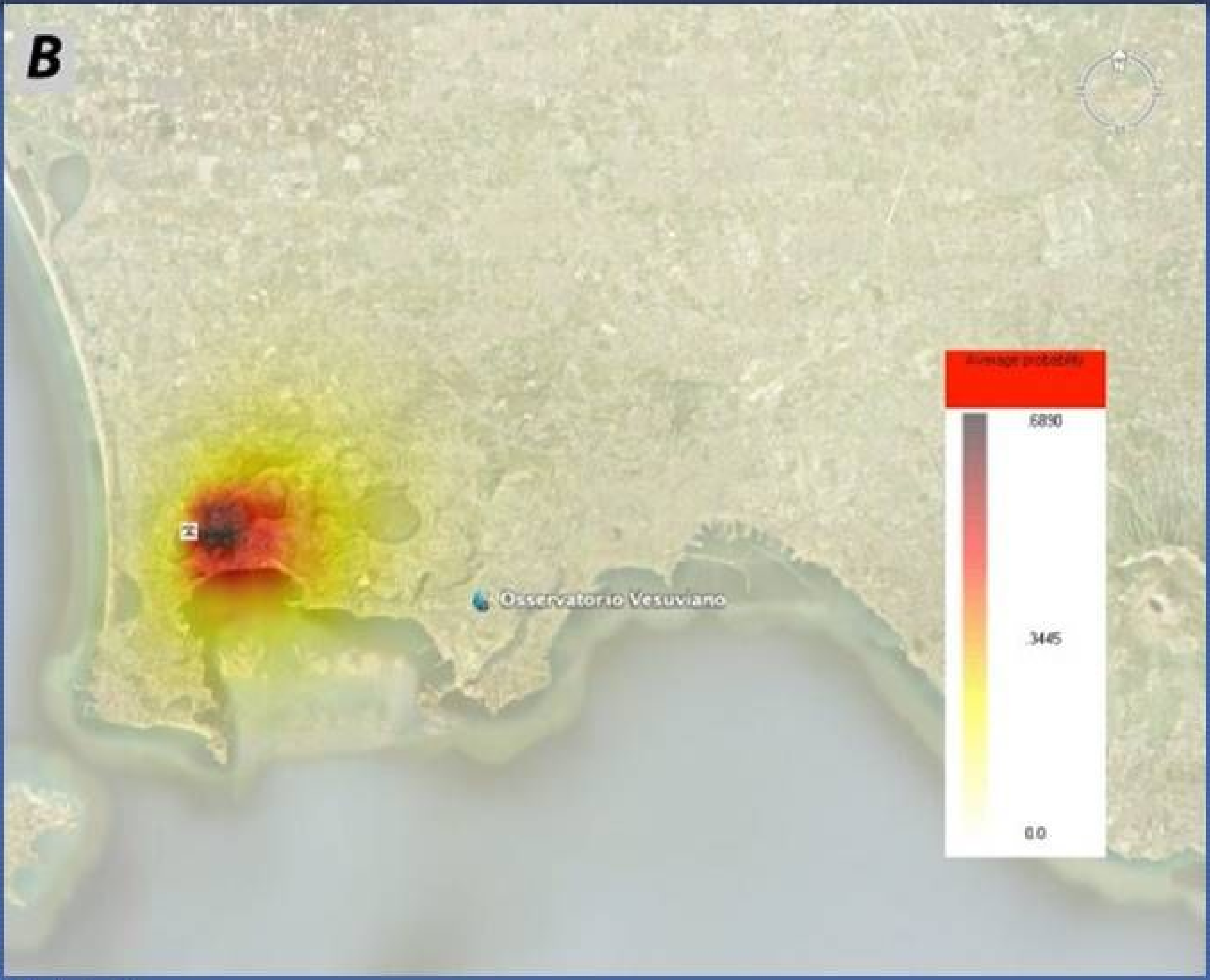
Probability of vent location



(da Selva et al., 2010)

IAEA

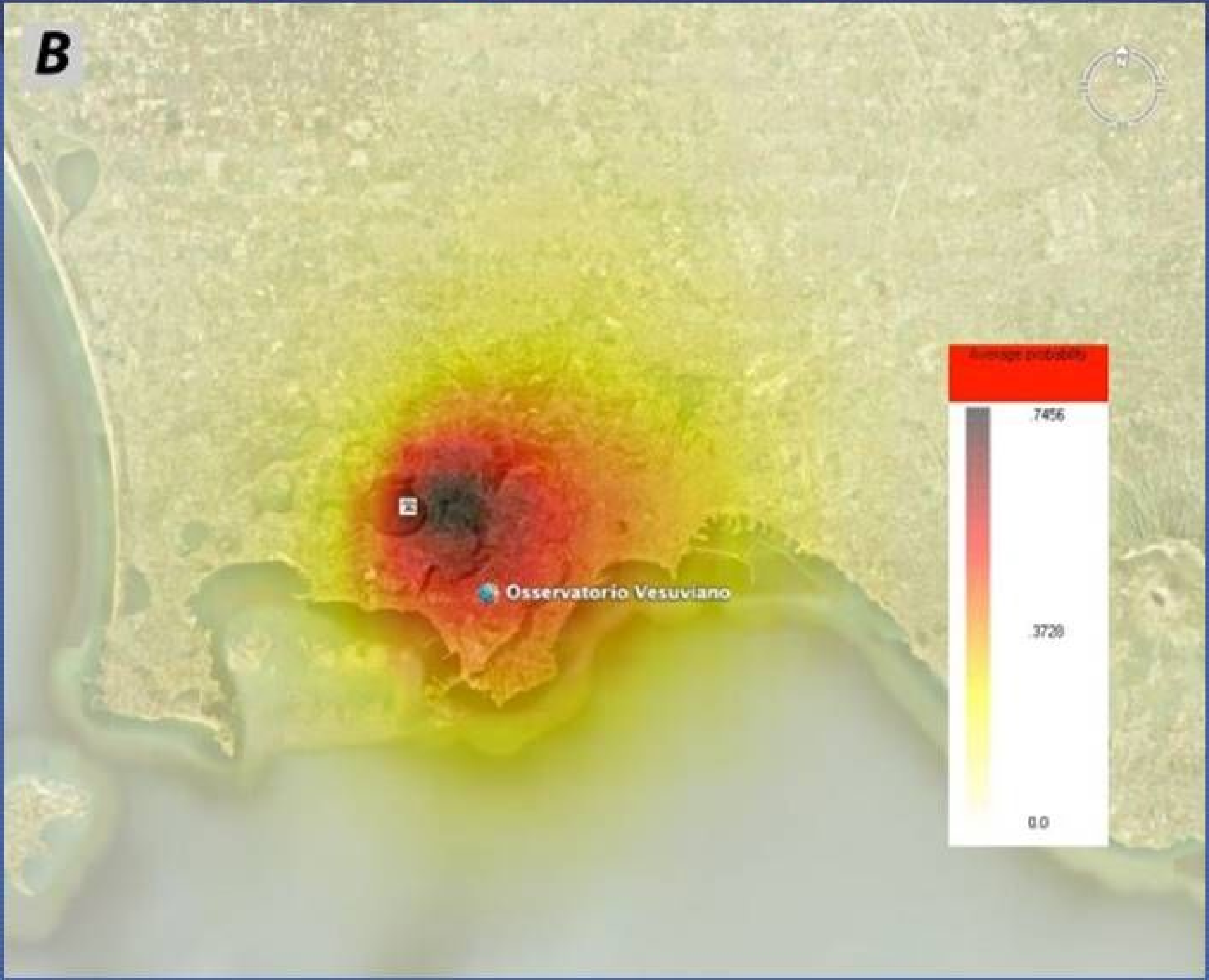
Probability of exceeding 300 kg/m^2 loading for the LM scenario



IAEA

One single vent

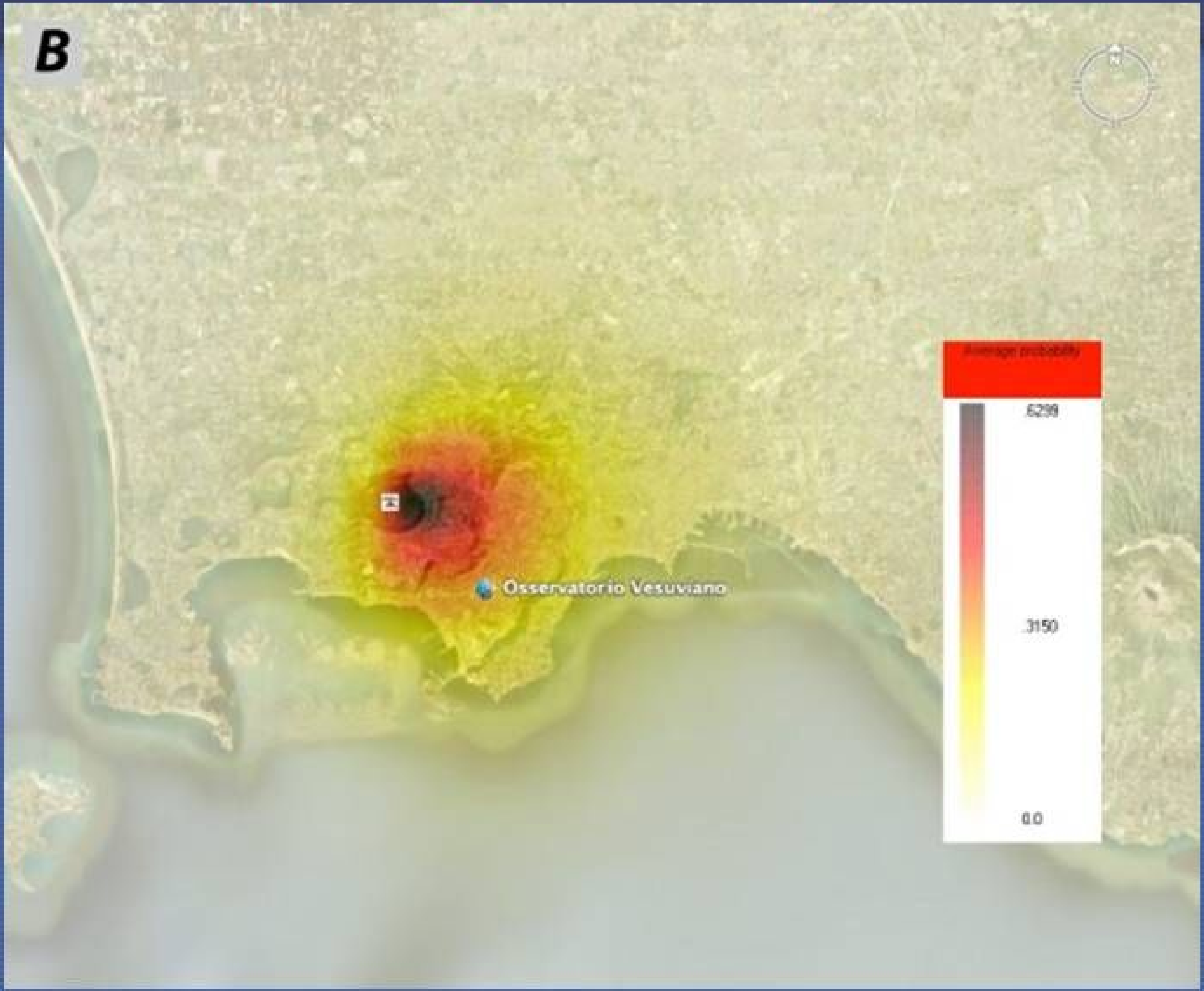
Probability of exceeding 300 kg/m^2 loading for the MM scenario



IAEA

One single vent

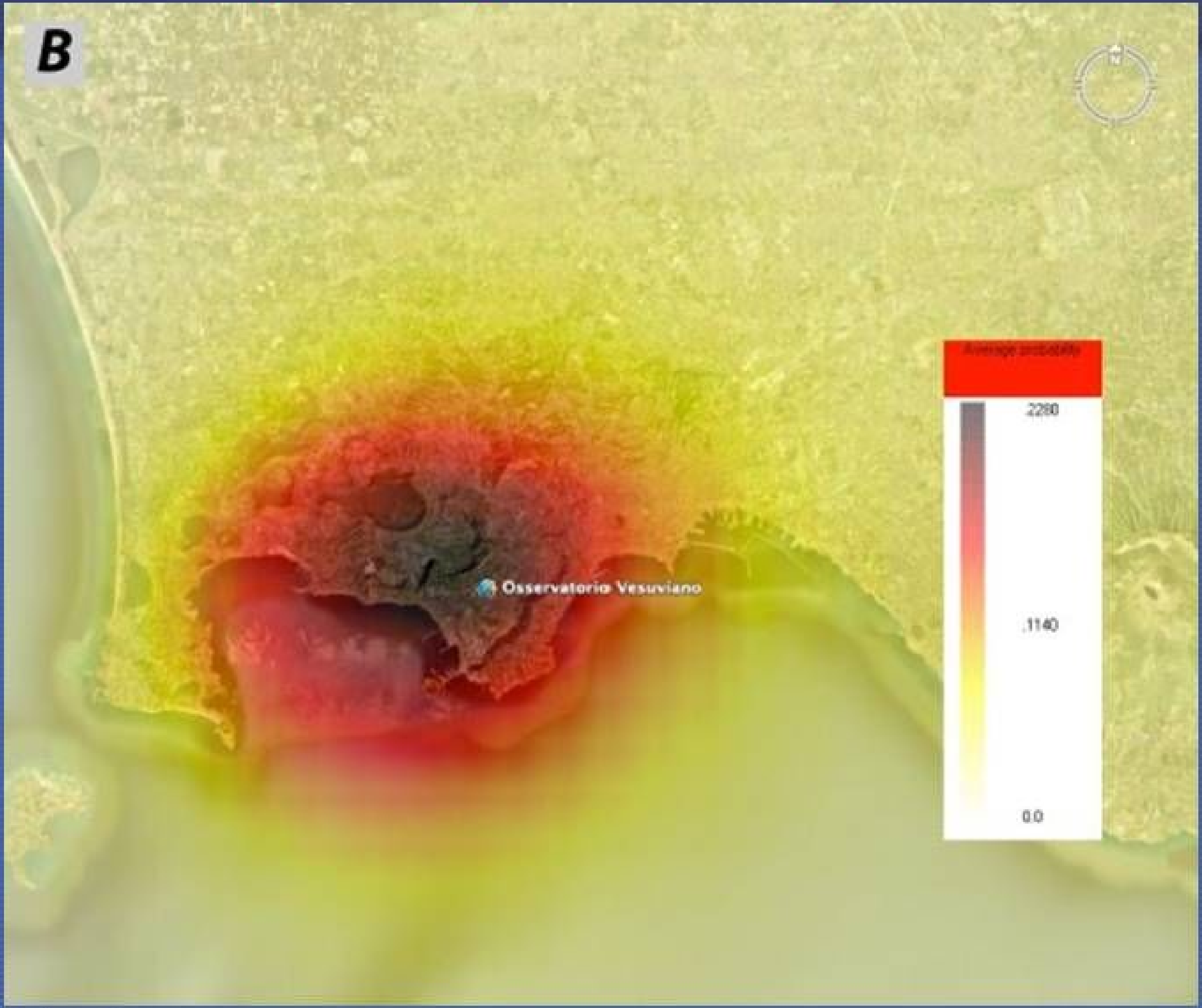
Probability of exceeding 300 kg/m^2 loading weighting all scenarios



IAEA

One single vent

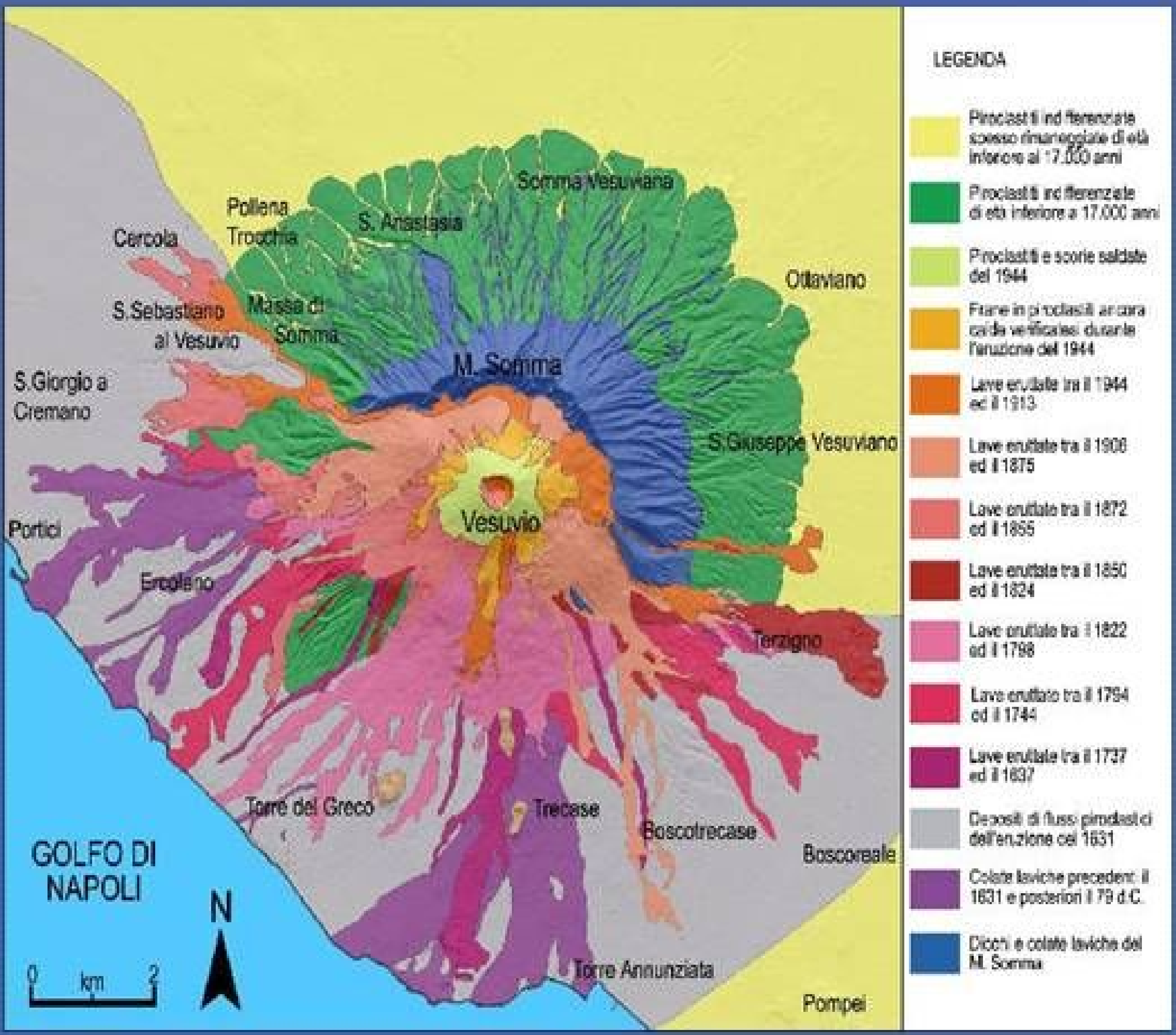
Probability of exceeding 300 kg/m^2 loading weighting all scenarios

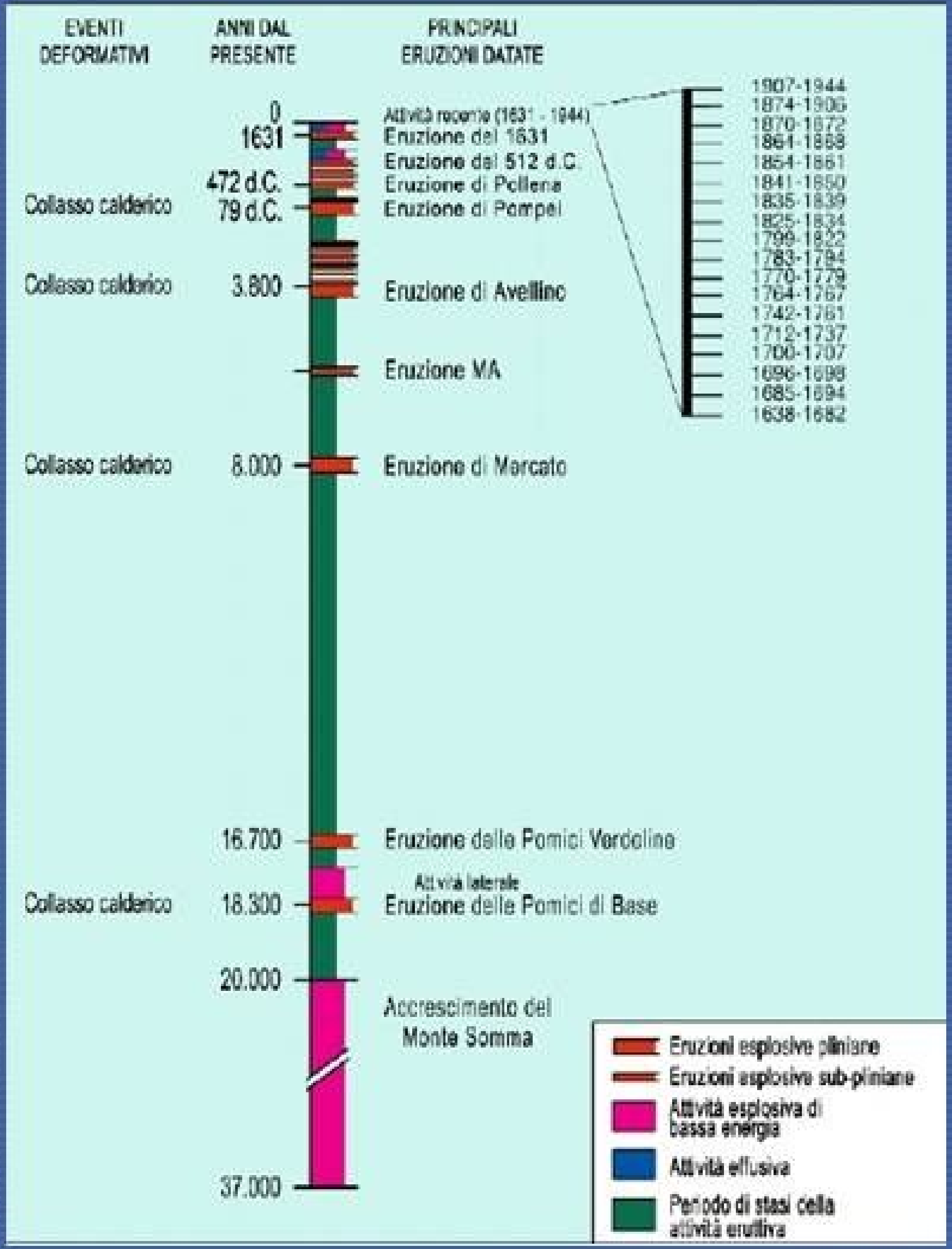


IAEA

All possible vents

Geological map and stratigraphic data of Vesuvius





IAEA

Reference eruption (subplinian)

Volume	0.1 km^3
Massa	2.5 10^{11} kg
Flusso di massa	10^7 kg/sec
Durata	7 h
Altezza colonna	16 km (+ Test 22km)

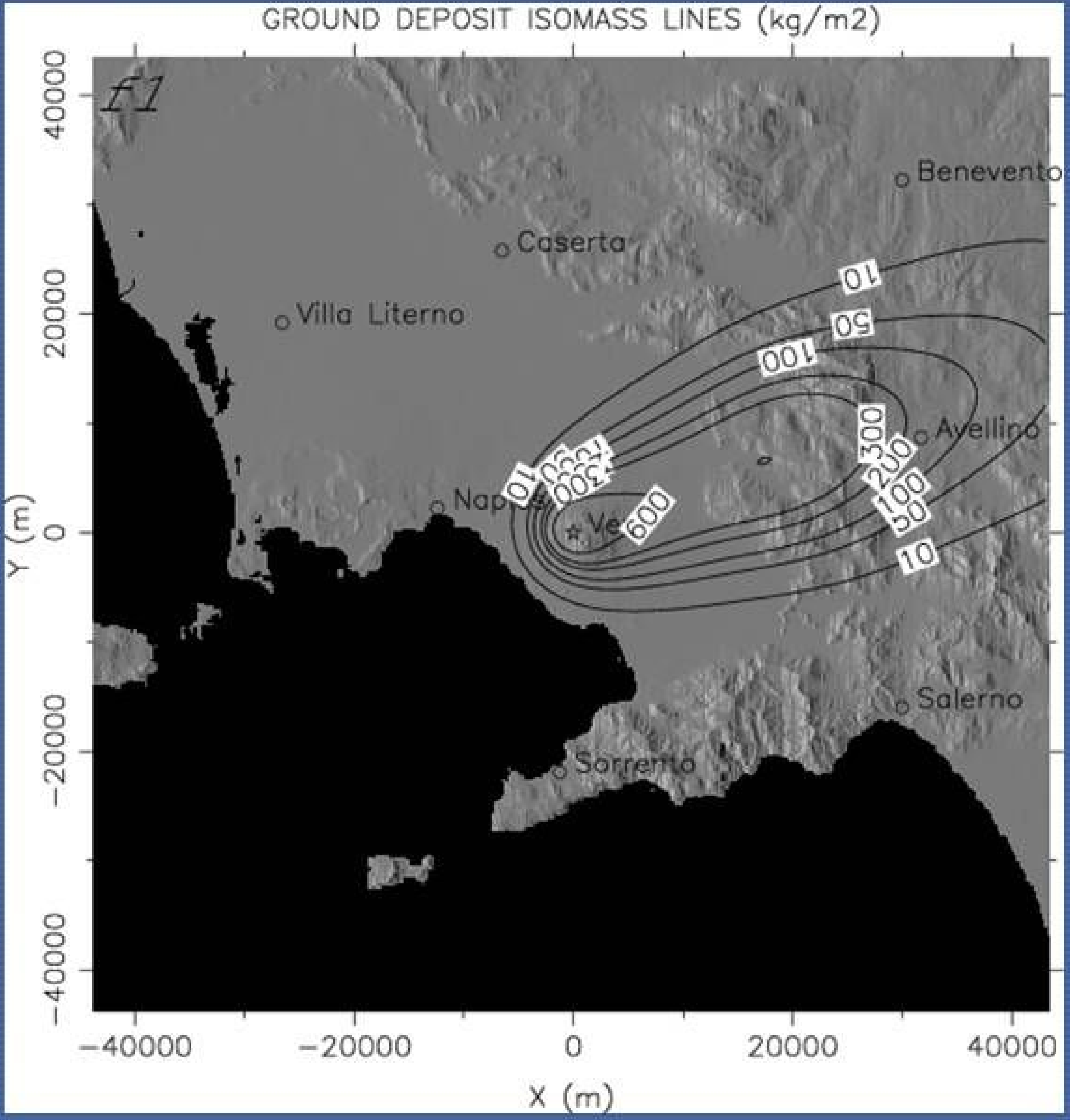
Reconstruction of the Vesuvius 472 AD eruption

Total deposit
(units L1, L2-3, L4, L6, L8)

Total mass*: ~2 × 10^{11} kg

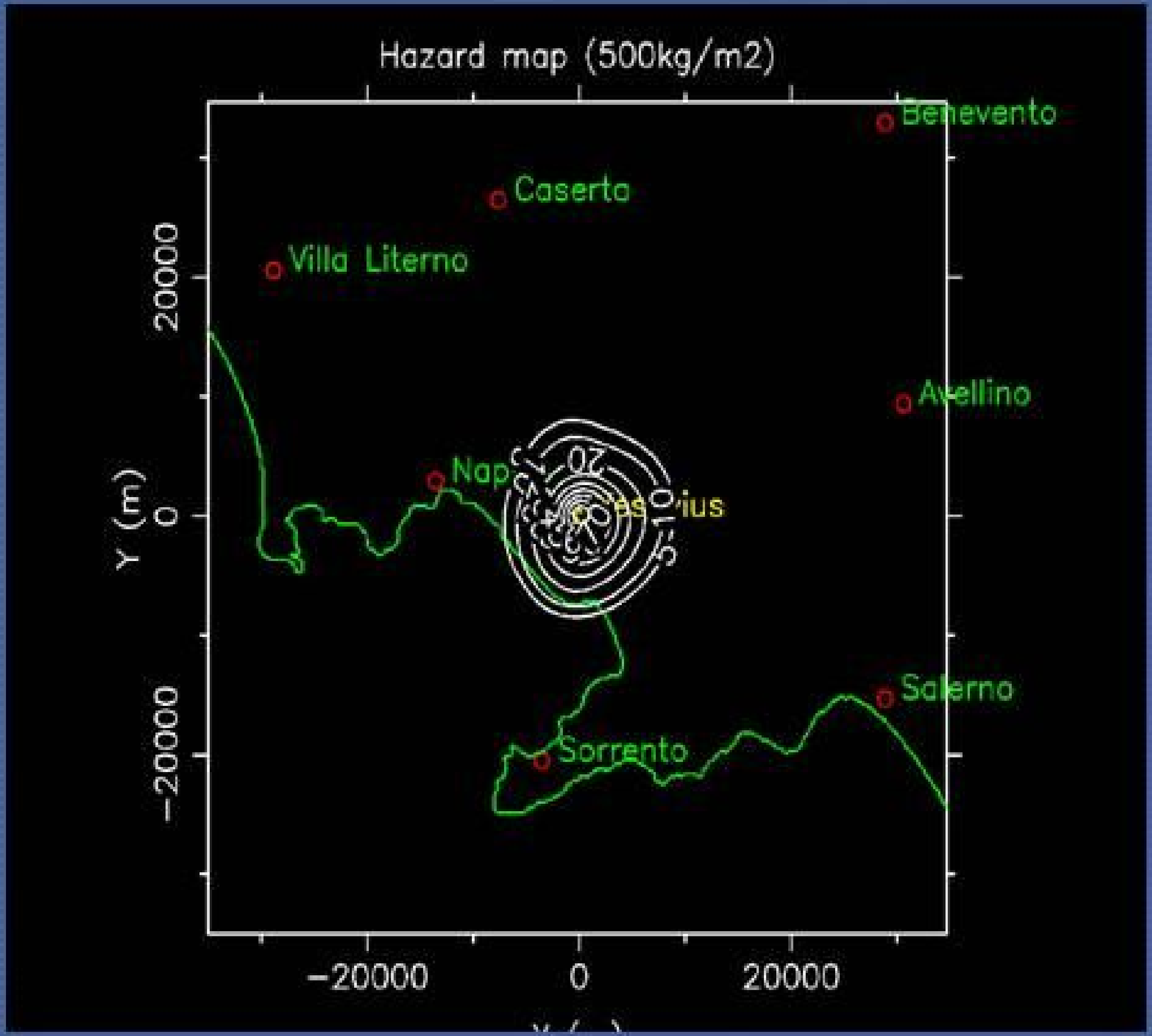
*: Total mass does not include coarse and fines (about 50%)

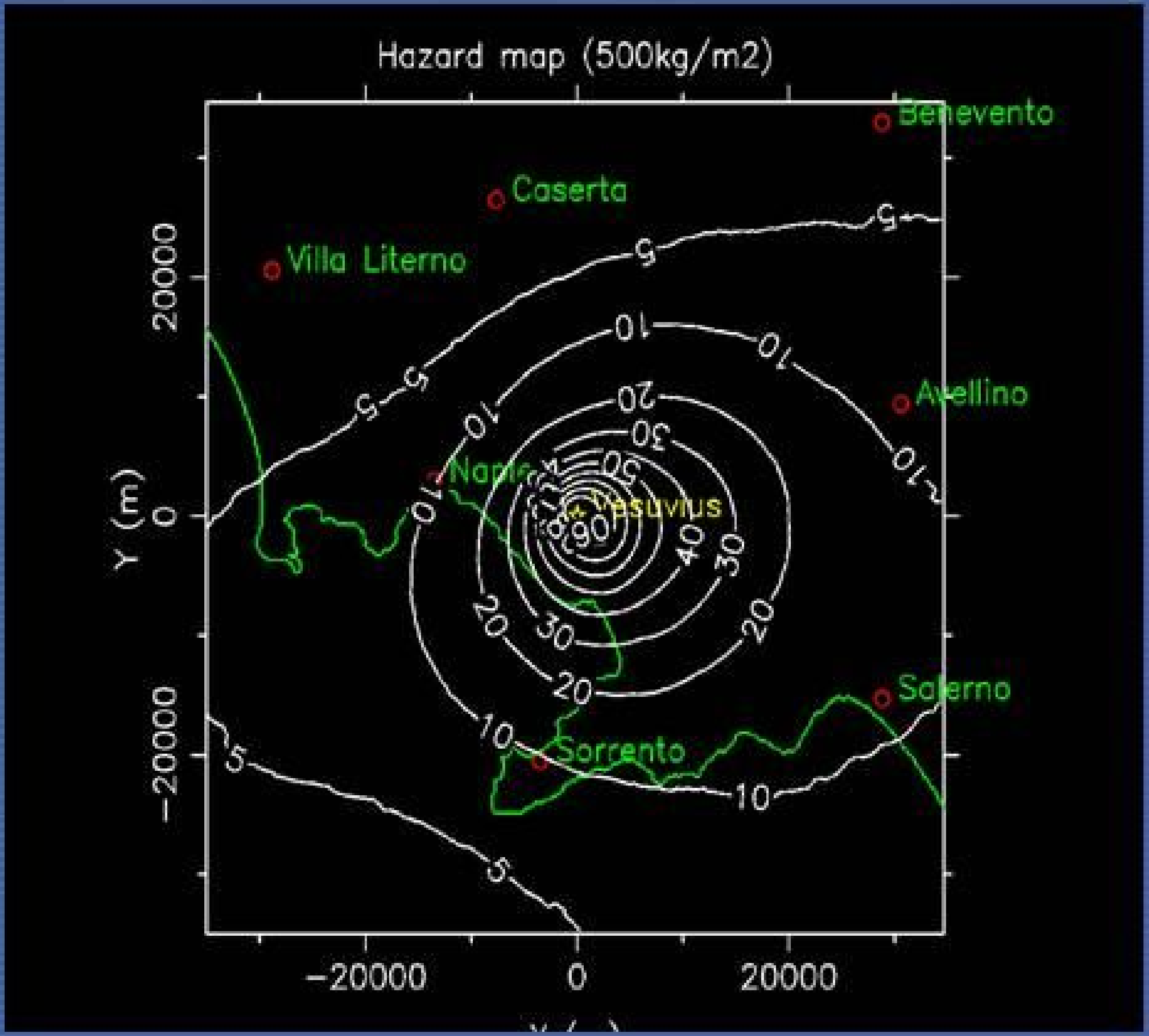
(Bonasia et al. 2010)



HAZMAP: hazard maps

Subplinian I (column=16km) (30% probability in 200 years)	Plinian (column=22km) (1% probability in 200 years)

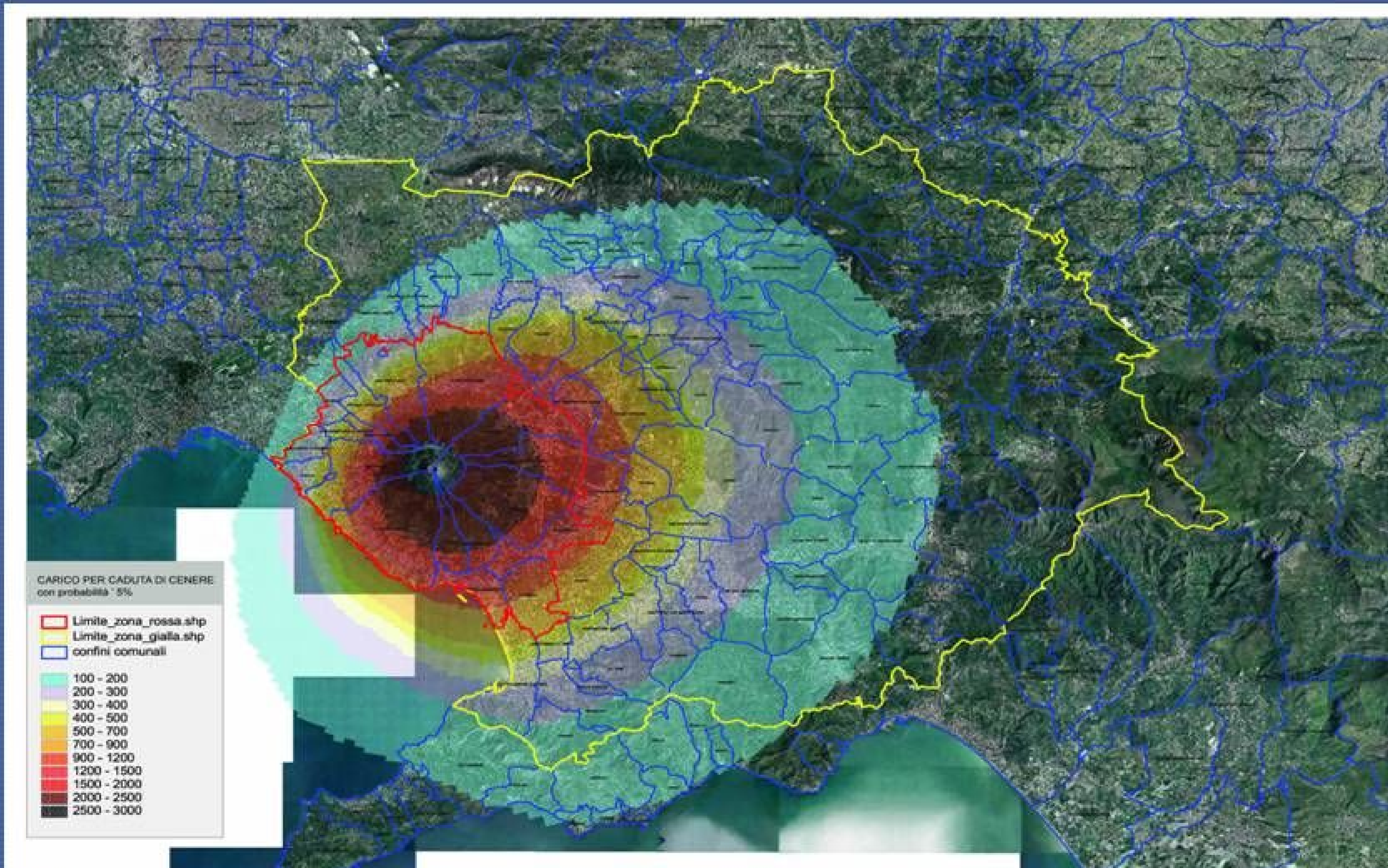




IAEA

~70% probability of smaller eruptions in 200 years

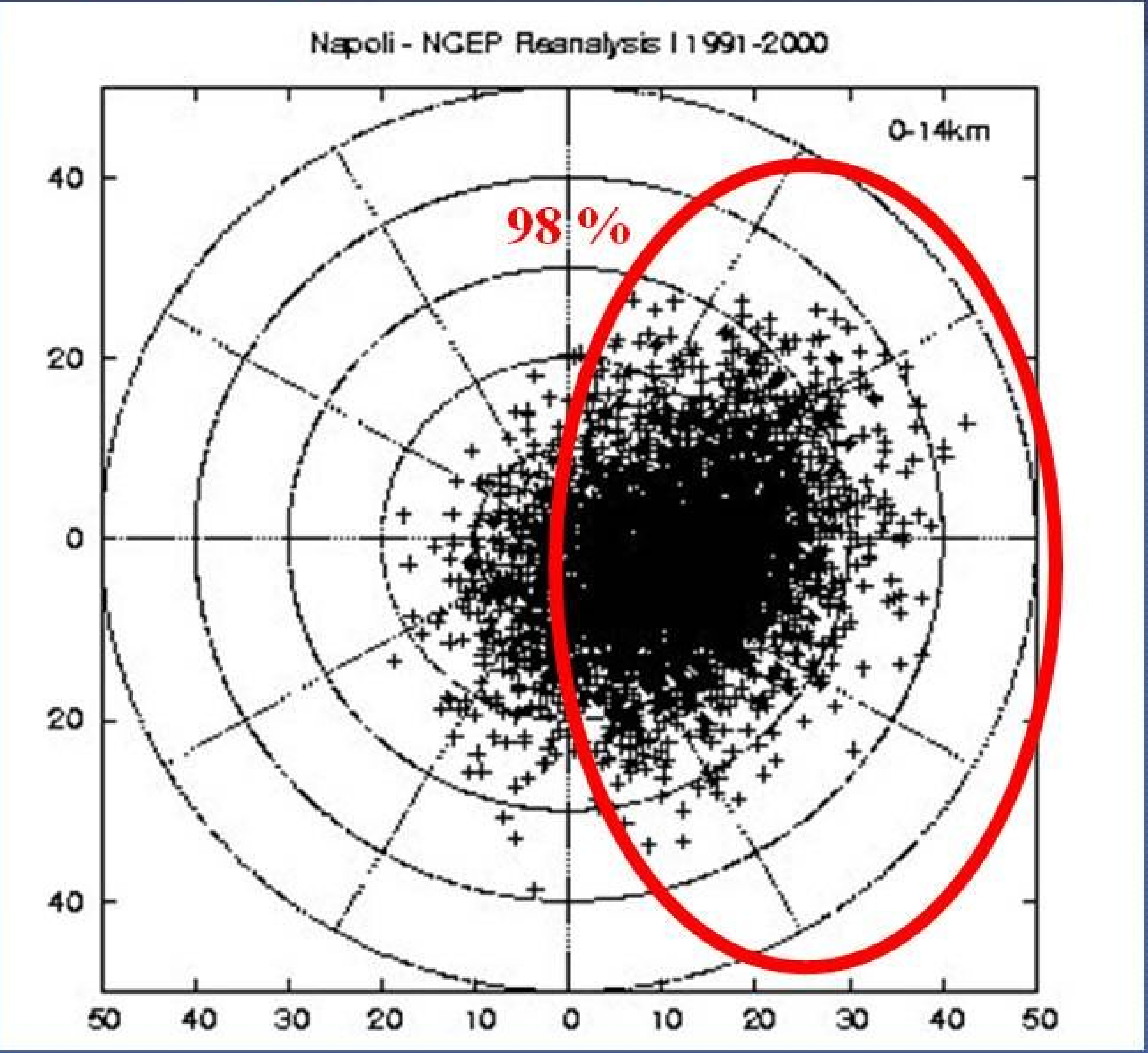
Ash loadings (5% probability to be exceeded)



IAEA

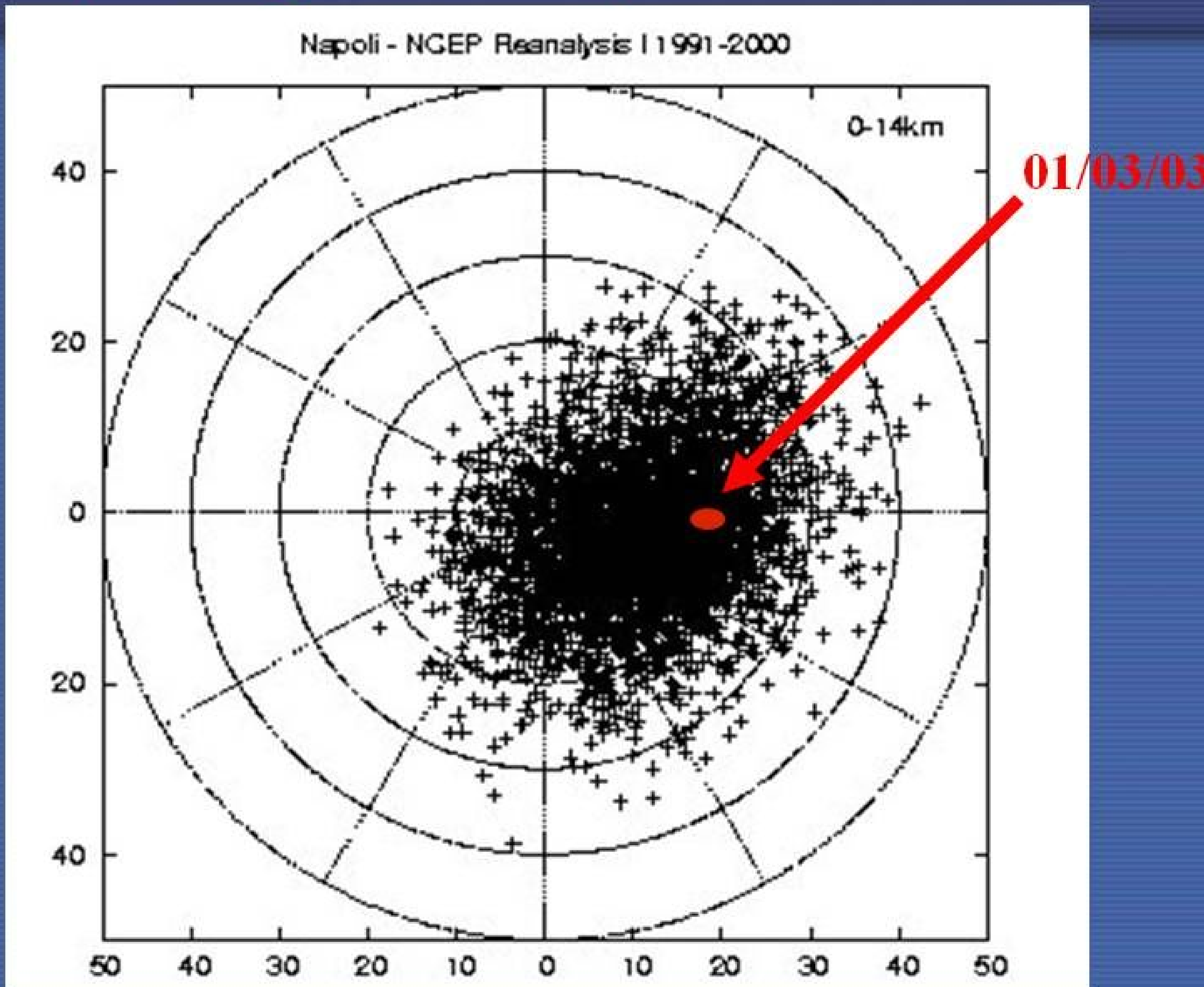
Subplinian I (column height=16 km)

Wind dataset: NCEP Reanalysis I 1991-2000

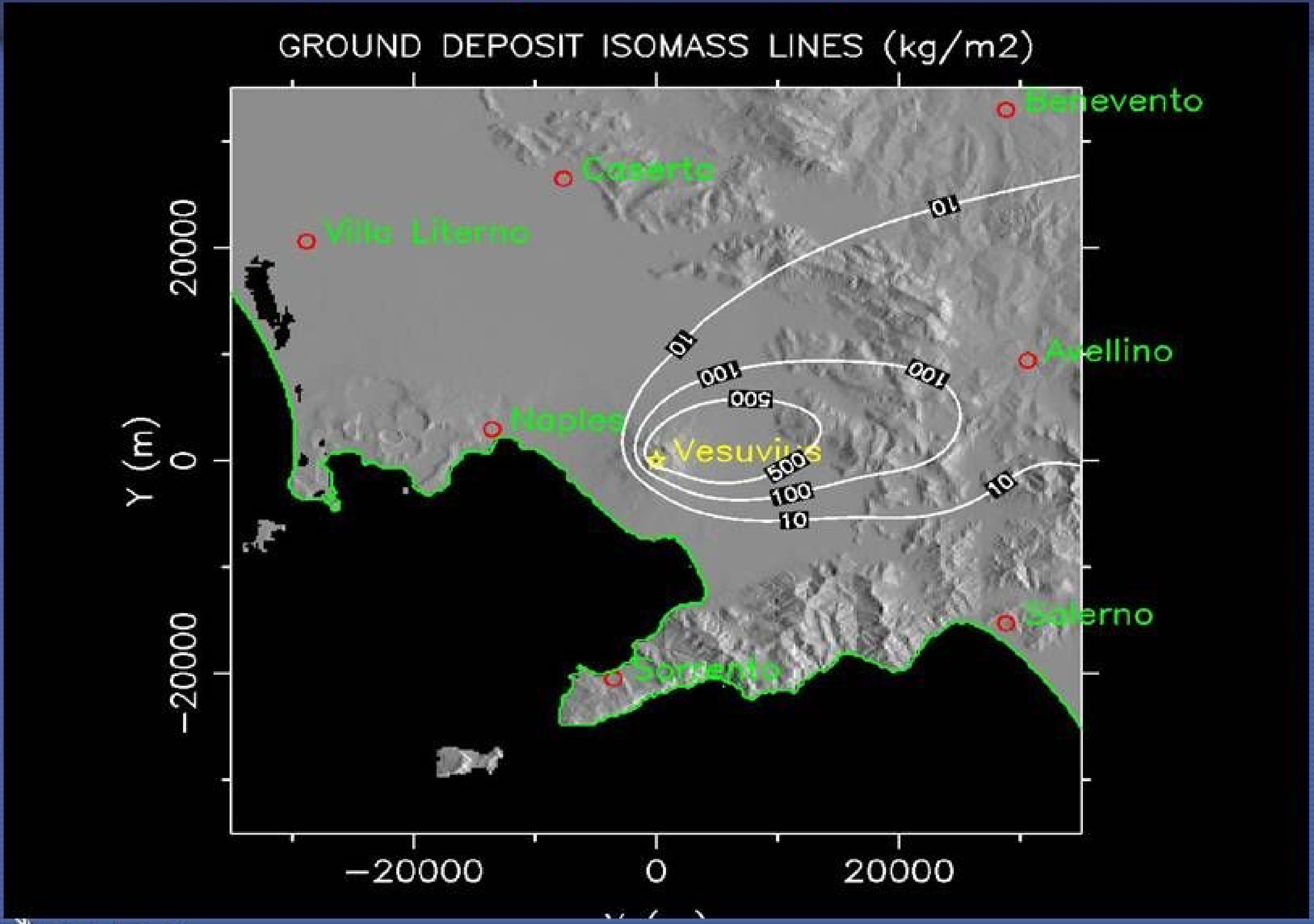


IAEA

High probability case: example 01/03/2003

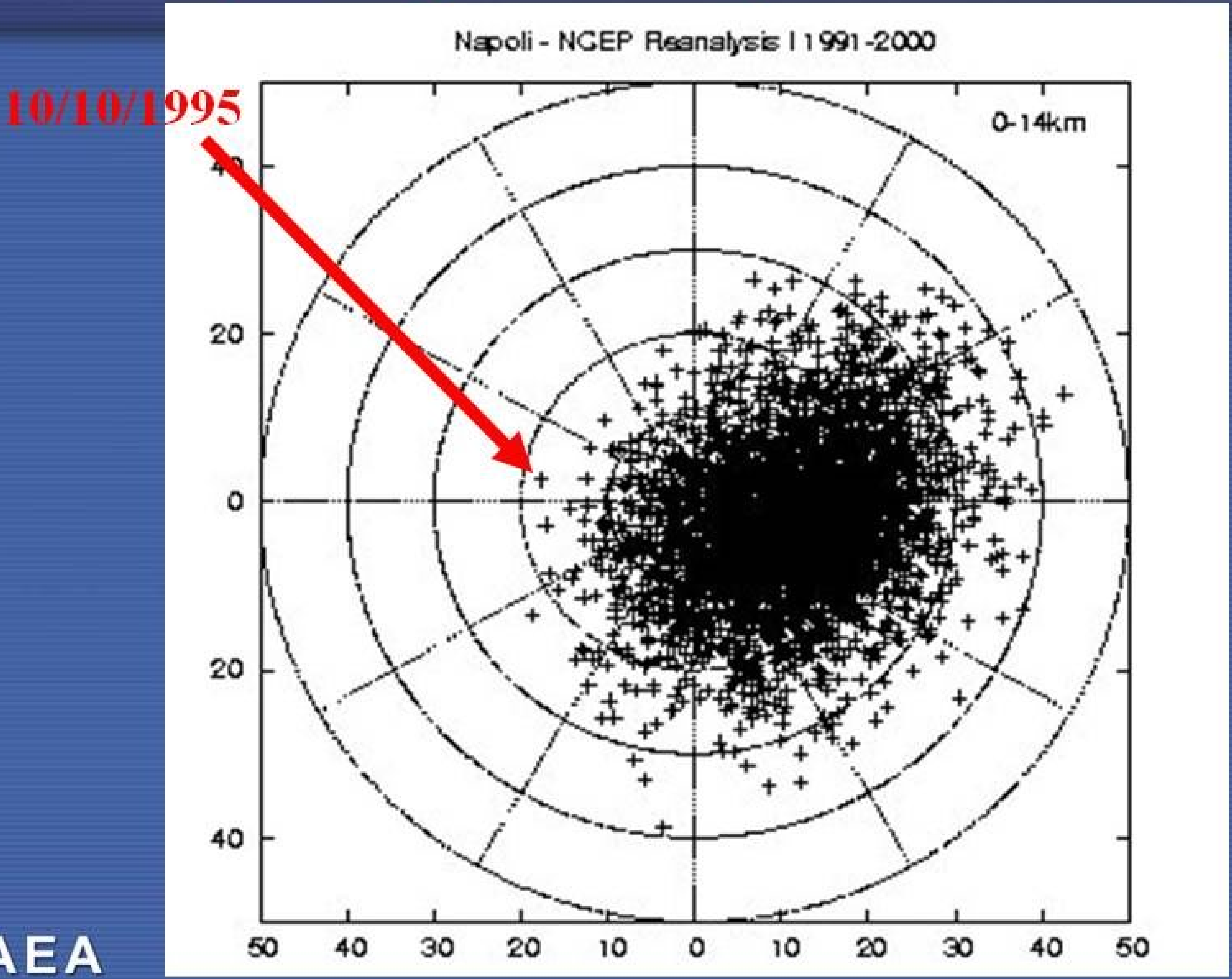


HAZMAP output (e.g., 01/03/2003; H=16km)



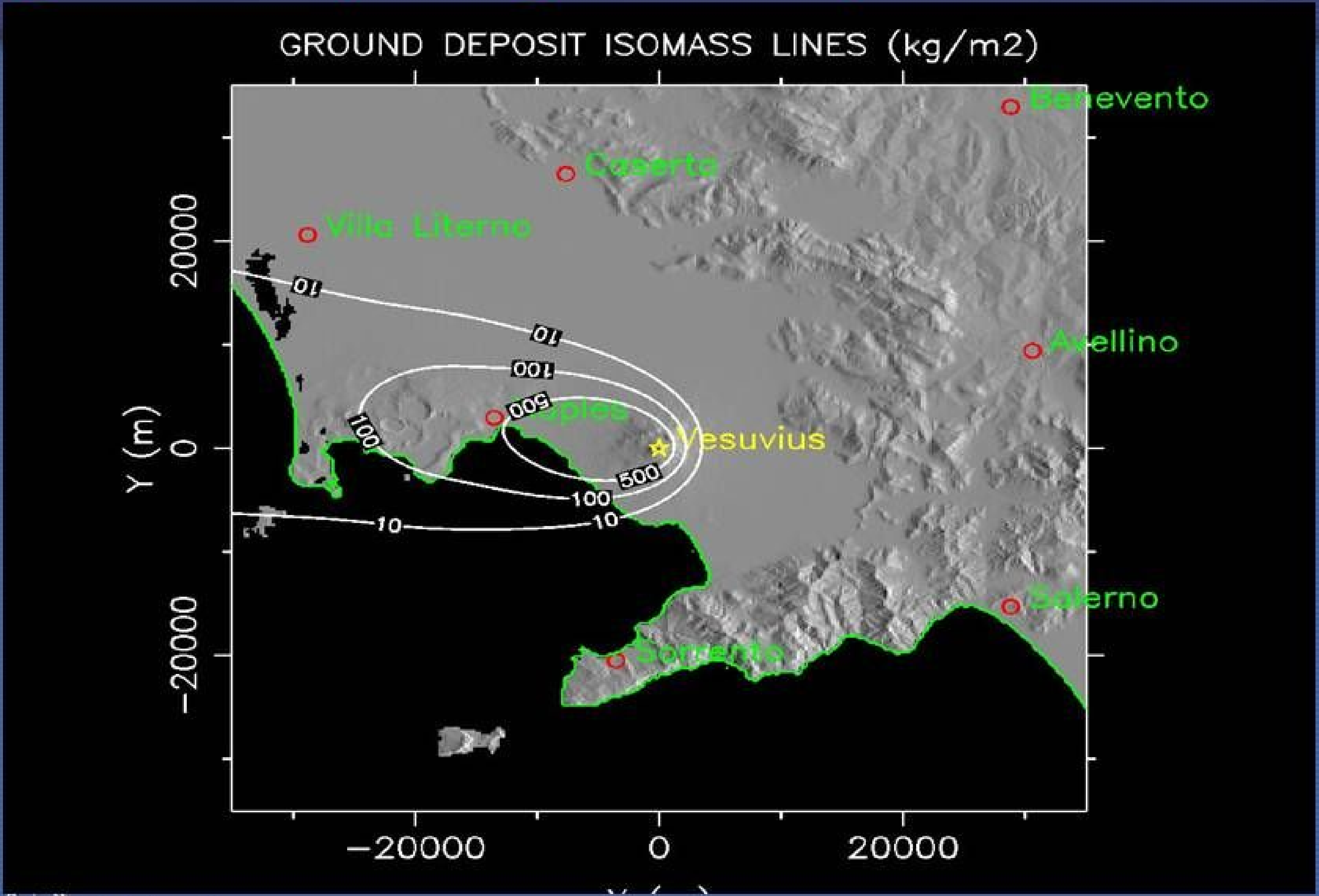
IAEA

Low probability case: example 10/10/1995

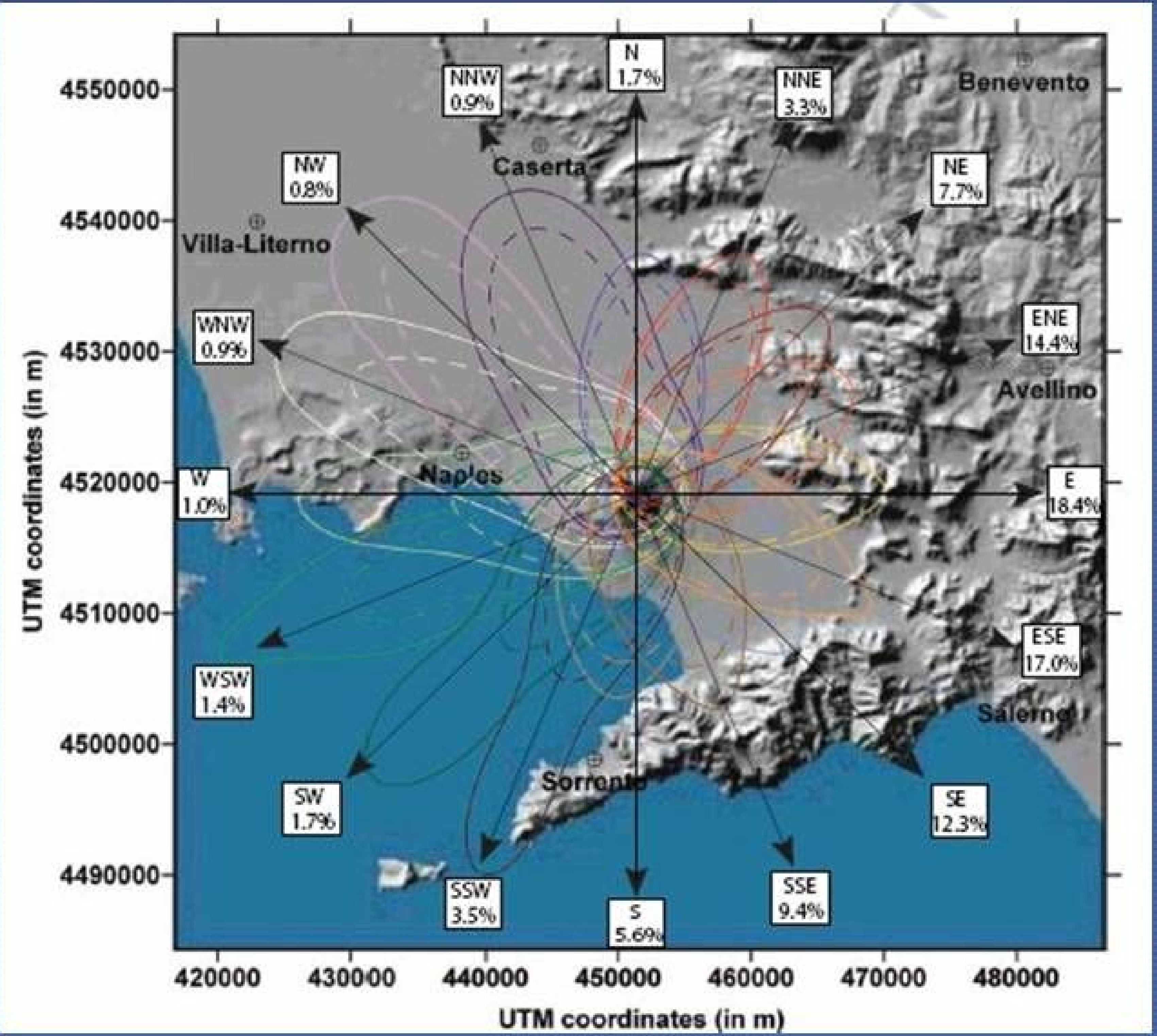


IAEA

HAZMAP output (e.g., 10/10/1995; H=16km)



Probability of ash deposits in different sectors at Vesuvius

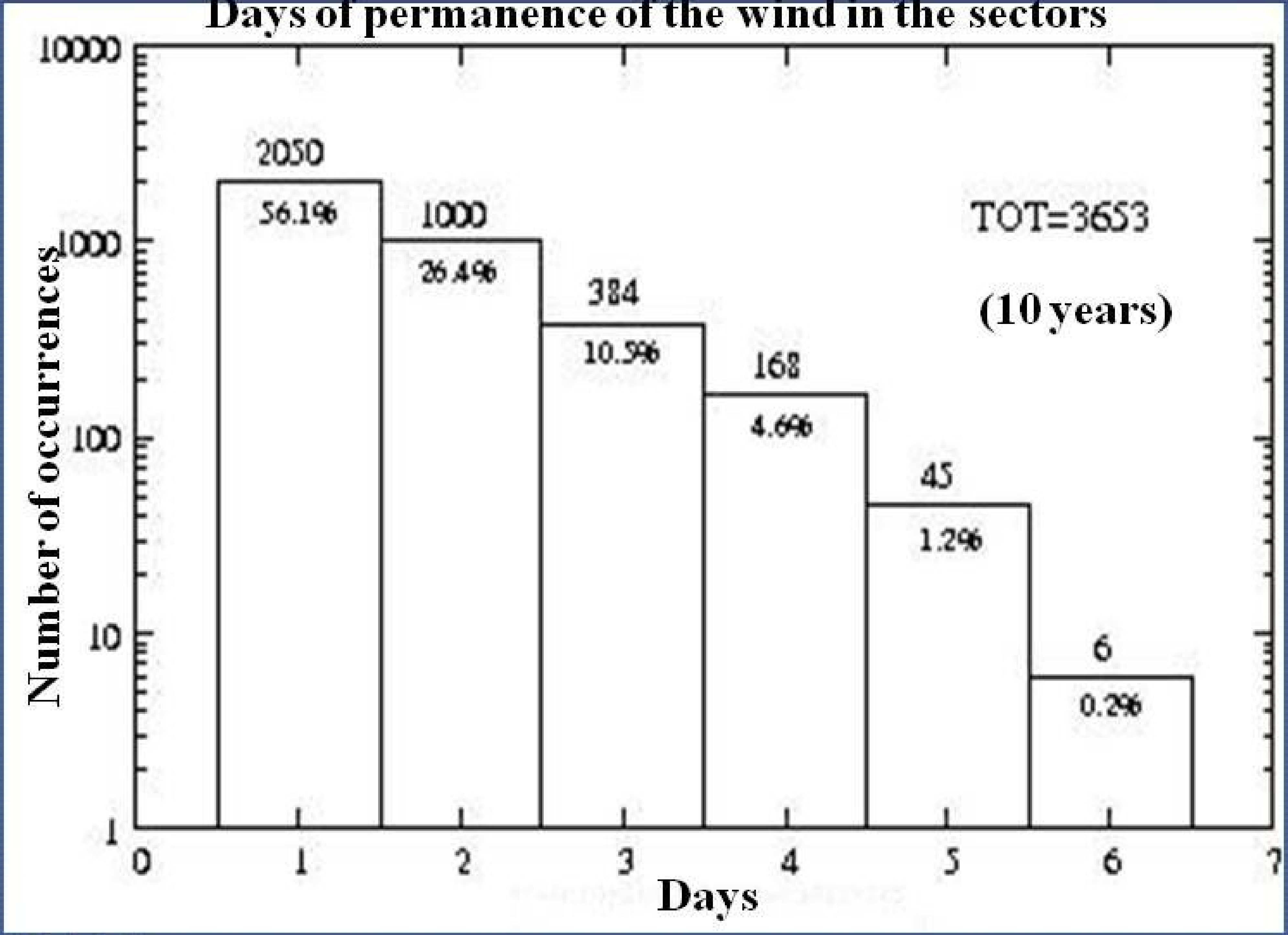


Full line > 300 kg/m²

Dashed line > 400 kg/m²

IAEA

Analysis of wind stability: 16 sectors (width 22.5°) around Vesuvius



IAEA

MESIMEX 2006: daily simulated (deterministic) scenarios

- **Scenario I:** **Subplinian starting at 00UTC of the same day**
- **Scenario II:** **Subplinian starting at 00UTC of the day after**
- **Scenario III:** **Subpliniana starting at 00UTC of two days after**

For each scenario the deposit accumulated on the ground after 24 h from the start of the eruption was calculated (high resolution meteorological forecasts from National Met Office were used).

IAEA

MESIMEX 2006: used models

1. **HAZMAP** (Macedonio et al., 2005): analytical model; quasi-steady; it solves advection-diffusion-sedimentation equation discretizing the eruption column considering a finite number of point source along a vertical line above the vent.

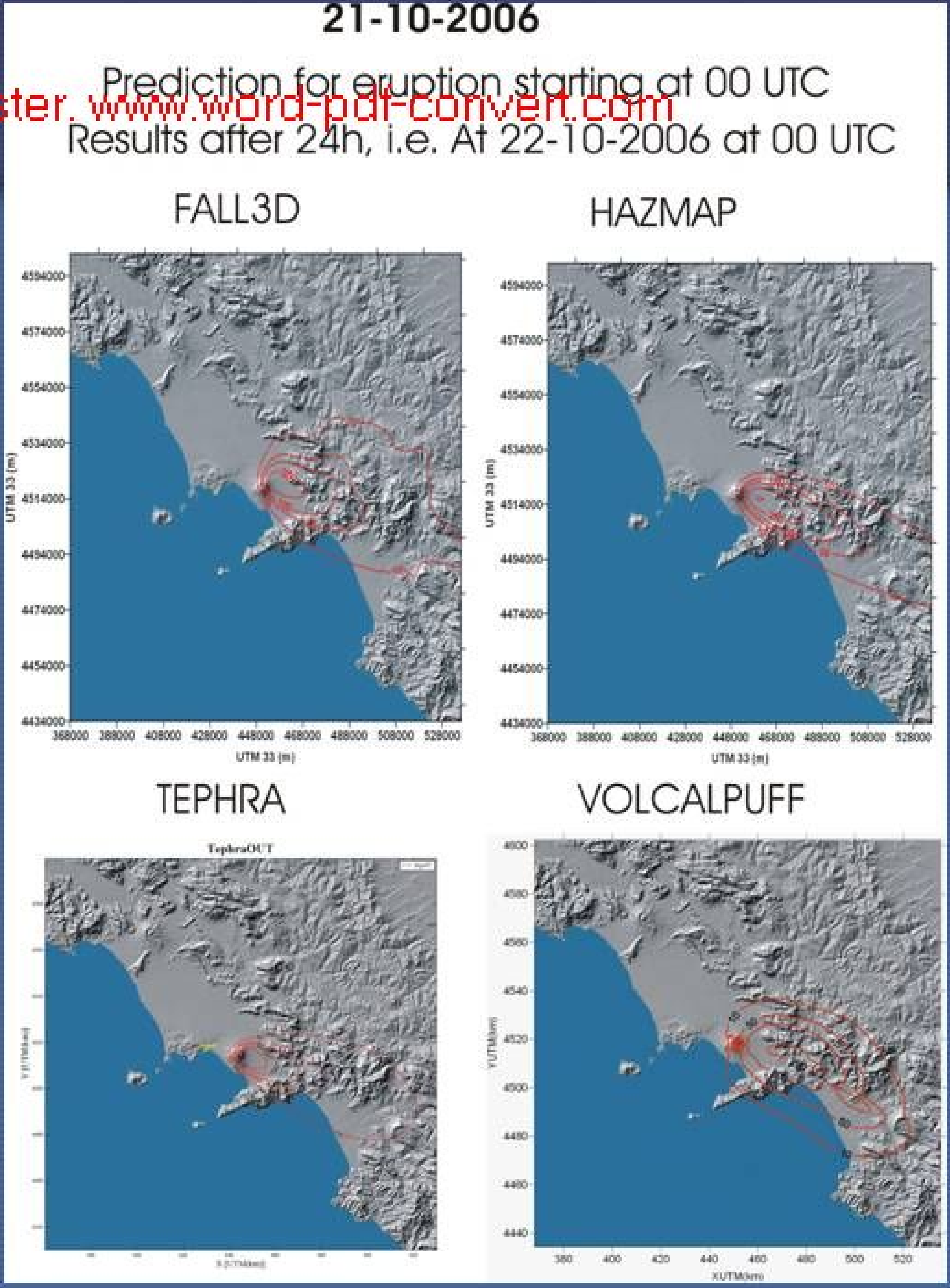
2. **TEPHRA** (Bonadonna et al., 2005): based on an approach similar to HAZMAP but uses a different parameterization of the diffusion coefficient and different discretization of eruption coloum.

3. **FALL3D** (Costa et al., 2006): numerical Eulerian model that solve a 3D time dependent advection-diffusion-sedimentation equation. Eruption column can be described empirically or calculated using a model based on the BPT.

4. **VOL-CALPUFF** (Barsotti et al., 2006): It is hybrid Eulerian-Lagrangian model that describes the eruption column through the BPT whereas dispersal is calculated following the movement and diffusion of a discrete number of puffs.

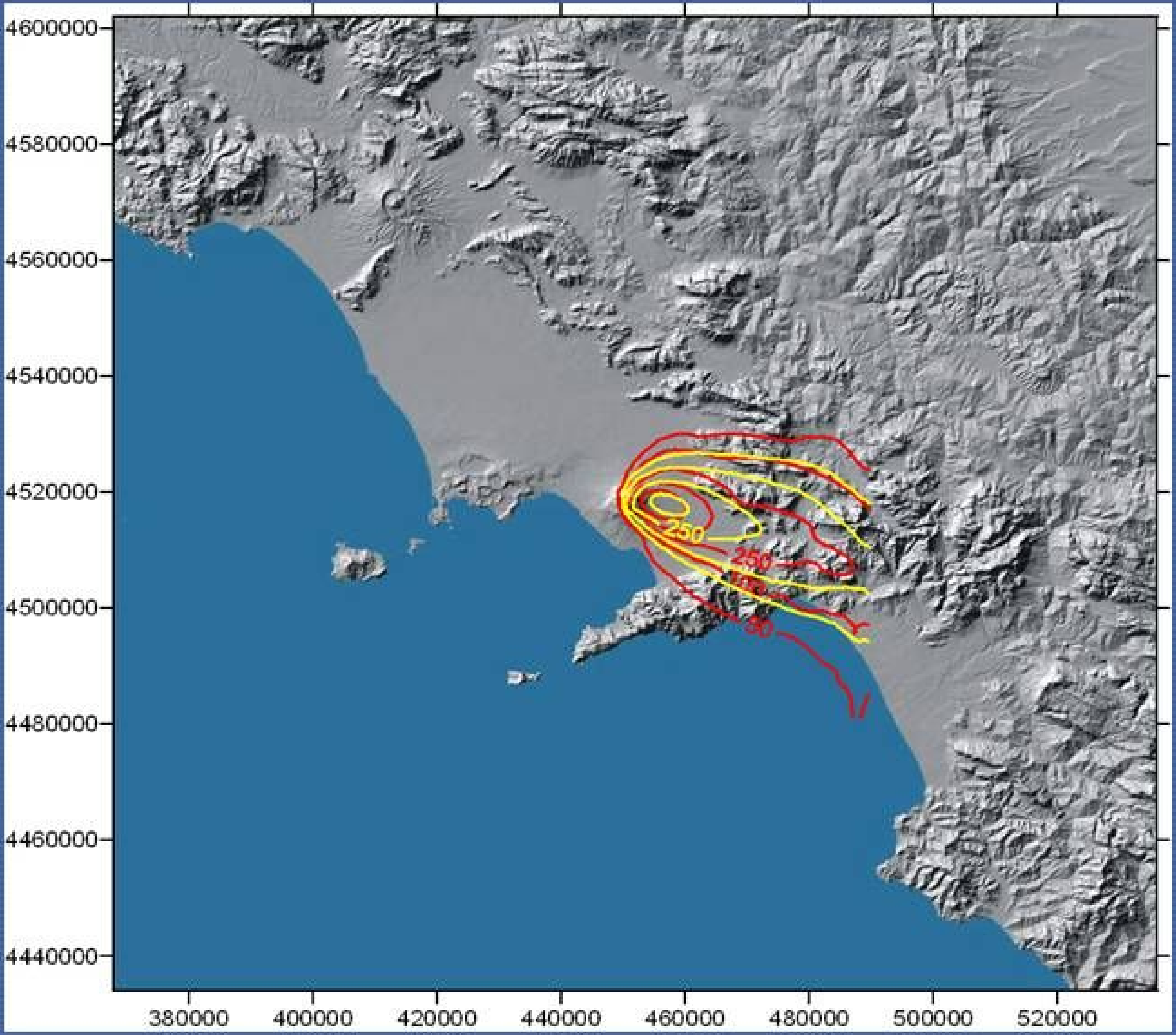
IAEA

MESIMEX 2006



IAEA

MESIMEX 2006: maximum vs mean load (kg/m^2); example of 21/10/2006 (forecast of 21/10/06)



Red contour = maximum load

Yellow contour = mean loading

IAEA

CONCLUDING REMARKS

- Definition of eruption scenarios through field studies.
- Assessment of their probability.
- Estimation of the control parameters for tephra fallout through best fit with observations.
- Probabilistic tephra loading maps.
- Effect of uncertainties (e.g. vent location).
- Deterministic ash fallout forecast based on a reference scenario.

IAEA

International Atomic Energy Agency

Thank you for your attention

IAEA

[antonio.costa@ov.ingv.it]