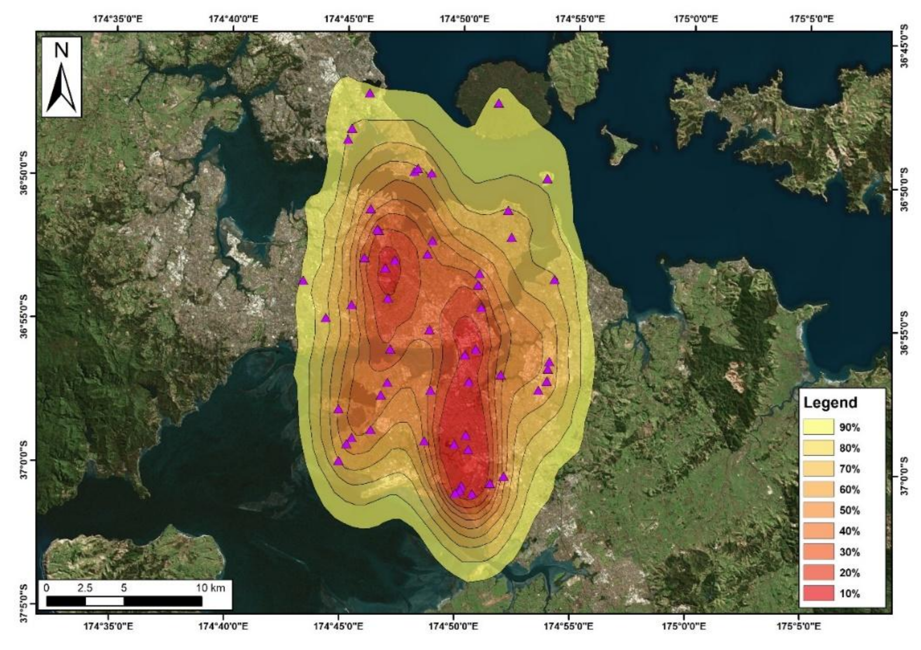
Pillar 1: Disaster risk knowledge

Approaches and methodologies for individual- and multi-hazard assessment

Laura Sandri[1], Daniel Bertin[2], Chuck Connor[3]



[1] Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Bologna, Bologna, Italy

[2] Servicio Nacional de Geología y Minería, Santiago, Chile

[3] University of South Florida, Tampa, United States

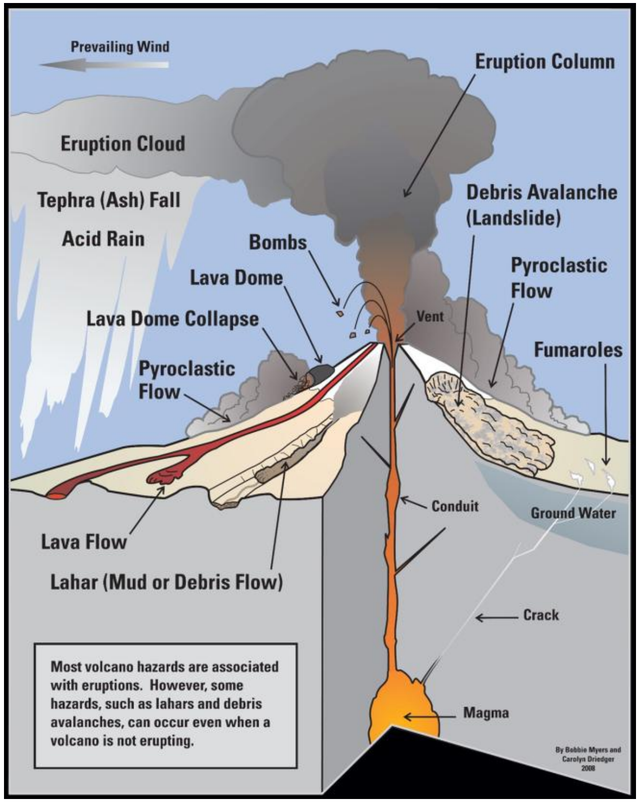
Background on VHA

Aim: To provide an **objective quantification of the expected hazard intensities in space and time**.

VHA → A basic ingredient for DRR.

Different approaches to cope with:

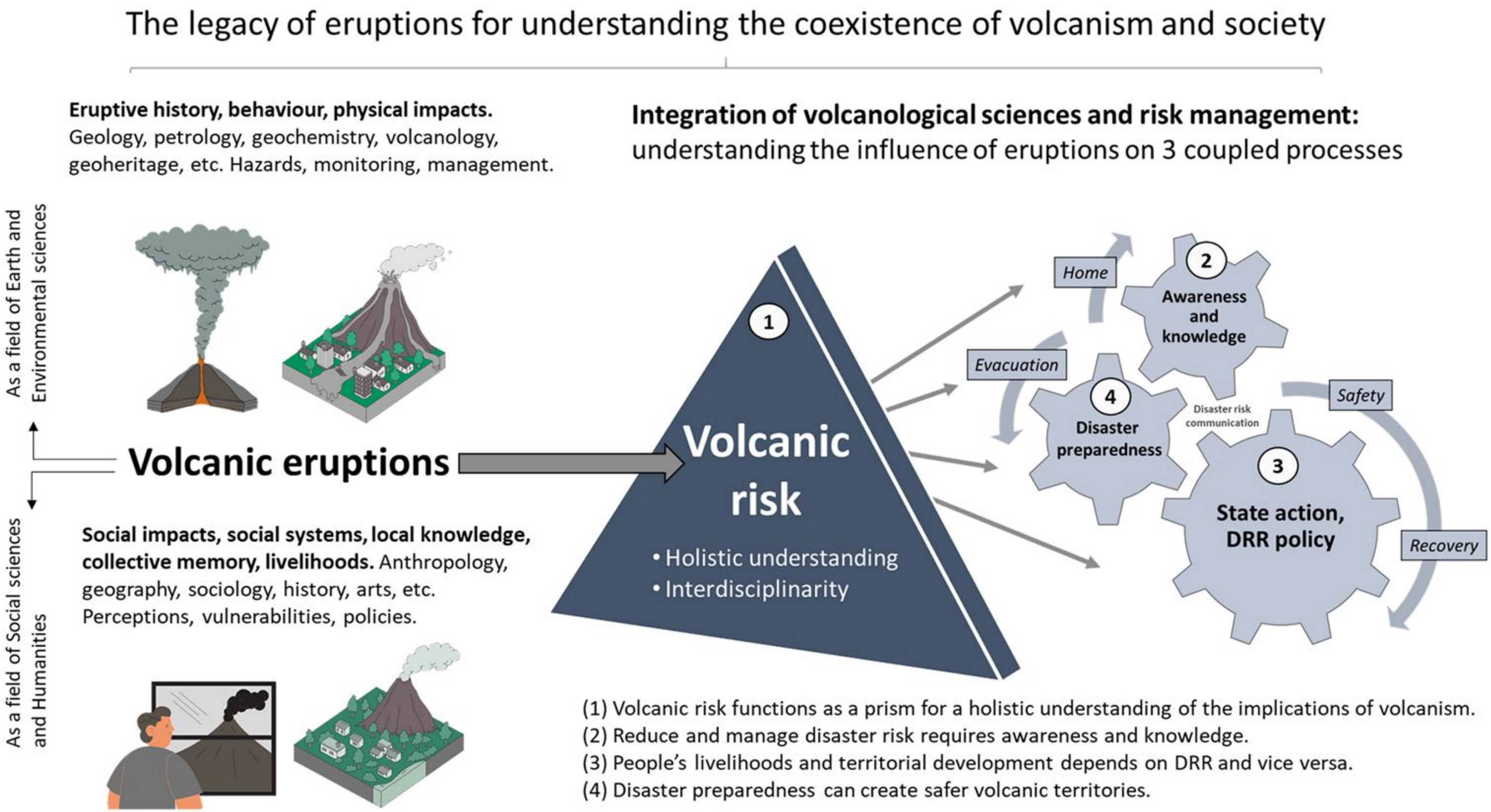
- The inherent **complexity** of hazardous volcanic processes → **probabilistic** methods.
- the **temporal horizon**, from **short-term** (hours to weeks, **supports crisis management**) to **long-term** (years to >centuries, **supports long-term risk reduction plans**) → different types of data, from geology to monitoring data.
- the large range in **spatial scale**, from near-vent to regional (even global).
- the **multi-hazard nature of volcanoes.**



USGS - Volcano Hazard Program

User needs

VHA: Prerequisite to DRR



Romero *et al*. (2024, AG)

Assumptions and key elements

Assumption: Future activity will follow a similar pattern to what has happened in the past, so it critically relies on the knowledge of the eruptive history of the volcano.

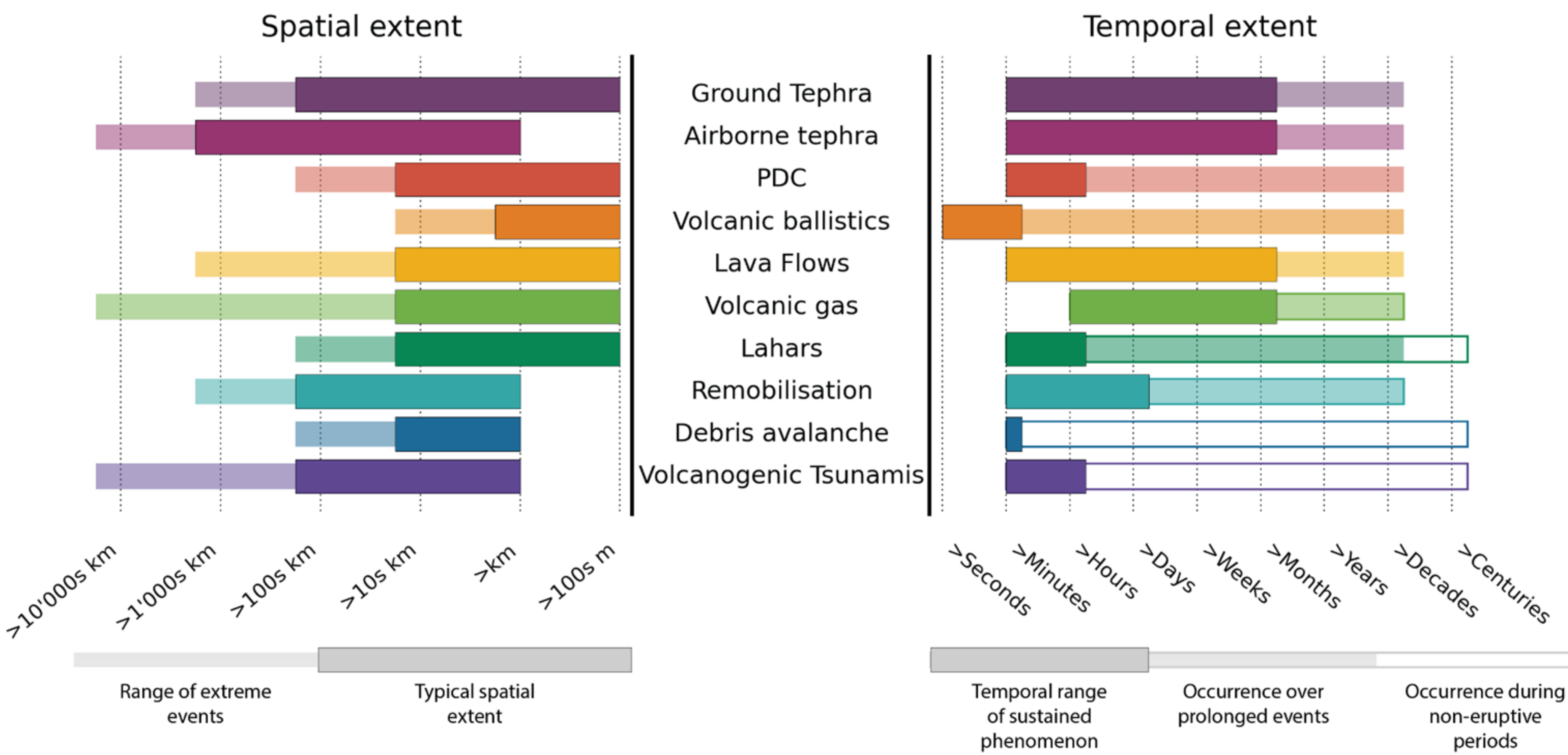
→ What is it required? Detailed information on eruption frequency, magnitude, and style.

Key points

- There is no continuous scale to measure the 'size' and 'energy' released in an eruption → This prevents the generalization of globally applicable laws linking magnitude, intensity and frequency.

- Eruptions occur at a lower frequency compared to other natural hazards → Information on past events comes from disparate records with biases (incompleteness, missing in memory).

Ranges in space and time scales of volcanic processes



Duration (of what?)

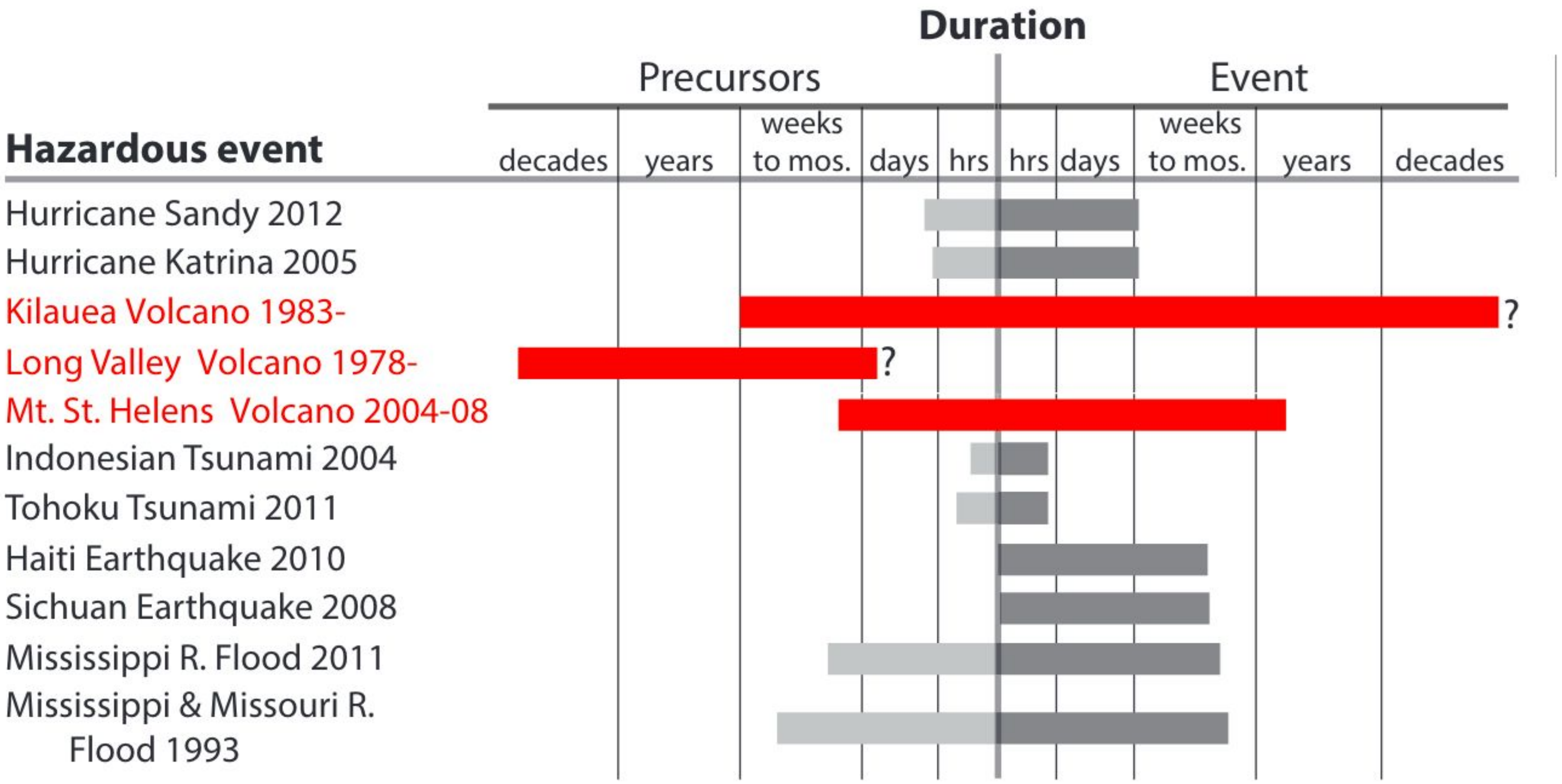


FIGURE 1.3 Duration of precursors and events for selected natural hazards, including hurricanes, volcanic eruptions, earthquakes, and floods.

National Academies of Sciences, Engineering and Medicine (2017)

Multiple hazards vs multi-hazard

Cascading and concomitant events - hazardous events interacting

1. at hazard level (*cascading events*): one hazardous event triggering another one (e.g., hot ballistics igniting wildfires)

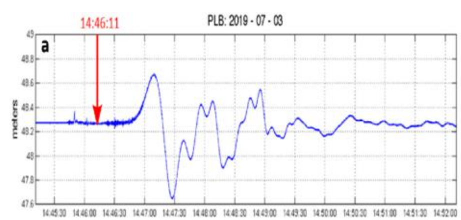
1. at vulnerability level (*concomitant hazardous events* on the same exposed value or asset)

Example 1:
Stromboli,
3rd July 2019

Photos from
www.volcanodiscovery.com

Paroxysmal eruption → Ballistics → Wildfires

Paroxysmal eruption → PDC → Tsunami



Selva et al, 2021, Rivista del Nuovo Cimento

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Example 2:
La Palma, 2021

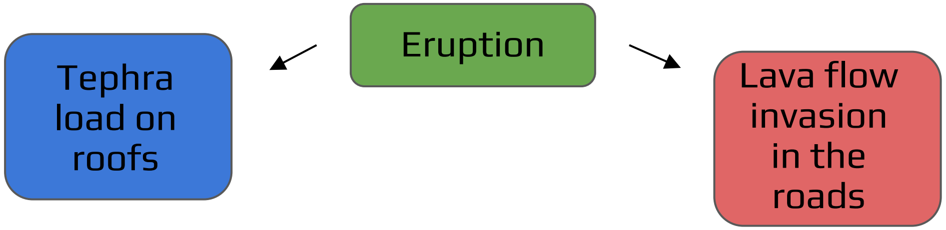
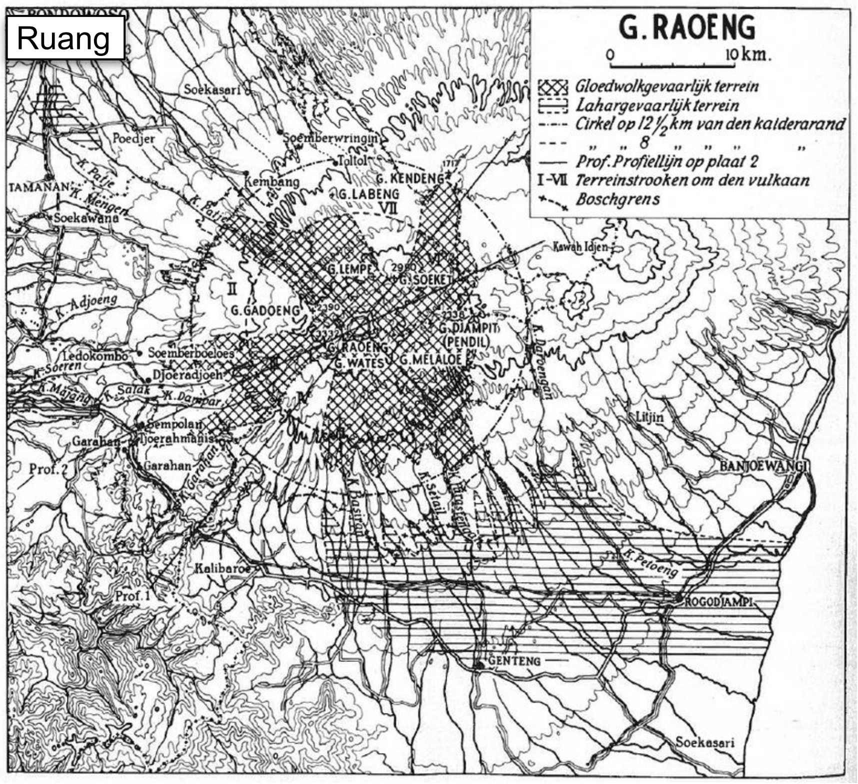


Photo: courtesy of Sebastien Biass

A brief history of VHA

Pre-1980:

- Field observations. Maps drawn from the study of volcanic deposits.
- Strictly based on known previous occurrences. Dependent upon the completeness of the geological record.



Neumann van Padang (1937, OOVHALS)

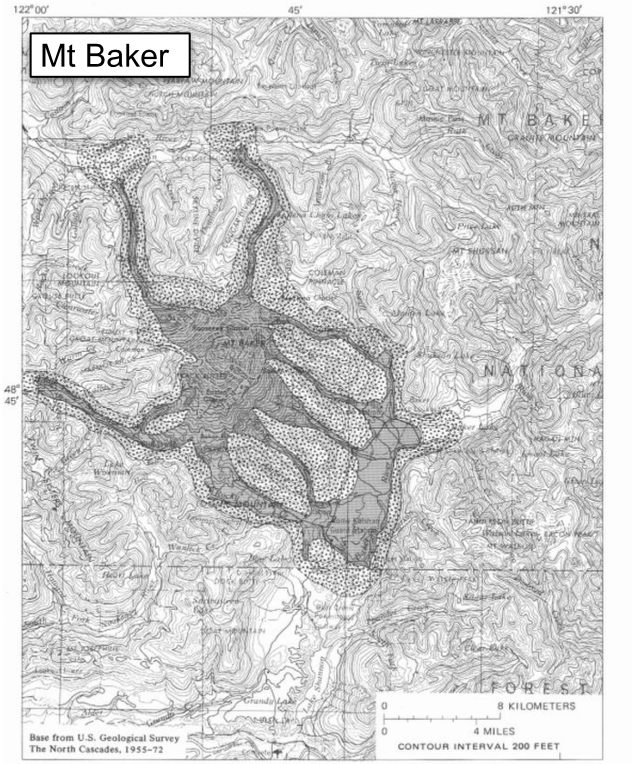
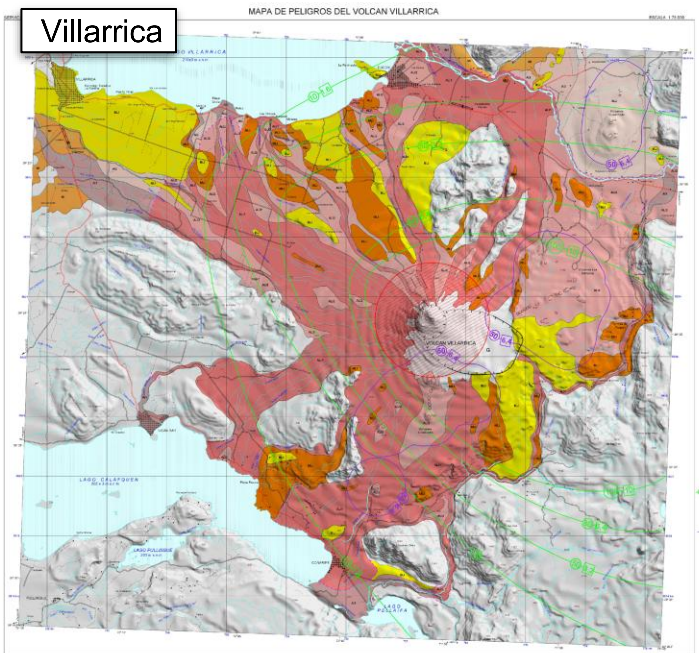


FIGURE 7. — Areas near Mount Baker that could be affected by lava and pyroclastic flows (shaded) and by ash clouds associated with pyroclastic flows (stippled; approximate limit shown by dashed line).

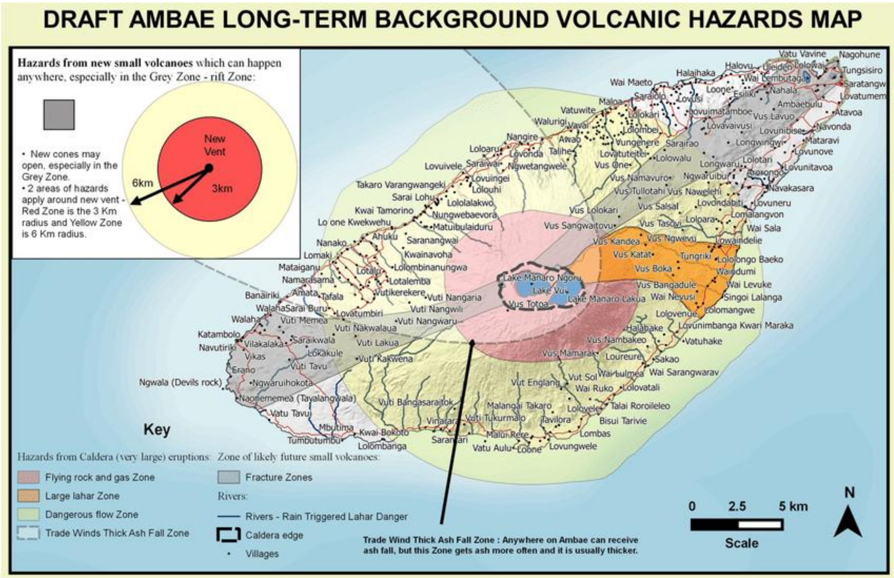
Hyde and Crandell (1978, USGS PP)

Deposits-based maps

- Broad category that includes interpretation of deposits and/or documentation from the historic record.
- Limitation: Preserved geologic record represents an incomplete and biased catalogue of the eruptive history.
- Solution: Methodologies and techniques available to correct biases, supplemented with additional, indirect sources of data from analogue volcanoes, expert judgement and/or empirical relationships to fill gaps.



Moreno and Clavero (2006)

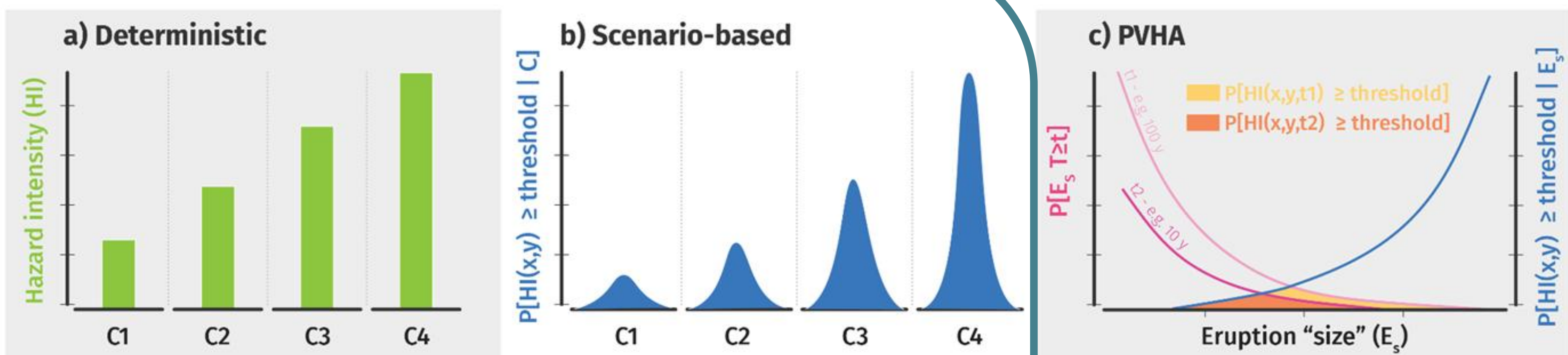


Vanuatu Meteorology & Geo-Hazards Department (2019)

A brief history of VHA

Post-1980:

- Predictive models -> Use of computational resources to <u>simulate</u> hazardous processes under specific Eruption Source Parameters (ESPs).



	a) Deterministic	b) Scenario-based	c) PVHA
$P_{Eruption}$	1	1	$P_{Eruption}(T \geq t)$
ESPs	Single set per eruption class	Sampled range per eruption class	Weighted across eruption "size"
Realisations	Single per eruption class	Multiple per eruption class	Continuous across eruption "size"
Uncertainties	None	ESPs	ESPs, $P_{Eruption}$, ± vent location
Output	Hazard intensity	P[HI(x, y) ≥ threshold | C]	P[HI(x, y, t) ≥ threshold]

These consider one amongst multiple possible eruptive behaviours. Do not express hazard as an aggregation of the full spectrum of likely eruptions.

A brief history of VHA

a) Deterministic

- Based on the simulation of a hazardous phenomenon under <u>specific</u> initial conditions described by a single, unique set of fixed ESPs.
- Results usually provided as <u>single</u> outcomes or map representations. Typically describe the spatial distribution (left figure) and the temporal evolution (right figure) of the intensity metric of the phenomenon simulated for a specific single event.

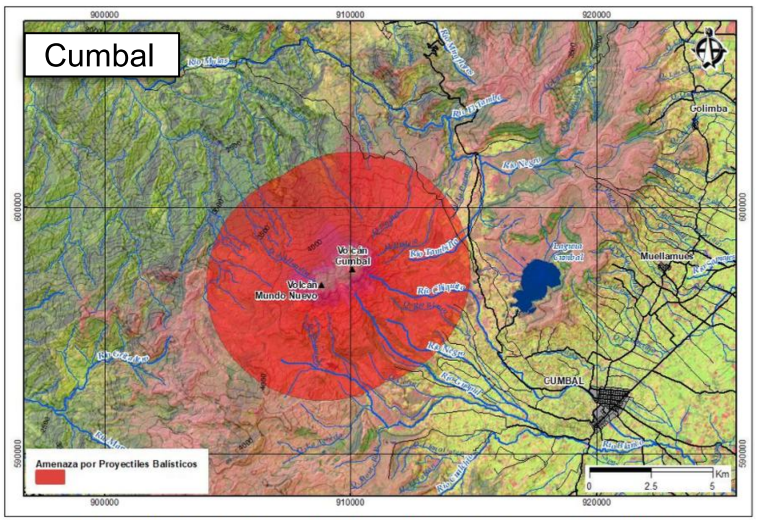
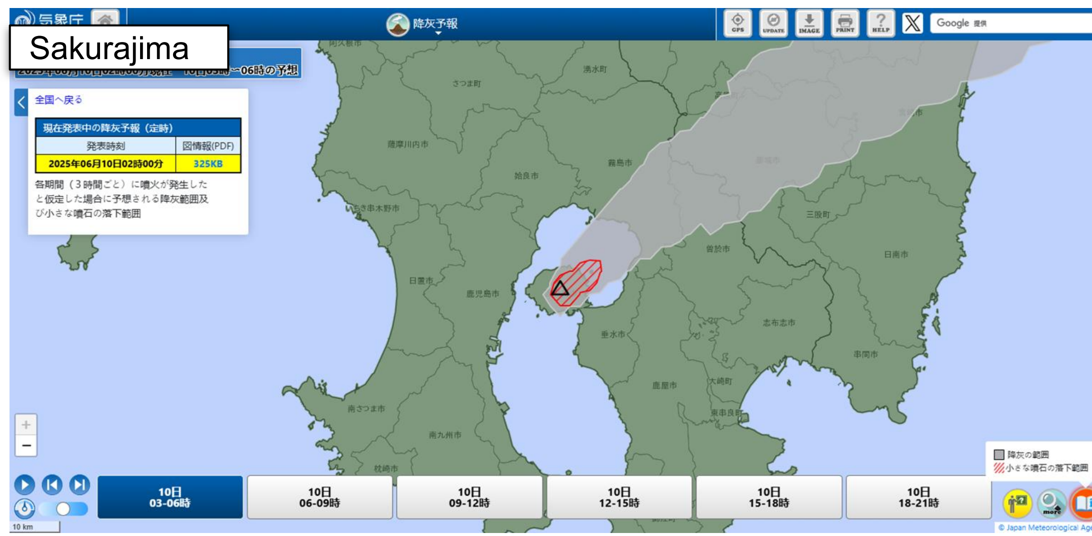


Figura 15. Amenaza por caída de piroclastos por proyección balística.

Méndez et al. (2014)



Japan Meteorological Agency, website

Scenario-based maps

b) Scenario-based

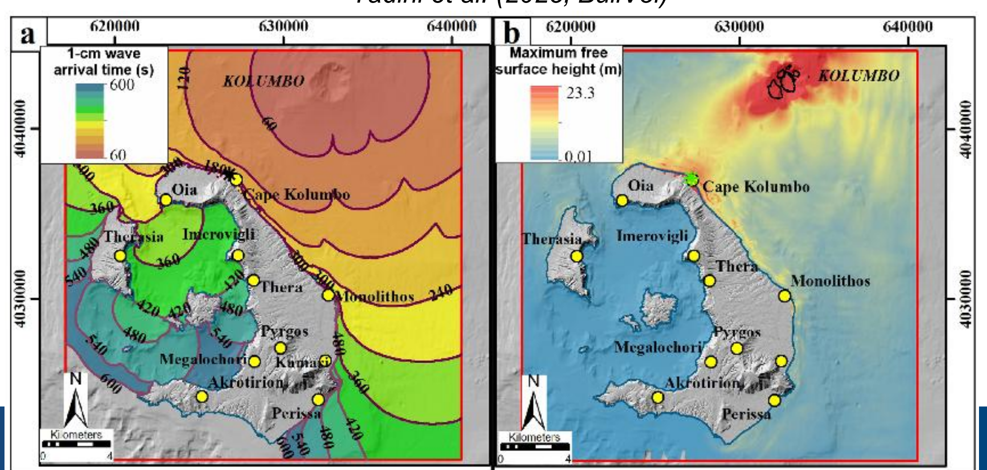
- It accounts for eruption scenarios that are either not preserved in the eruptive record or have not yet occurred.
- Described by a continuous distribution of ESPs, either from the volcano or from analogue datasets. Accounting for a large array of possible eruptive scenarios.
- The frequency exceedance among the set of simulations is computed as a proxy for the exceedance probability.

Wave height on NE Thera	Scenarios from literature: Submarine explosion *energy*	Scenarios from literature: Pyroclastic flow *volume flux*	Scenarios from literature: Caldera collapse *duration*	Scenarios from literature and this project: Landslide *volume* – Kolumbo crater internal slopes	Scenarios from literature and this project: Landslide *volume* – Kolumbo crater external slopes
Q14d1. > 1 m [15.1-***51.7***-92.7]	> $3x10^{14}$ J *a,b*	> 10^5 m^3/s *a*	< 20 min *a*	n.a.	> 0.002 km^3 *this study*
Q14d2. > 5 m [4.8-***18.8***-63.8]	> $5.6x10^{14}$ J *a*	> 10^6 m^3/s *a*	< 5 min *a*	> 0.14 km^3 *this study*	>1.2 km^3 *b*
Q14d3. > 10 m [1.5-***7.4***-29.7]	> $2.2x10^{16}$ J *a,b*	> 10^7 m^3/s *a*	< 1 min *a*	> 0.3 km^3 *this study*	n.a.

Tadini et al. (2025, BullVol)

Example for a scenario-based assessment for tsunami from Kolumbo

Tadini et al. (2025, BullVol)



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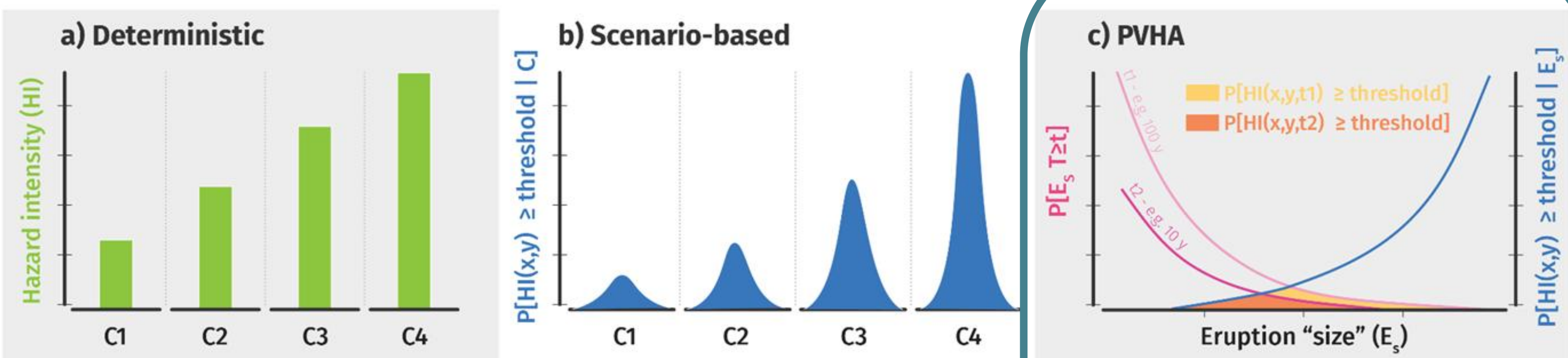

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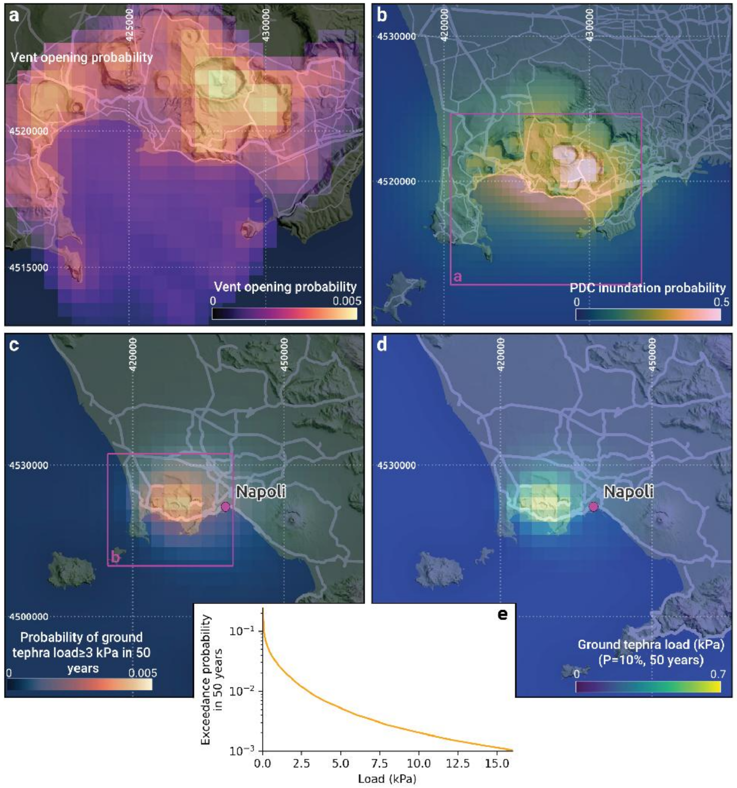
Output	Hazard intensity	P[HI(x, y) ≥ threshold | C]	P[HI(x, y, t) ≥ threshold]

Addresses hazard as a continuum of possibilities rather than discrete scenarios only

A brief history of VHA

PVHA: Probabilistic Volcanic Hazard Assessment

- **Objective**: To estimate the **probability** of a given hazardous event impacting a given **point** in a defined **time window**, with a **hazard intensity metric** exceeding a given threshold.
- Aggregates all possible eruption scenarios and assigns weight to the contributions from various scenarios, accounting for a range of different event scales, ranging from **high-probability/low-impact to low-probability/high-impact events.**
- It quantifies and propagates **uncertainties** inherent to the source datasets.
- Hazard probabilities usually expressed per unit of time (*e.g.*, annual probability to exceed a ground tephra accumulation of 1 mm).



Sandri et al. (in review, EoV)

Acknowledging users' needs

Example of a 'development cycle' for hazard maps that integrates user needs

Lindsay et al. (in review, EoV)

VHA has seldom been performed with sufficient consideration for **user needs.**

Examples:

- What is the purpose of the assessment?
- Who is the intended audience?
- What resources are available?
- What representation style is appropriate?

- Short-term or long-term?
- *Volcano-centric* vs *site-centric* approaches? Global analysis of the hazard from *multiple sources of volcanic hazard*?

The assessment methodology should ideally match the stakeholders' needs → content, design, and format are increasingly identified through co-development with stakeholders.

Long-term vs short-term VHA

The temporal horizon depends on the purpose of the assessment
→ driven by the **needs and goals of the stakeholders**

	Short-term	***Long-term***
Time scale of the VHA	hours to weeks	years to centuries (and more)
Purpose	To inform and support **crisis management**	- To inform long-term risk reduction strategies (e.g. **land use, building codes**) - To feed **risk ranking**
Data	All as in long-term but, above all, **monitoring observations**	Geology, past frequencies and occurrences, analog volcanoes, model simulations

Long-term vs short-term

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Time scale of the VHA	hours to weeks	...s (a...
Purpose	To inform... **crisis mana...**	... risk
Data	All as in long-... above all, **mo...** **observatio...**	

Volcanic eruptions cannot be predicted deterministically, but **monitoring** techniques make **forecasting an eruption over timescales of hours to weeks** feasible.
No monitoring observation has proven to be useful in forecasting the intensity and erupted mass of an eruption, and thus the expected hazards.

Summarizing the state of the art

Clearly define the purpose of the VHA and associated user needs → inform which approach to use

Different methods:

0) **AT MINIMUM**: VHA based on the interpretation of the **eruptive history based on stratigraphy and age determinations.**
This is also critical to **inform the scenarios** and their frequencies. Scenarios are associated to ESP ranges.

1) **Deterministic VHA** based on the simulation of **specific scenario(s) with fixed ESP.**

1) **Scenario-based**: exploring variability around a fixed scenario.

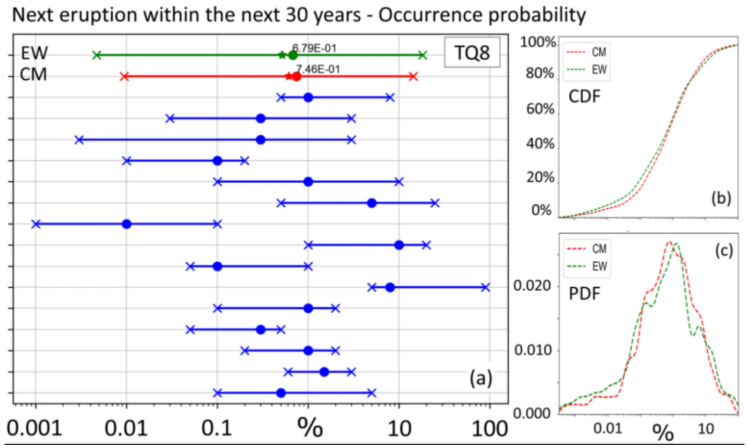
1) **Full PVHA**: combining the whole spectrum of possible scenarios → **full quantification of the uncertainty.**

Limitations to VHA

Aleatoric uncertainties - Irreducible by nature
→ can be quantified through probabilistic approach

Data gaps - **Epistemic uncertainties**
→ Use of *analogue volcanoes* (pyVOLCANS) and *global databases* on volcanic activity (e.g. WOVODat, IVESPA, LaMEVE, CONVERSE, VICTOR)

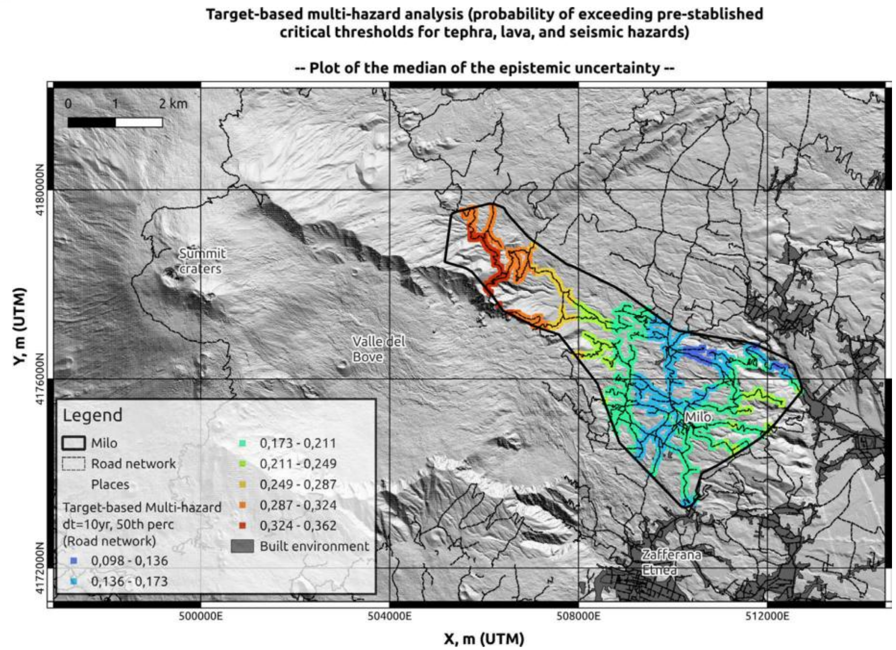
In data-poor and time-sensitive crises, rapid but informed decisions are critical
→ Use of expert elicitation to distill expert opinion for decision-makers

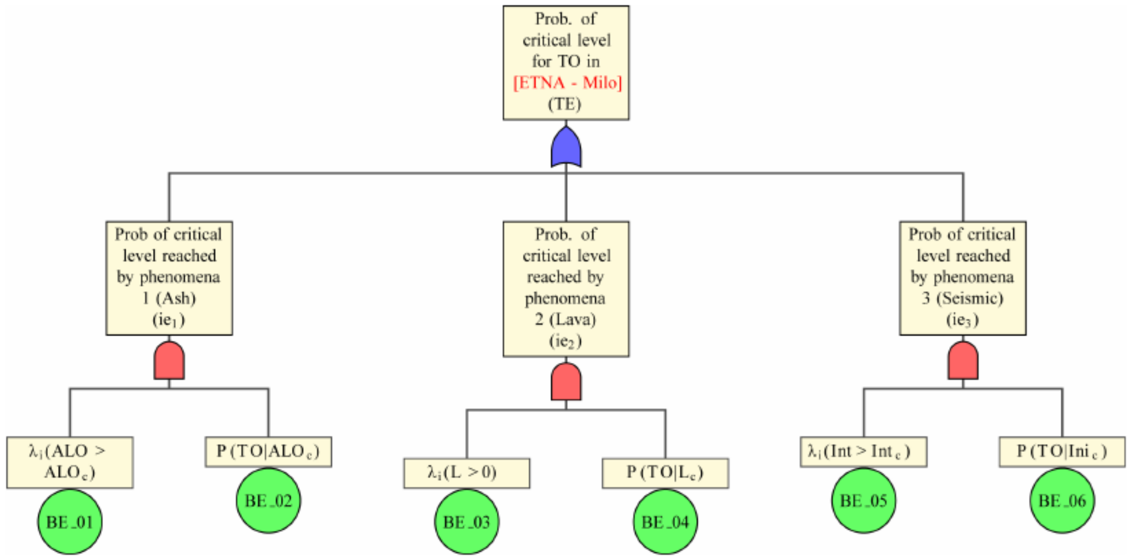


Bevilacqua et al, 2025, Bull Volcanol

Future challenges

VHA should ideally account for the intrinsic <u>multi-hazard</u> nature of volcanism → identification of chains of hazardous events and methods to combine them (e.g., **fault trees**)





Garcia et al. (2025)

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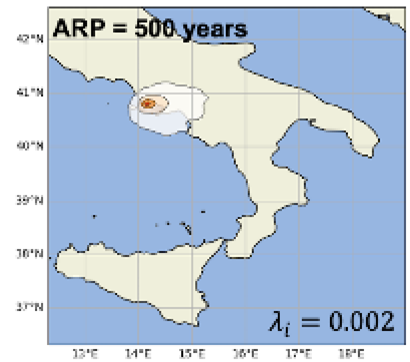
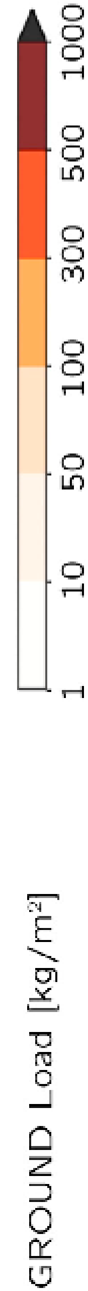
Long-term vs short-term → Pressing need to **integrate these two** into a cohesive temporal continuum that spans dormancy, unrest, pre-crisis, crisis, and post-crisis

Ground load simulated for the 5th Dec, 2019
(Martinez-Montesinos et al, 2022, Frontiers)

↕ ???



Ground load of tephra with annual frequency of 0.02 in 50 years
(Massaro et al, 2023, NHESS)



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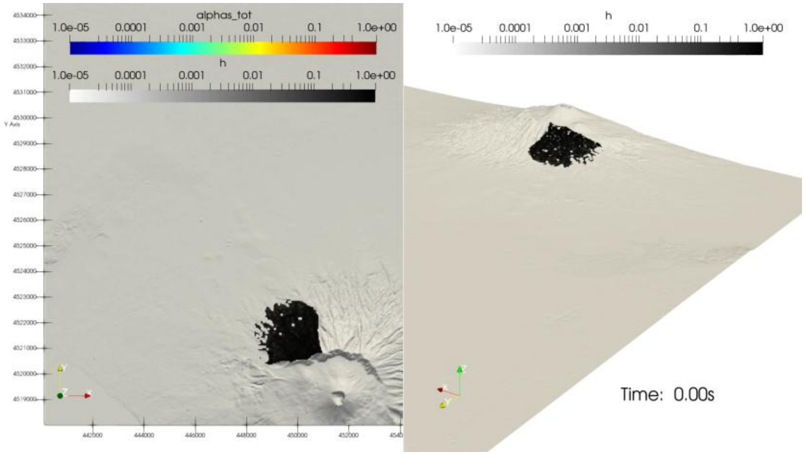
Collaboration with end-users and **multidisciplinarity** in addressing volcanic hazard: hydro-meteorology (lahars), engineering (concomitant hazards), health and air quality (gas hazard), aviation (airborne tephra)...

Simulation of a lahar from Vesuvius (Italy)



Courtesy of Mattia de' Michieli-Vitturi

The pathway to VHA

Geology

defines past eruption scenarios, characteristic eruptive parameters and frequencies

Computer models

explore scenario variability beyond events that occurred in the past and are preserved in the geologic record

Probabilistic approaches

combine the results from geology- and model-driven information to weight scenarios and to assess uncertainties

Clarke et al. (2020) Frontiers in Earth Science