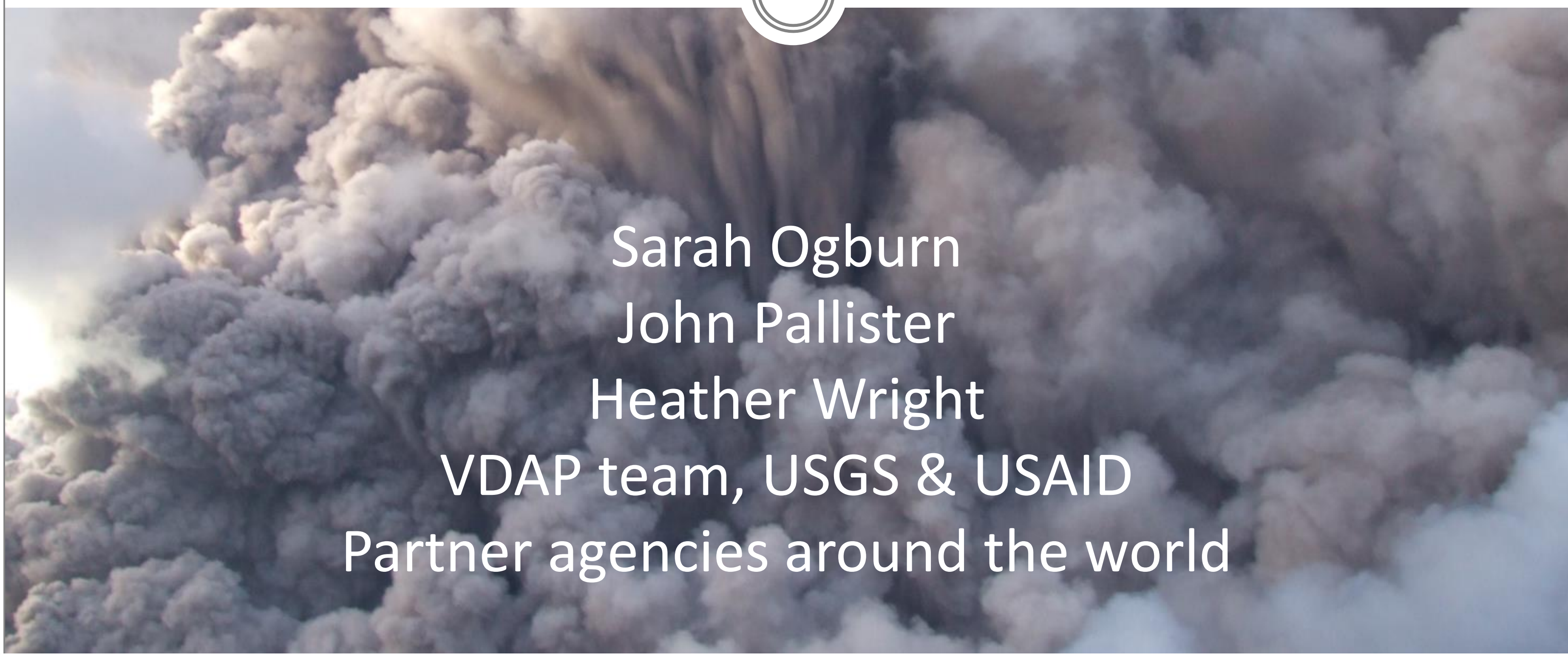
Uncertainty during volcanic crises



Sarah Ogburn
John Pallister
Heather Wright
VDAP team, USGS & USAID
Partner agencies around the world

Overview of VDAP

- Only rapid volcano crisis-response team
- Cooperative program between US Geological Survey and US Agency for International Development (USAID) Office of Foreign Disaster Assistance (OFDA)
- Mission: reduce loss of life and property; limit economic impact; prevent crises from becoming disasters
- Crisis response, capacity building, hazard communication, and science diplomacy

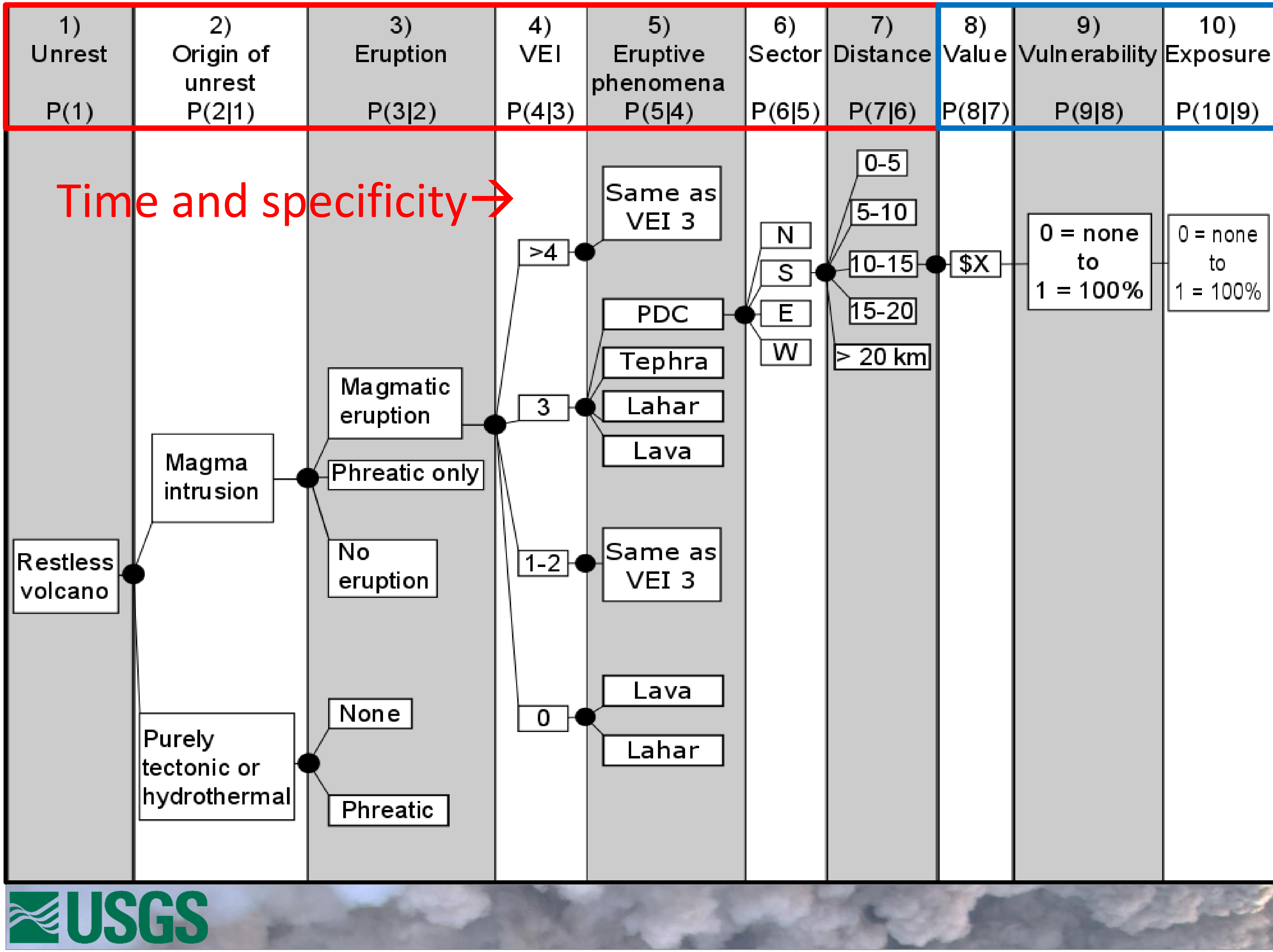
- >25 major crisis responses since 1986
- Helped partners save 10's of thousands of lives, 100's of $ millions
- 2003-2014:
  - > 60 infrastructure missions
  - ~25 on-site responses
  - many remote responses
  - 15 countries

USGS

Overview of VDAP

- International crisis response is both on site and (increasingly) remote and includes eruption forecasting using event trees

USGS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4) VEI P(4|3)
5) Eruptive phenomena P(5|4)
6) Sector P(6|5)
7) Distance P(7|6)
8) Value P(8|7)
9) Vulnerability P(9|8)
10) Exposure P(10|9)
Time and specificity→
Restless volcano
Magma intrusion
Purely tectonic or hydrothermal
Magmatic eruption
Phreatic only
No eruption
None
Phreatic
>4
3
1-2
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Same as VEI 3
PDC
Tephra
Lahar
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N
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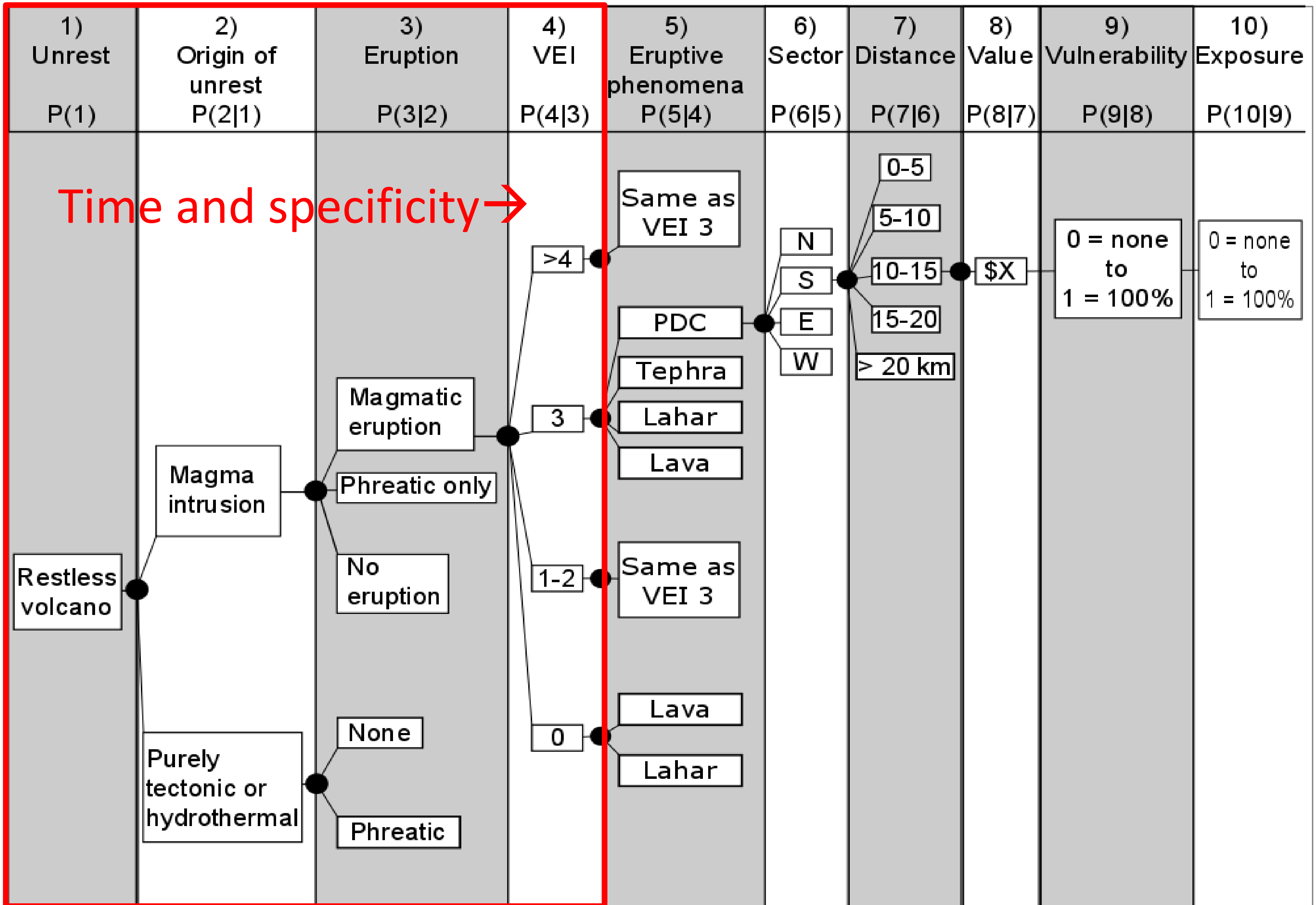
5-10
10-15
15-20
> 20 km
$X
0 = none to 1 = 100%
0 = none to 1 = 100%
USGS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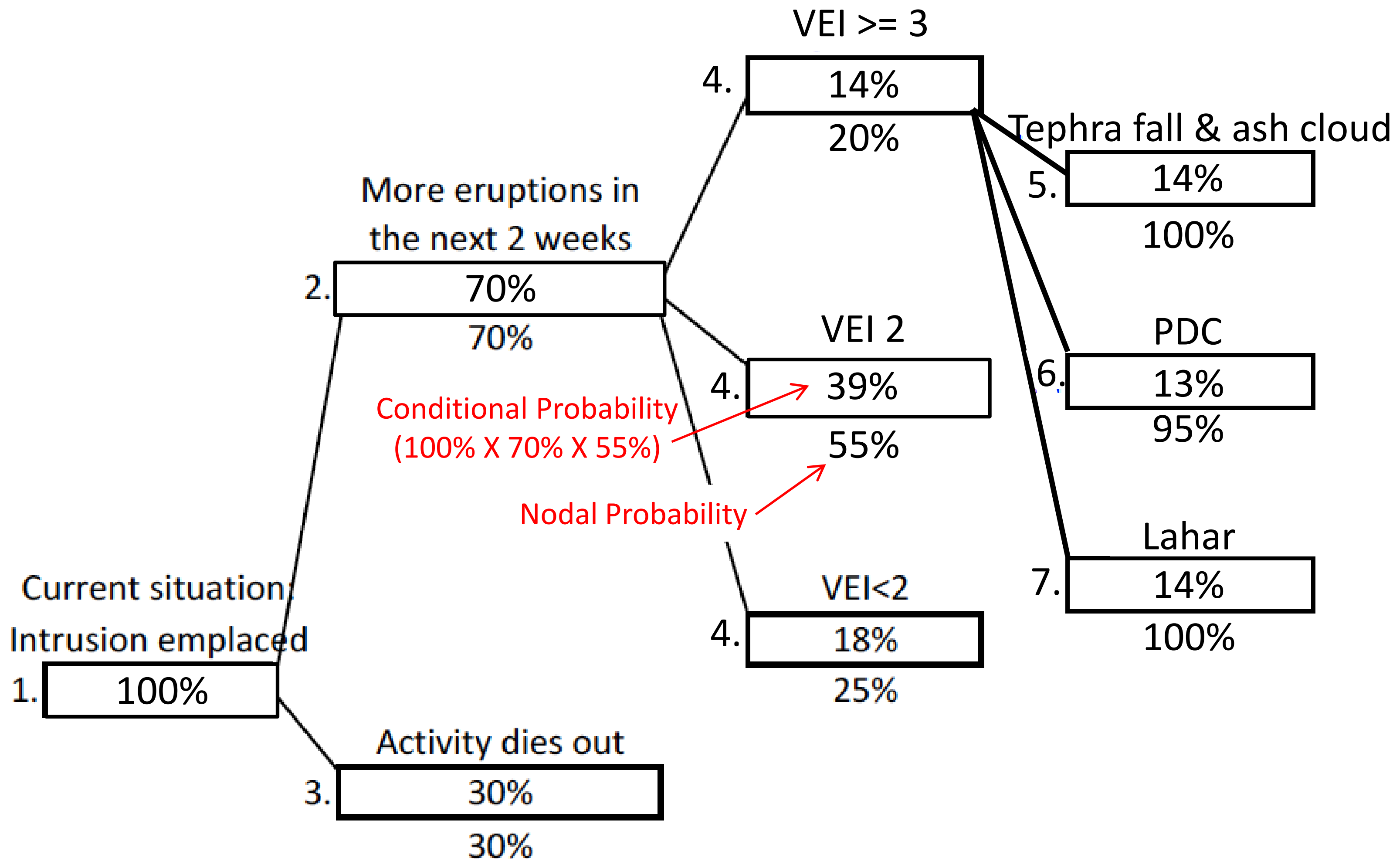
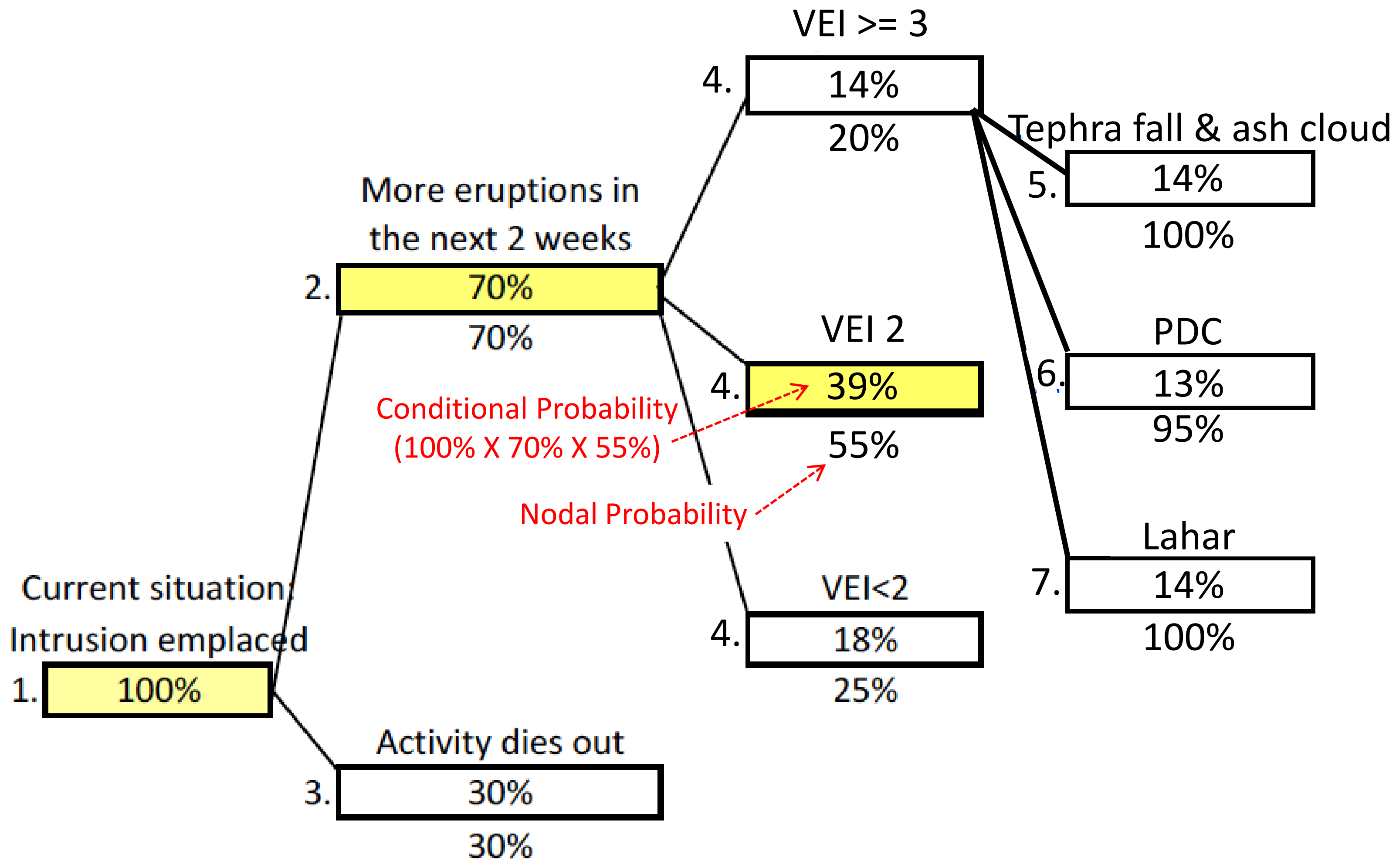


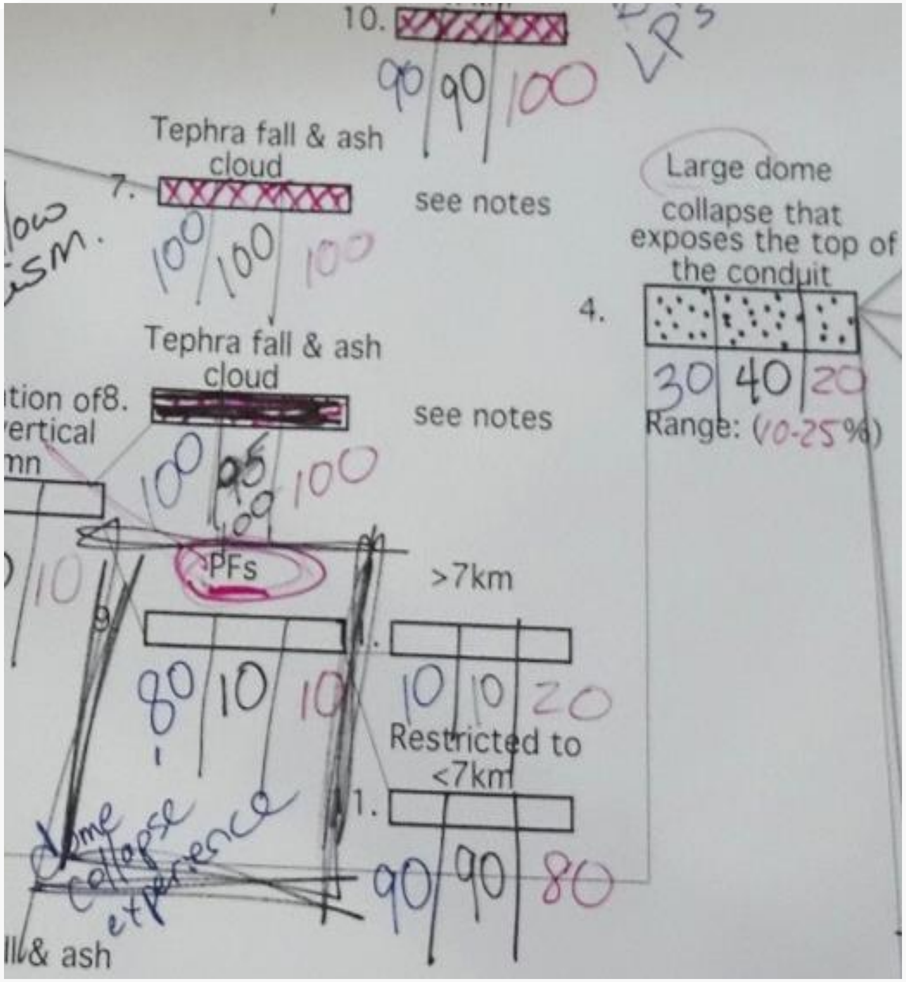
Probabilities are *conditional;* equal to the product of the probability of the event in question multiplied by all previous probabilities "upstream" in the tree



VDAP uses a “multiple datasets method” (Newhall & Pallister 2015) for creating crisis response event trees

Assigning probabilities

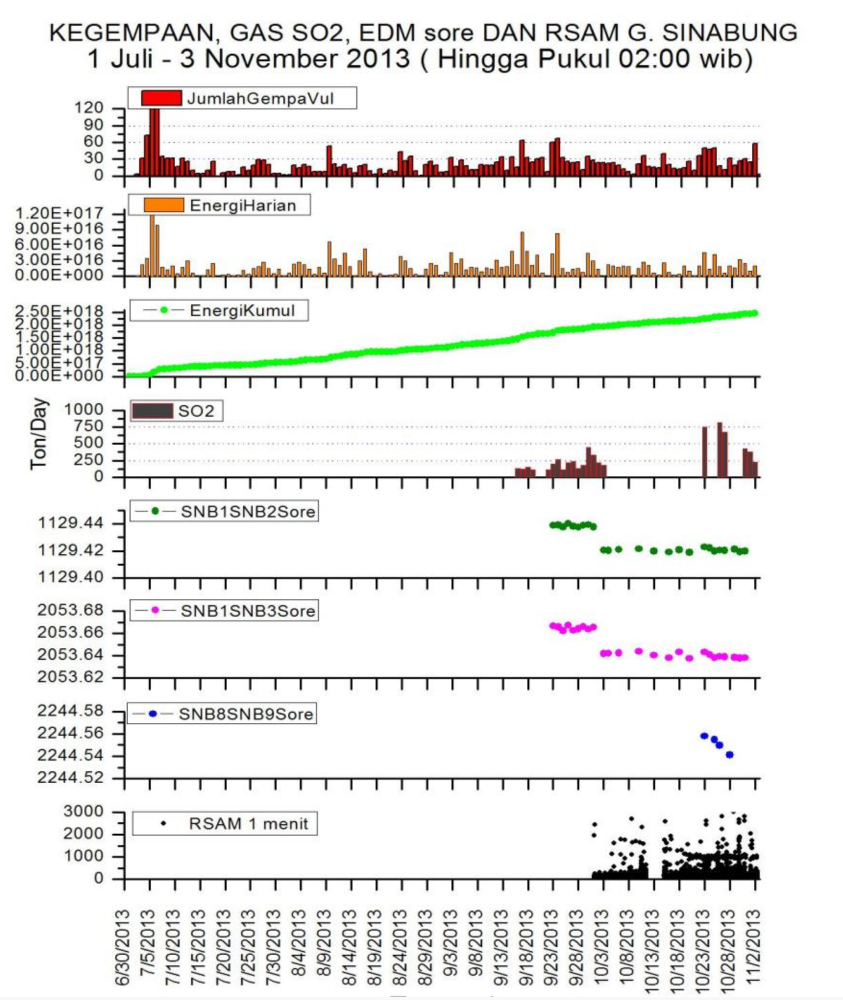
- Conducted as a group exercise; ideally in person, but sometimes remotely. Use an informal expert elicitation.
- Initial estimates are modified based on new data and <u>group discussions</u>
- Rationale for assignment of probabilities is recorded in a written document that is linked to the tree to serve as a permanent record
- **Great value in enhancing understanding of the system in question & raising capabilities of the response team**



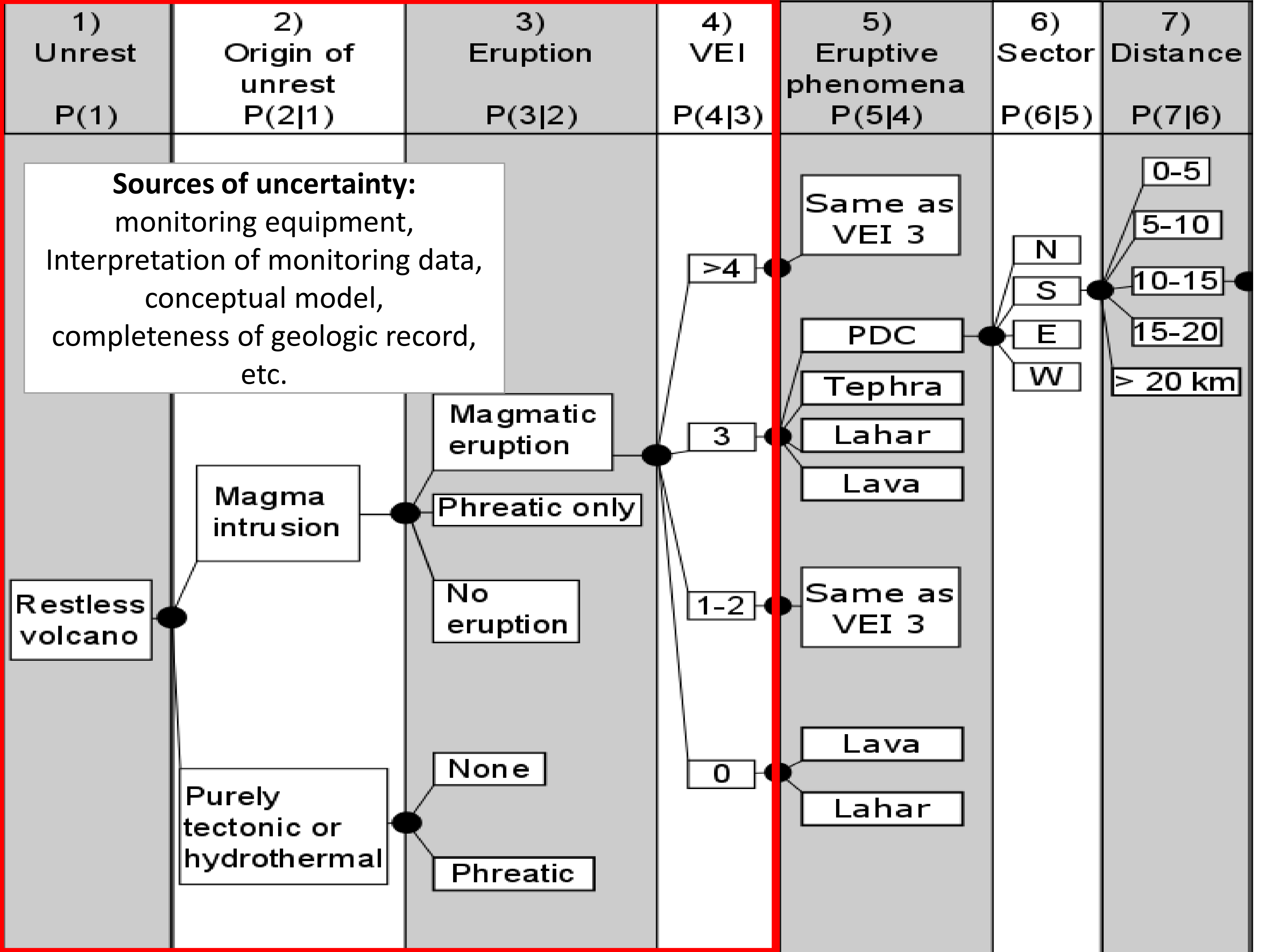
Assigning probabilities

(1) Use local information

- Geologic maps
- Past history of eruptions
- Monitoring data for past unrest
- Monitoring data for current period of unrest up to this point
    - Seismicity, Deformation, Gas
- Conceptual model for the volcanic system



USGS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Sources of uncertainty:
monitoring equipment,
Interpretation of monitoring data,
conceptual model,
completeness of geologic record,
etc.
Restless volcano
Magma intrusion
Purely tectonic or hydrothermal
Magmatic eruption
Phreatic only
No eruption
None
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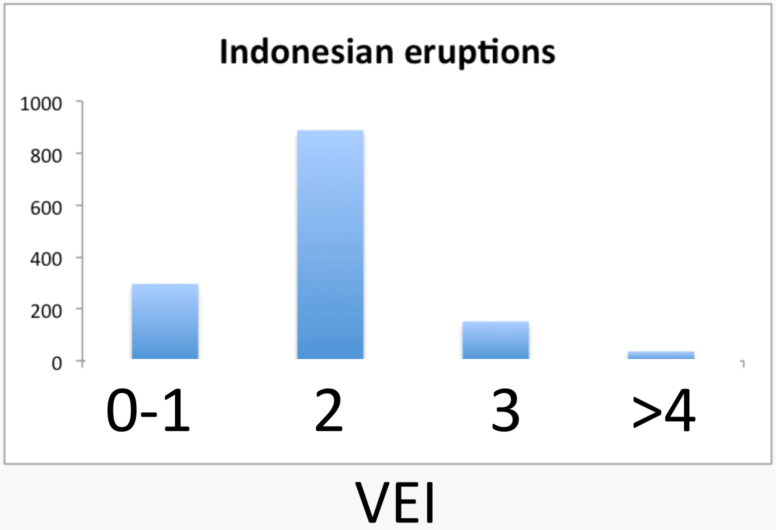
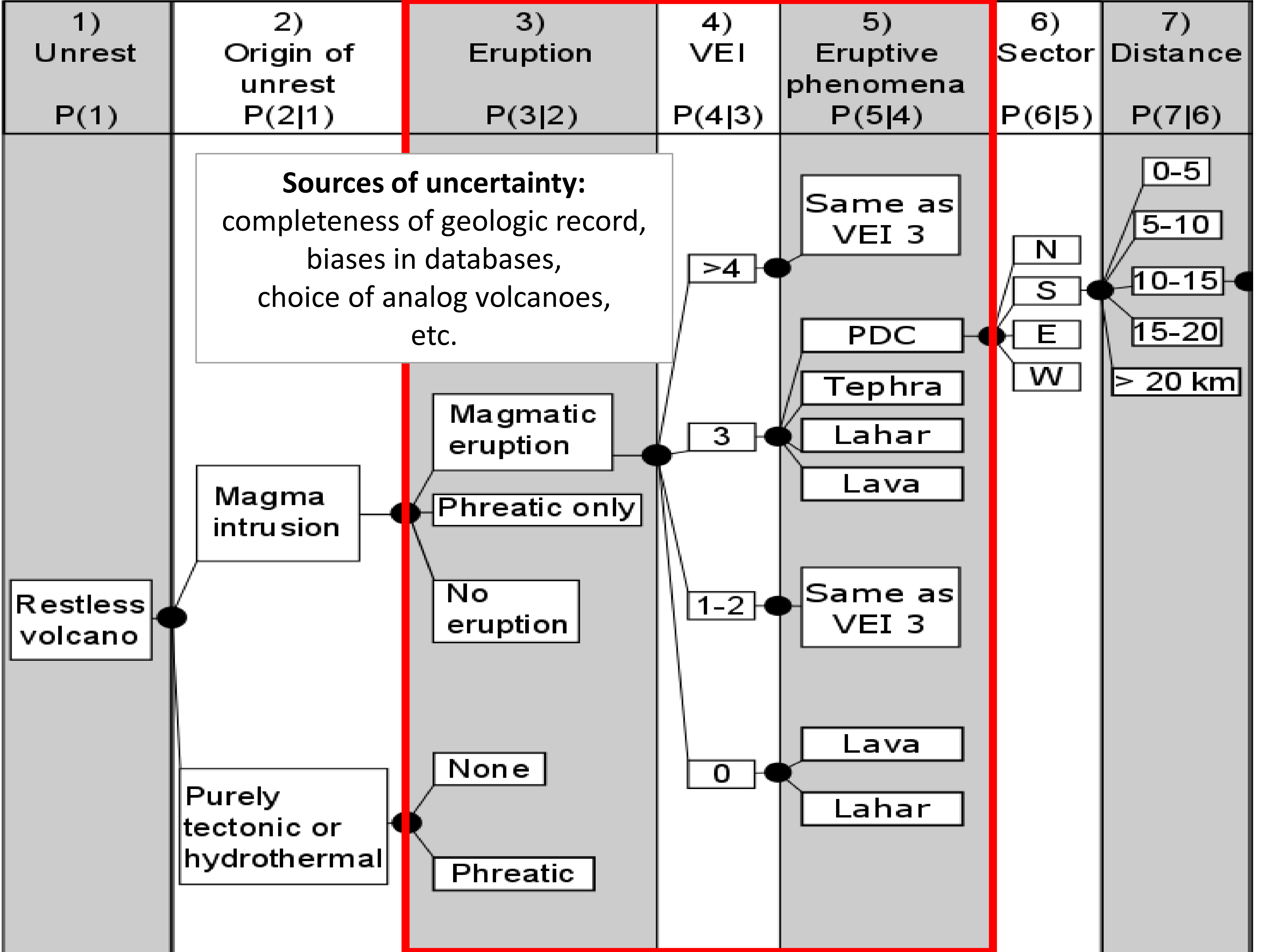
Assigning probabilities

(2) Use global data to fill in holes in local knowledge of this volcano

- Collective memory of scientists
- Published databases – examples:
  - Global Volcanism Program: global eruptive histories
  - WOVOdat: global monitoring data
  - DomeHaz (Ogburn et al. 2015): global dome-forming eruptions
  - FlowDat(Ogburn 2012): global mass-flows database
  - EFIS (Eruption Forecasting Information System) Project

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Sources of uncertainty: completeness of geologic record, biases in databases, choice of analog volcanoes, etc.
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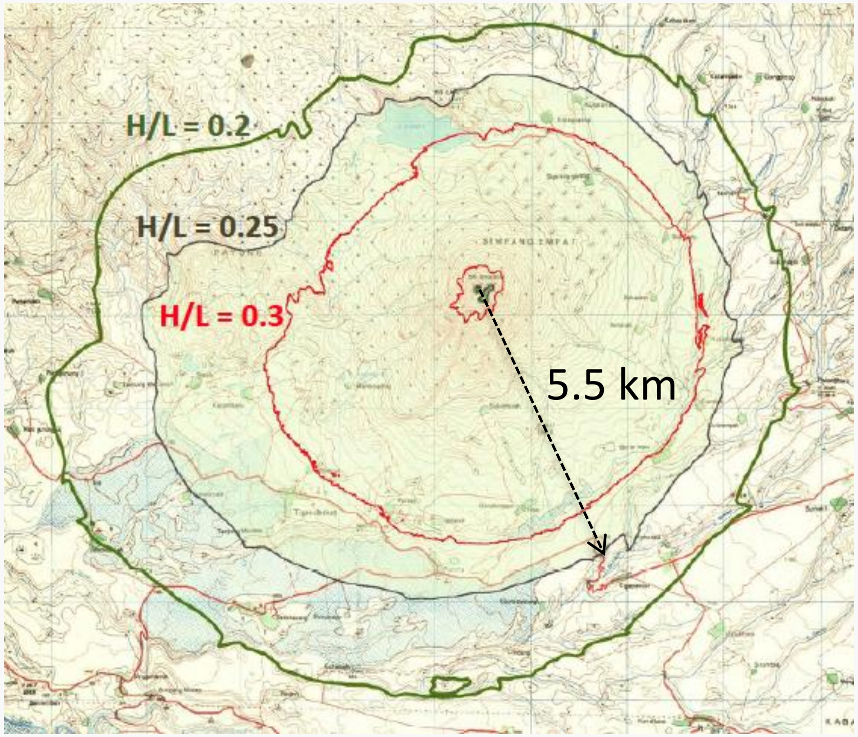
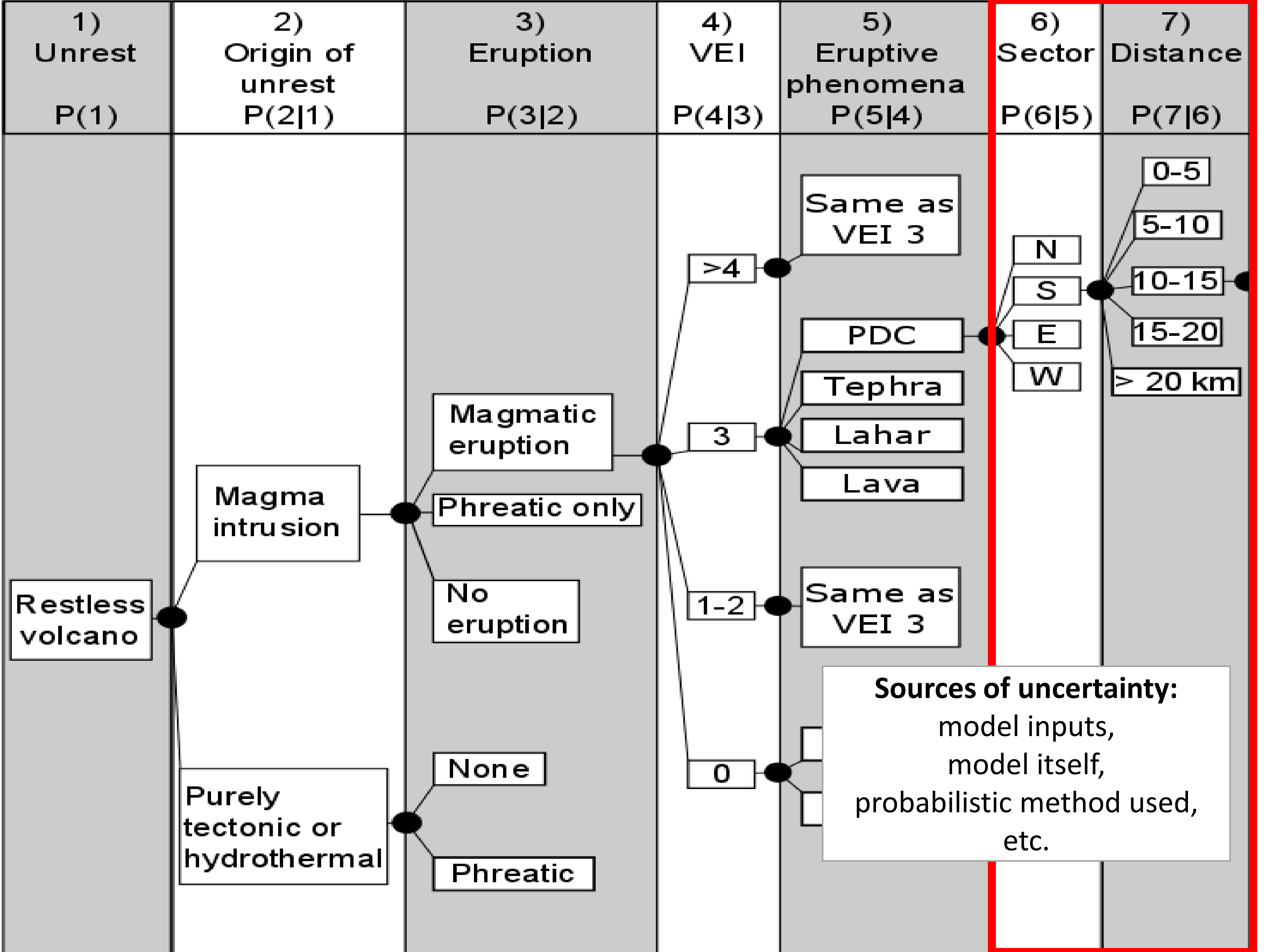
Assigning probabilities

(3) Use models of particular phenomena

- For example:
  - ΔH/L or energy line/cone model for PDCs
  - Geophysical flow models
  - LAHARZ
  - ASH3D



USGS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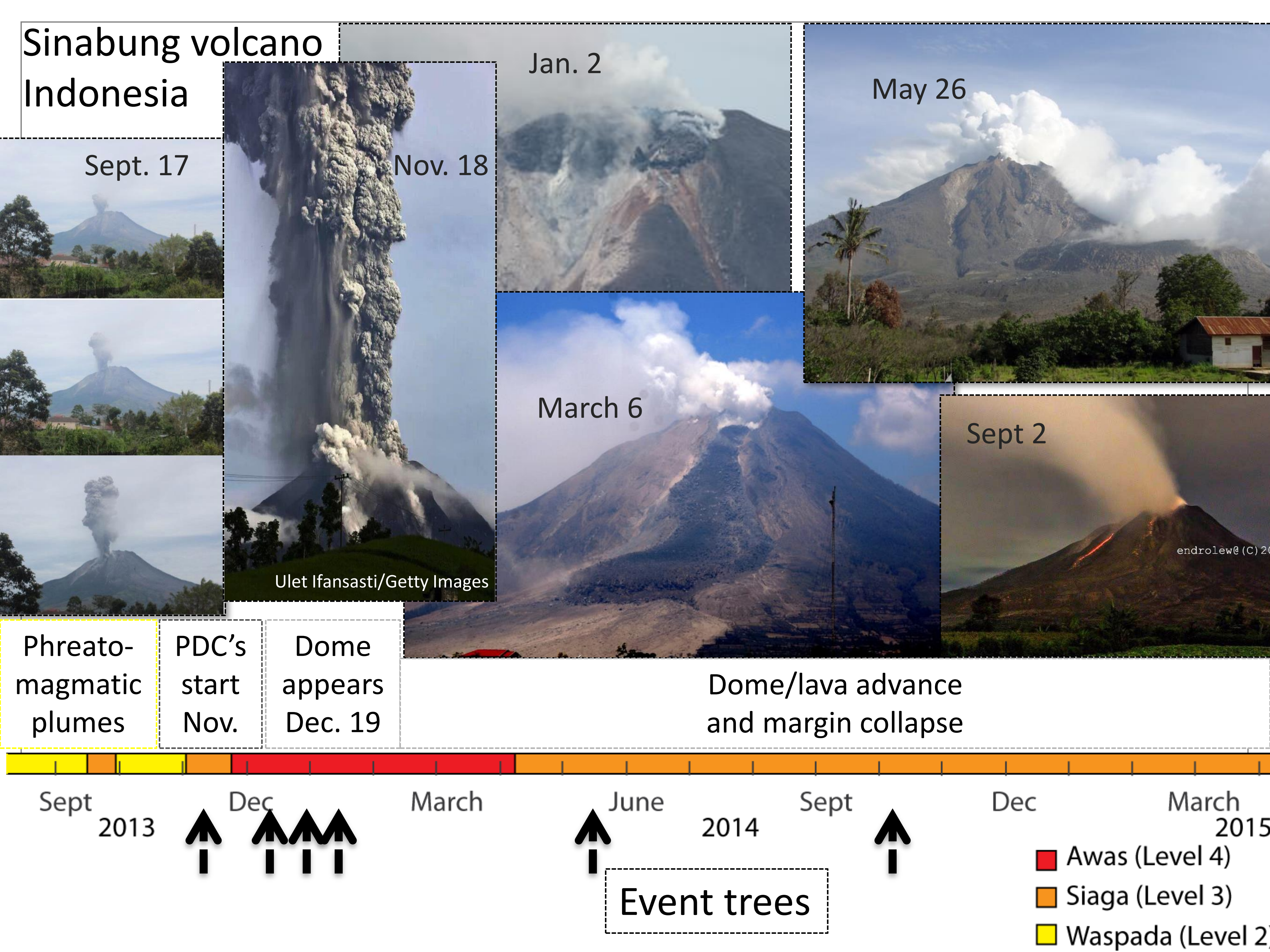
> 20 km
Sources of uncertainty:
model inputs,
model itself,
probabilistic method used,
etc.

Temporal validity of event trees

- Trees are valid for a stated time period.
- Consecutive forecasts (revisit and update tree or create new event tree) prompted by
  - Change in character of observed eruptions
  - Change in character of eruption monitoring data, e.g. gas, deformation, seismic, visual observations
- Often constructed for specific time periods of operational significance:
  - ~1 month for local gov't and evacuations
  - ~6 months for estimating observatory staffing needs
  - >1 year for relocation/land use planning


Sinabung volcano
Indonesia
Sept. 17
Nov. 18
Ulet Ifansasti/Getty Images
Jan. 2
March 6
May 26
Sept 2
endrolew@(C)20
Phreato-
magmatic
plumes
PDC's
start
Nov.
Dome
appears
Dec. 19
Dome/lava advance
and margin collapse
Sept
2013
Dec
March
June
2014
Sept
Dec
March
2015
Event trees
Awas (Level 4)
Siaga (Level 3)
Waspada (Level 2

Assigning Uncertainties

- Trees are created rapidly; forecasts are imprecise, but informative.
- Where data are very limited, we assign probabilities in qualitative/semi-quantitative fashion
  - "Roughly equal probability": 50% probability
  - "More likely than not": 70% probability
  - "Almost certain": 90% probability
- Uncertainties are quantified and carried through the event tree by assigning high-low-median nodal values.
  - i.e. 30-50%
  - Ranges for early nodes are assigned through consensus or through the high and low ranges provided by surveying the group
  - Ranges for later nodes are drawn from database statistics, model uncertainties

Characterization of uncertainty

Comparison of different eruption forecasting methods shows that the VDAP method differs mainly in its informality, which allows us to create event trees in response to **poorly known volcanic systems**, at **short notice** and under **crisis conditions.**

	Cooke-Aspinall (MVO -Montserrat)	Marzocchi et al. (BET-EF; INGV)	VDAP (Many)
Sudden crisis at previously unstudied volcano	*Y*	*Not intended*	*Y*
Weights diagnostic value of parameters	*Indirect*	*Direct*	*Indirect*
Weights experts	*Y*	*N*	*N*
Requires expert facilitator or software package	*Y*	*Y*	*N*
Basis for each probability is easy to see and reconstruct	*N*	*Relation of activity to predefined thresholds and bins is clear; basis for those thresholds, bins, and weights is in prior publication*	*Y*
Formal statistical uncertainty	Y: Weighting of expertise, self-reported uncertainty	Y: Each probability is estimated as a PDF, not as a single value	N: High-med-low consensus values

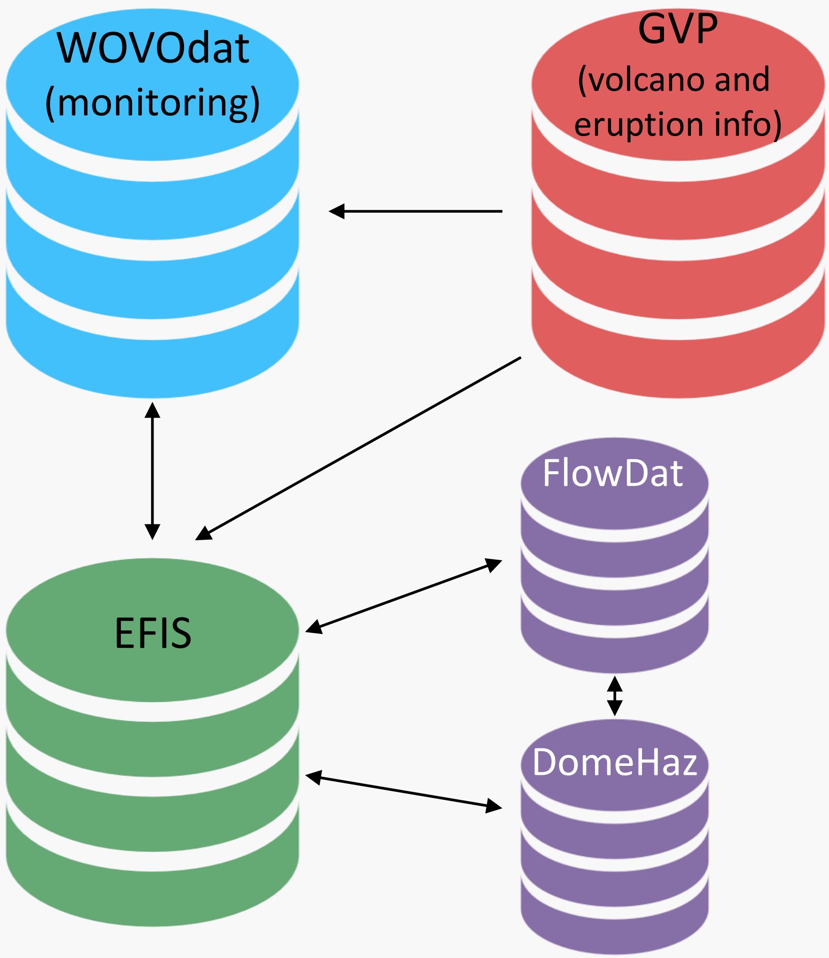
Newhall and Pallister (2015)

Value of event trees for VDAP

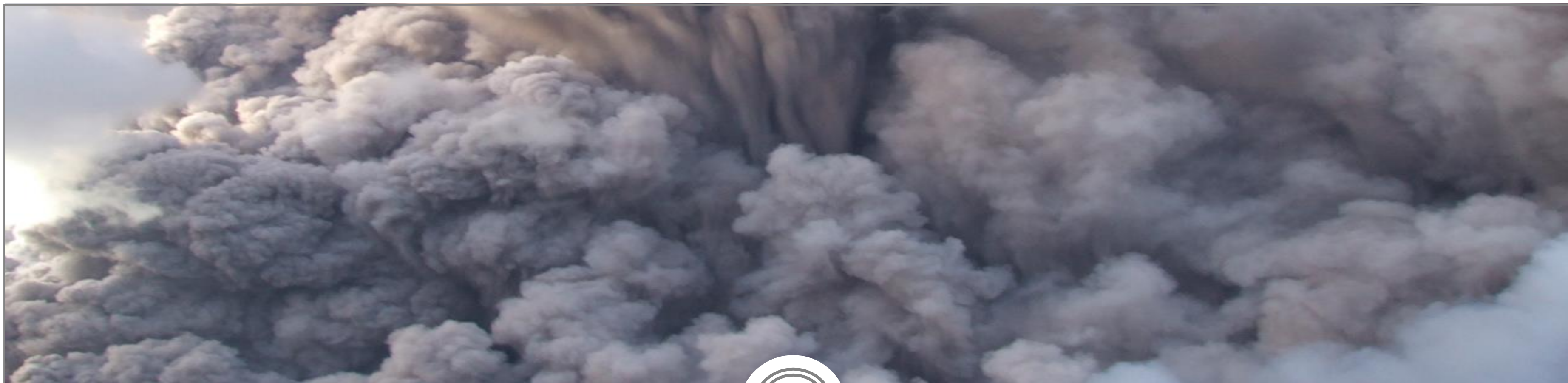
- Elicits effective communication & debate among volcano scientists with expertise in different disciplines
- Provides a structure to help reach consensus and to logically combine and weigh the meaning and predictive value of geophysical monitoring, historical/ geological records, and modeling
- Enables evaluation of uncertainty through variance in opinion or variance in model outcomes
- Documents the rationale and communicates forecasts (either directly as numerical probabilities, or in more general terms (e.g., " one out of three")
- High probability forecasts generally match outcomes

Eruption Forecasting Information System (EFIS)

- Move away from relying heavily on collective memory to probability estimation using databases
- Create databases useful for answering common VDAP questions; e.g. how often does unrest lead to eruption?
- Create generic probability trees using global data for different volcano 'types'
- Create background, volcano-specific, event trees for frequently active or particularly hazardous volcanoes in advance of a crisis
- Quantify and communicate uncertainty in probabilities



USGS

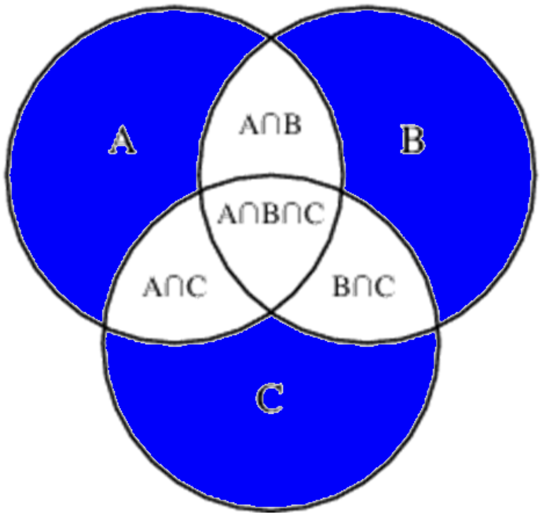


QUESTIONS

Call the collective probability of being killed by a pyroclastic flow $P(A)$, lahars $P(B)$ and tephra fall $P(C)$.

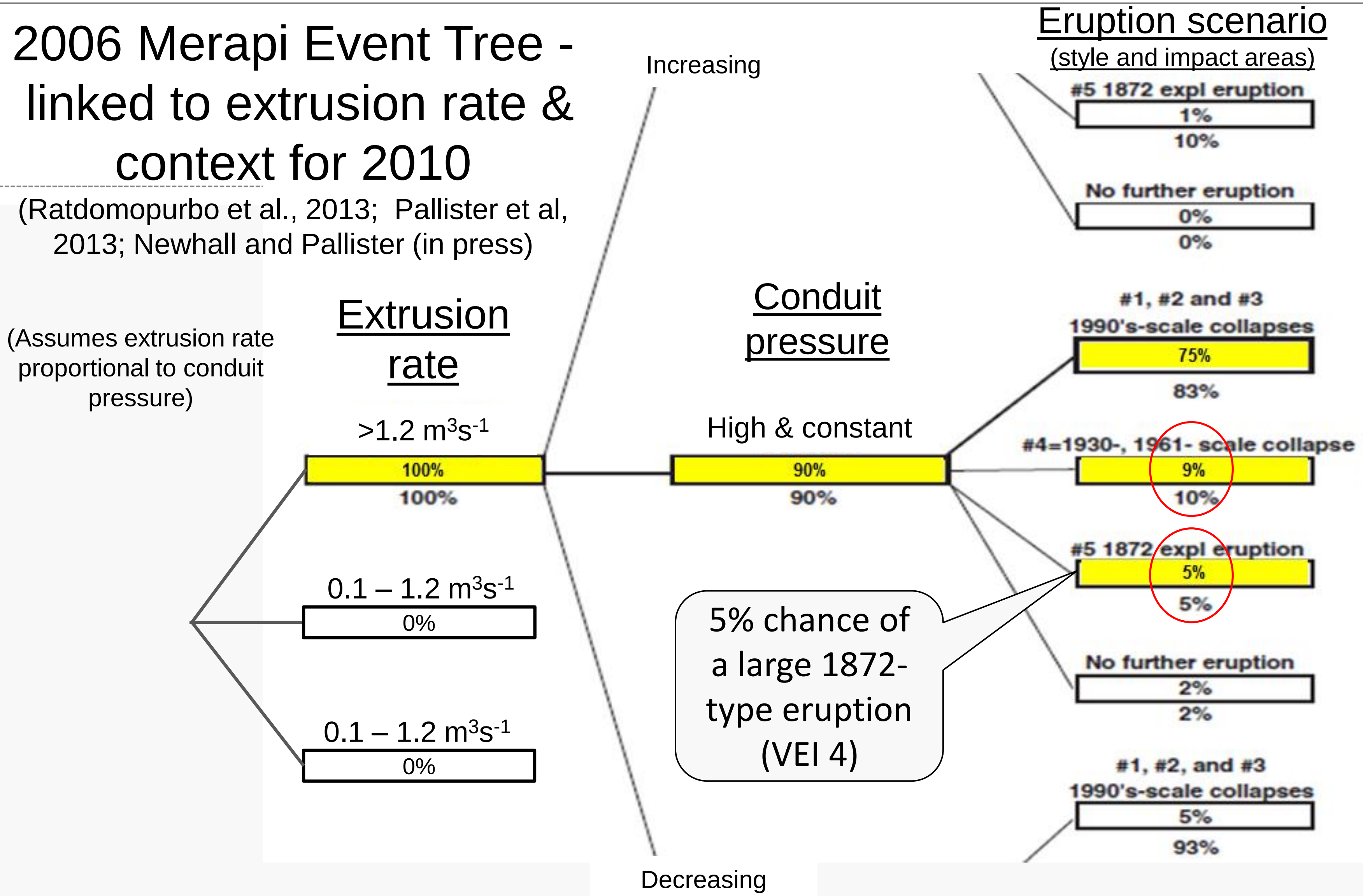
Because the various eruptive phenomena are not mutually exclusive and because one cannot be killed twice, we must subtract out overlap. The general equation for estimating the probability of A or B or C is

$$\begin{aligned} P(A \cup B \cup C) &= [P(A) + P(B) + P(C) - P(A \cap B) \\ &\quad - P(A \cap C) - P(B \cap C) + P(A \cap B \cap C)] \\ &= P(A) + P(B) + P(C) - P(A)P(B) \\ &\quad - P(A)P(C) - P(B)P(C) \\ &\quad + P(A)P(B)P(C). \end{aligned}$$



2006 Merapi Event Tree - linked to extrusion rate & context for 2010

(Ratdomopurbo et al., 2013; Pallister et al, 2013; Newhall and Pallister (in press)



In 2006, the **extrusion rate was 1.2 – 2.4 m^3s^{-1}, well above the range of 0.05 m^3s^{-1}– 0.32 m^3s^{-1} for eruptions between 1984 and 1996.** Forecast: probability of Vulcanian (1930 or 1872) type eruption 5-10% when rates exceed 1.2m^3s^{-1} and are increasing (CVGHM-USGS, 2006)

Examples (VDAP in Blue)

During Crises

- Mount St. Helens, 1980
- Popocatepetl, Mexico, 1995 (S. de la Cruz, personal communication, 1995)
- Soufriere Hills, Montserrat, 1996 and following (Aspinall et al., 2002)
- Tungurahua, Ecuador, 1999
- Guagua Pichincha, Ecuador, 1998-99
- Nyiragongo, DRC, 2002 and following
- Pago, Papua New Guinea, 2002
- Mount St. Helens, USA, 2004
- Garbuna, Papua New Guinea, 2006
- Merapi, Indonesia, 2006
- Huila, Colombia, 2007
- Chaitén, Chile, 2008
- Harrat Lunayyir, Saudi Arabia, 2009
- Mayon, Philippines, 2009
- Nevado del Ruiz, Colombia, 2012, 2013
- Sinabung, Indonesia, 2013-2014
- Chiles-Cerro Negro, Colombia 2014

Outside of crises

- Arenal, Costa Rica (Meloy, 2006)
- Auckland Volcanic Field, New Zealand (Lindsay et al., 2010; Sandri et al., 2012)
- Campi Flegrei, Italy (Selva et al., 2012)
- Chiltepe-Apoyo, Nicaragua (Freundt et al., 2006)
- Colima, Mexico (Fedde, 2009)
- El Misti, Peru (Constantinescu et al., 2012)
- Etna, Italy (Brancato et al., 2011, 2012; Acocella and Puglisi, 2013)
- Miyake-jima, Japan (Garcia-Aristizabal et al., 2013)
- Ruapehu, New Zealand (G. Jolly, personal communication, 2013)
- Sete Cidades, Azores, Portugal (Queiroz et al., 2008)
- Soputan, Indonesia, 2011 (Kushendratno et al., 2012)
- Soufrière Guadeloupe, France (Komorowski et al., 2008)
- Teide-Pico Viejo, Canary Islands, Spain (Marti et al., 2008)
- Vesuvius, Italy (Marzocchi et al., 2004; Neri et al., 2008; Baxter et al., 2008; Sandri et al., 2009)

From Newhall and Pallister (2014)

4. **Geologic mapping:** youngest Sinabung: **lava flows and block-and-ash type pyroclastic deposits…** No subplinian to plinian ashfall deposits found, but such deposits are easily eroded and likely underrepresented in the geologic record. These geologic data would suggest a 90% chance of VEI <3 vs. 10% VEI >3.

A global estimate of VEI <3 vs. VEI>3 is 90/10. A search of the GVP online database shows 22% VEI 0-1; 65% VEI 2; 10% VEI 3; 3% VEI >=4 in **Indonesia**.

For **andesitic dome-forming eruptions worldwide:** 10% associated with VEI>3, 75% with VEI 2-3; and 15% VEI 0-1 (DomeHaz; Ogburn et al.). Large events are slightly over-represented in this database.

In this eruption so far: ash plumes to 10-12 km, but small volumes <VEI 3

Monitoring: recent appearance of at least one deep or distal VT suggests renewed pressurization, but no evidence for significantly greater pressure increase at depth (e.g. inflation, many distal VTs, cessation of SO2 output)

Taken together, we assign a probability of >VEI 3 in this tree of 5%. Highest probability for continued VEI 2-3 eruptions (75%). We assign a probability of 20% to VEI 0-1 eruptions.

Eruption Forecasting Information System (EFIS)

- What percentage of intrusions lead to eruption? Does seismic evidence for multiple intrusions (e.g., multiple VT swarms) increase likelihood for eruption? What is global distribution of delay times between intrusion and eruption?
- What percentage of phreatic eruptions lead to magmatic eruption? What are recorded lead time intervals? Does the size and number of initial phreatic eruptions scale with the maximum eruption size?
- What percentage of dome extrusions were/were not accompanied by drumbeat seismicity (and inverse)?
- Does increasing frequency of VEI 1 emissions precede increase in explosive magmatic activity?
- What percentage of eruptions were preceded by zero measurable deformation?
- Is there a threshold for total quantity of SO_2 emitted or duration of sustained SO_2 emission that necessarily indicates eruption?
- Many many many more….

USGS

Long term forecasts

- Sinabung eruption continues
  - Lava flows continues to advance
  - Collapses continue along flow margins, producing pyroclastic density currents with up to 5 km runout
  - How long will eruption last?