Probabilistic Volcanic Hazard Assessment

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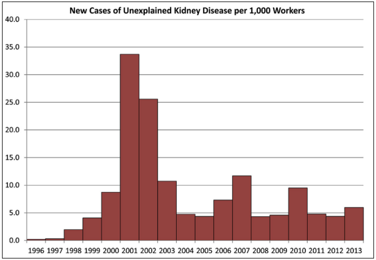
CIDER, June 2019

Practical application of volcano science

Right: Tephra fallout and kidney disease in Nicaragua. Data courtesy of Kristy Murphy (Texas Children's Hospital)

Top:Panabaj (Guatemala) debris flow (from Charbonnier et al., 2018).
Right: Aso volcano and the Ikata NPP



Japan Court Orders Shutdown of Nuclear Reactor Near Volcano

Dec 14, 2017

Hazard Forecasts

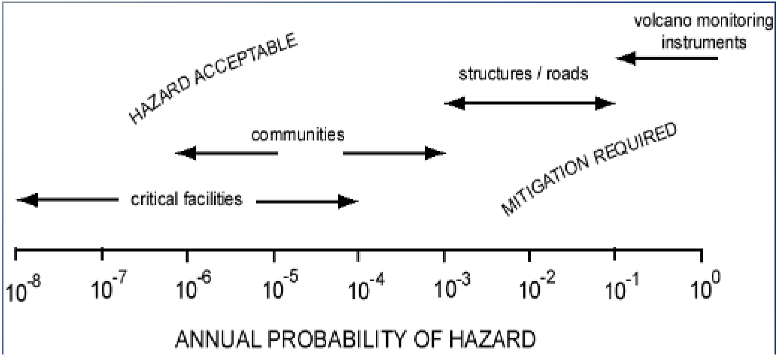
- *What hazardous phenomena are likely to occur associated with volcanoes?*
- *How frequently do they occur, or how likely are they in some timeframe?*
- *What areas are potentially impacted and how?*

Howel Williams (Williams and McBirney, 1979):

- Long-term volcanic hazard assessment - Primarily based on the geologic record and analogous volcanoes (should take place well in advance of unrest!)
- Short-term volcanic hazards assessment - incorporates data on volcanic unrest, uses geophysical signals and related data to forecast the timing and nature of volcanic eruptions.

Probability in hazard assessment

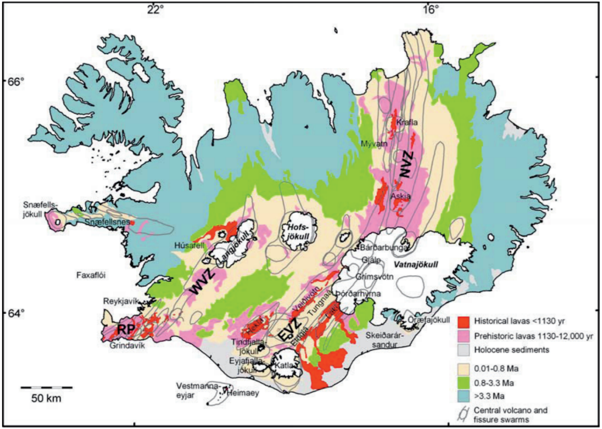
Are hazards "'high" or "low"? It depends who you are and what your problem is!



For example, 10^{-4} annual probability of lahar inundation is a very low hazard for an 80 yr old person, and a very high hazard for a 10 yr old person (Connor, 2011, Numeracy).

Long-term volcanic hazard assessment

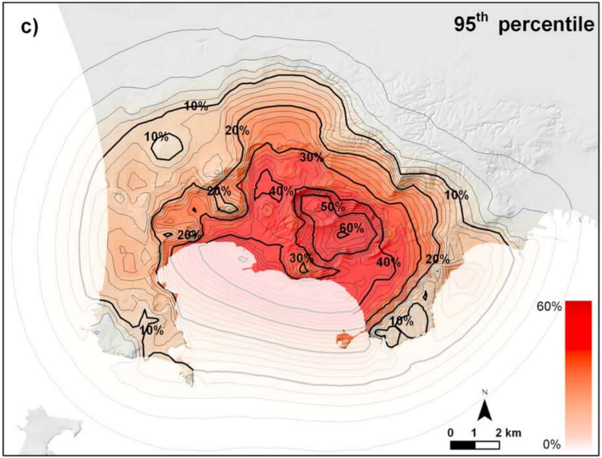
volcanic hazards in Iceland, based on the location and nature of past events. (e.g., data center / server farm)



from Gudmundsson et al., Volcanic hazards in Iceland, 2008

Long-term volcanic hazard assessment

Conditional probability of inundation by PDCs, Campi Flegrei



from Neri et al., 2015

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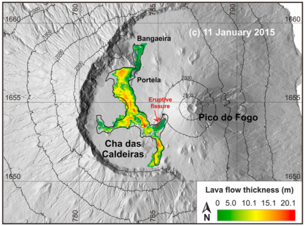
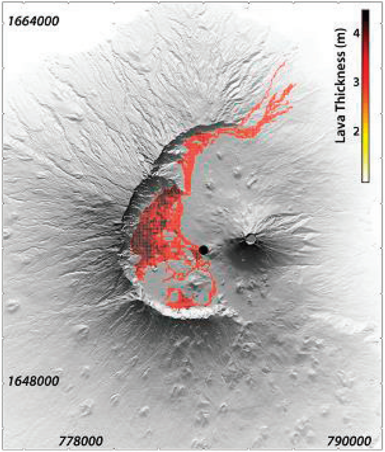
Short-term volcanic hazard assessment

Given lava effusion from a vent, what area might be inundated (Fogo, 2014).

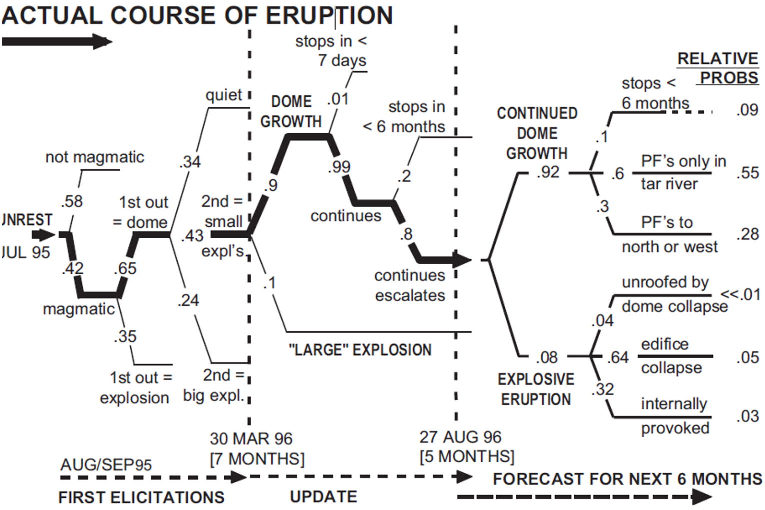
WIRED





Cappello et al., 2016

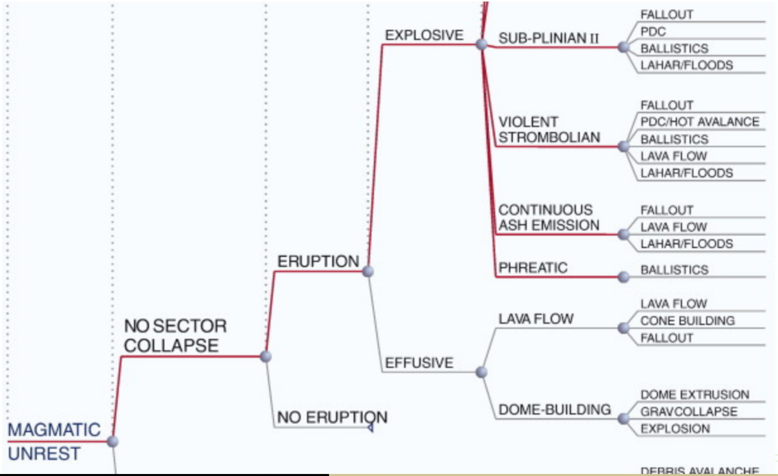
Short-term volcanic hazard assessment



Aspinall and Cooke, 1998

Event tree for renewed activity at Vesuvius (Neri et al. , 2008):

$$P[subplinian|unrest] = P[N_2|N_1]P[N_3|N_2]...$$



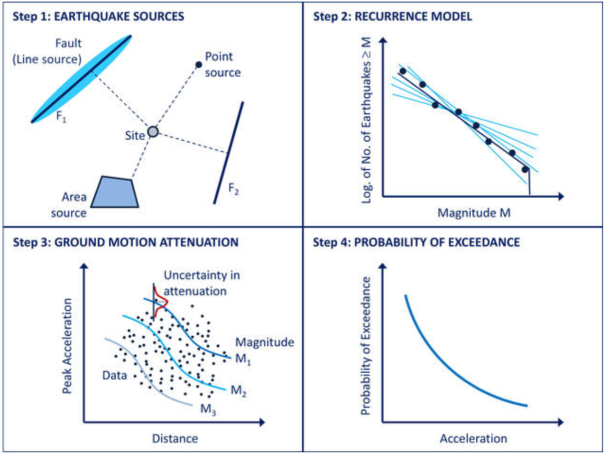
Steps in PVHA

1. Develop a conceptual model of how the volcano and its magmatic system work, What types of activity are possible, given how magma is stored and ascends in a particular system?
2. Assess rates of activity, using historical observations, radiometric dates, stratigraphy. Short-term forecasts are sensitive to changes in unrest and anticipate changes in activity
3. Assess the potential location of activity based on statistical analysis of past vents and/or monitoring
4. Assess the potential magnitude of activity, inferred from volumes of past events or magnitude of signals.
5. Assess the potential impacts of activity using geologic record and numerical models.

PSHA

PVHA
Background
Conceptual model
Rates
Location
Magnitude
Impacts
Future

Cornell (1968), Cornell and Hanks (1994), Stirling et al., (2009)



$$P[G > g|\Delta t] = P[G > g|M]P[M|x, y]P[x, y|\Delta t]$$

Building a probabilistic volcanic hazard assessment

PVHA
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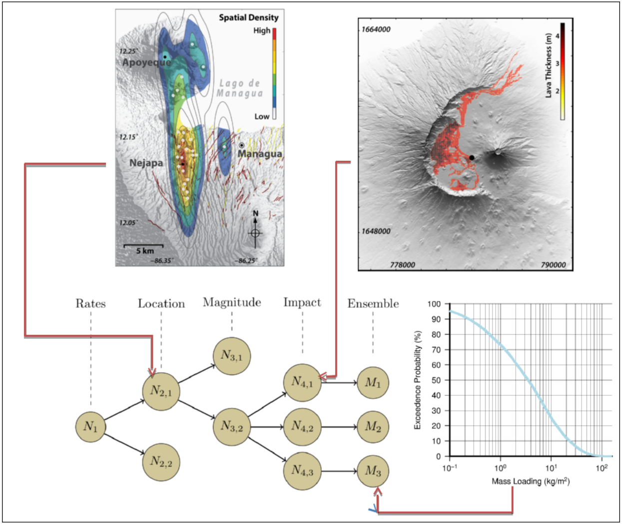
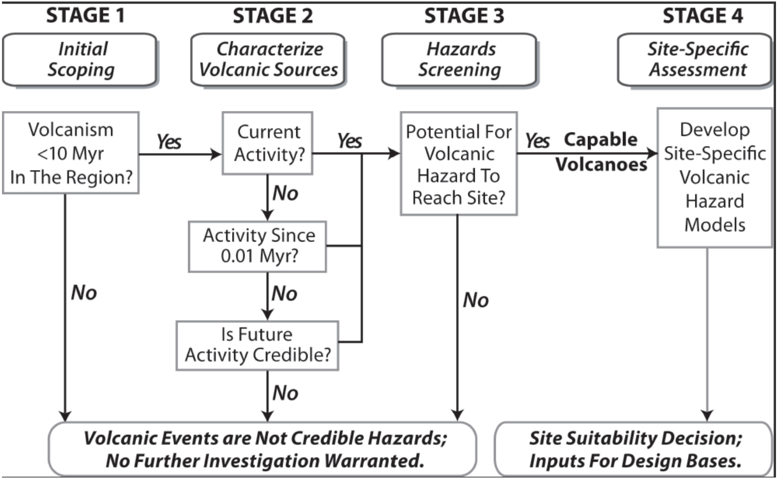


from NAS ERUPT report (2017)

International Atomic Energy Agency guidelines for site-specific long-term hazard assessment

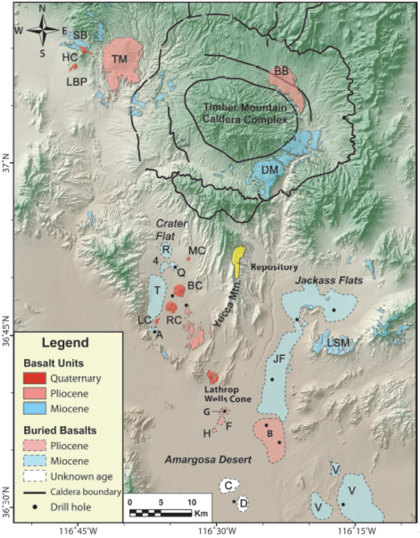


see: IAEA (2012) Volcanic Hazards in Site Evaluation for Nuclear Installations. International Atomic Energy Agency, Vienna. IAEA Safety Standards Series No. SSG-21. IAEA (2016) Volcanic Hazard Assessments for Nuclear Installations: Methods and Examples in Site Evaluation. IAEA Techdoc Series No. 1795.

Initial Scoping: Basin and Range volcanism near Yucca Mountain (NV)

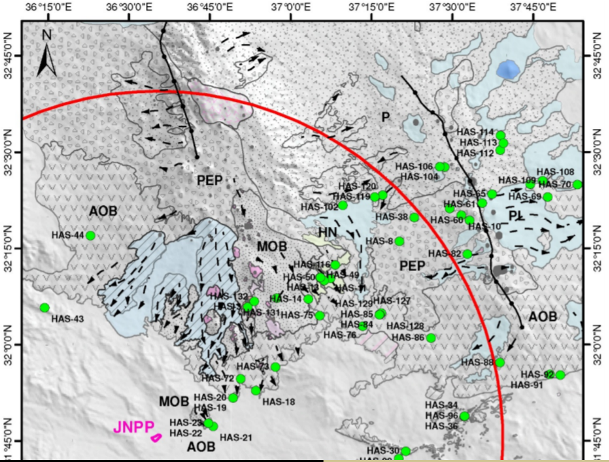
- Are there volcanoes in the site region and how old are they?
- Is the tectonic setting consistent with future volcanism?

from Valentine and Perry (2009)



Initial Scoping: Lava flows in the Harrat Al Shamm (Jordan)

Are there volcanoes in the site region and how old are they? Is the tectonic setting consistent with future volcanism? (Figure by WesternGeco, 2018, with permission from JAEC)

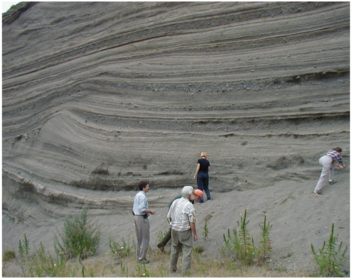


Characterize Sources: IAEA guidelines

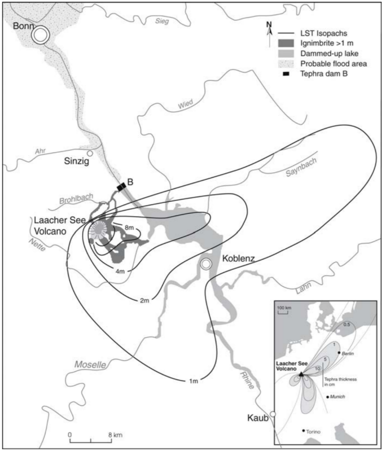
Consider potential for specific volcanic products in characterizing sources. Develop a conceptual model of potential volcanic activity based on geologic record, analog volcanic systems:

Phenomena	exclusionary?	migitation?
Opening of new vents	Yes	No
Sector Collapse	Yes	No
Pyroclastic density currents	Yes	No
Lava flows	Yes	No
Lahar	Yes	Yes
Tephra fallout	No	Yes
Volcanic gases	No	Yes
Volcanic earthquakes	No	Yes

Characterize Sources: Volcanism in the Eifel volcanic field (Germany)

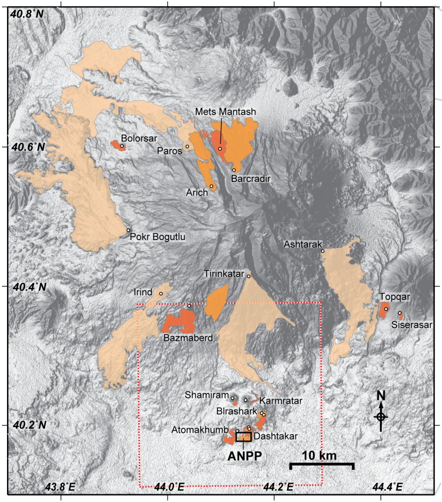


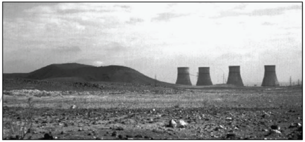
Pyroclastic surges, tephra fallout, and damming of Rhine:



From Park and Schmincke, 1997

Conceptual Model: Post-collisional volcanism (Armenia)

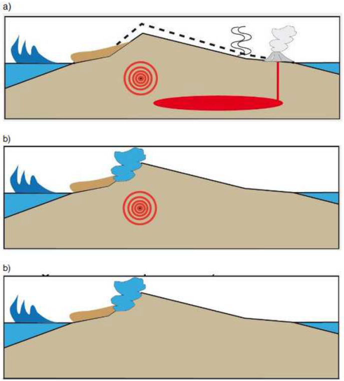


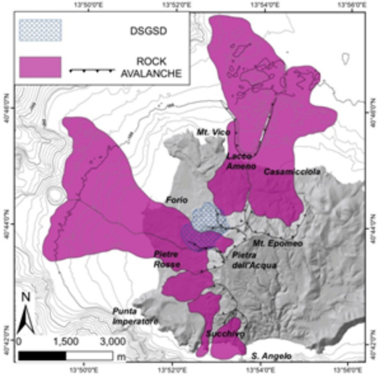


from L. J. Connor et al., 2012

Conceptual Model: volcanic hazards on Ischia (Italy)

What volcanic hazards do residents of Ischia face given the nature of volcanic activity during the last 150 ka?

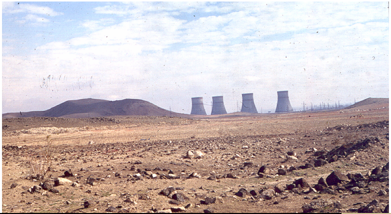




From Selva et al., 2019, JAV

Screening Hazards based on geologic record: Armenia

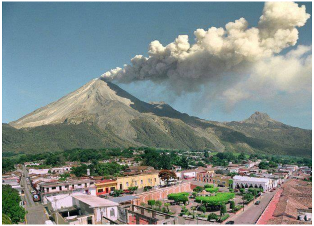
Given a volcanic eruption, is it possible specific volcanic phenomena can reach the site?



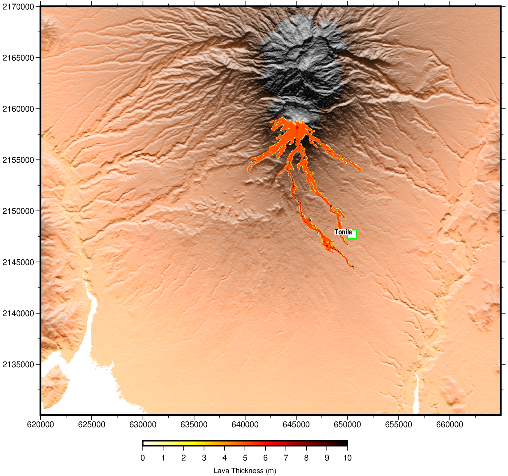
Low-aspect ratio ignimbrites and lava flows reach the Armenia Nuclear Power Plant site.

Screening Hazards based on simulations: Tonila (Mexico)

Given a volcanic eruption, is it possible specific volcanic phenomena can reach the site?

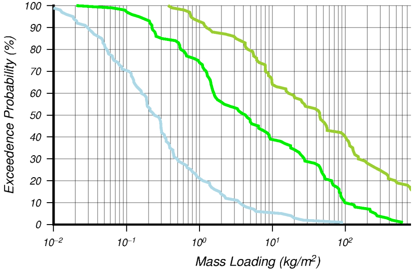


Based on simulations, lava flows from the summit of Volcán de Colima of 0.1 km^3 might reach the Tonila vicinity

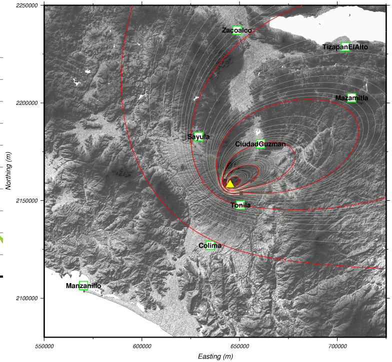


Screening Hazards based on simulations: Tonila (Mexico)

Given a volcanic eruption, what are the possible impacts?



tephra survivor models (VEI 3-5)



tephra simulation

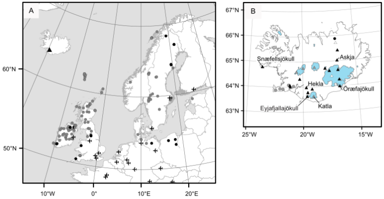
Screening Hazards: Ikata (Japan)

Kazuhiro Nakamoto, President, Japan Federation of Bar Associations

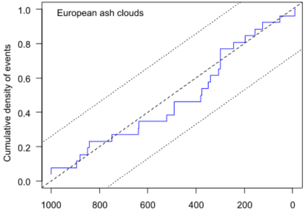
Today, the Hiroshima High Court handed down a temporary injunction compelling Shikoku Electric Power Corporation to stop operation of the No. 3 reactor of the Ikata Nuclear Power Plant. The decision was made according to the evaluation procedures in the volcanic eruption guidelines set by the Nuclear Regulation Authority (NRA). It was found that it was difficult to judge whether the volcanic activity of the Mt. Aso caldera, located 130 kilometers away from the Ikata NPP, was weak enough during the operation of the reactor. As it is impossible to estimate how big an eruption of Mt. Aso would be, the judgment took the largest past eruption of Mt. Aso "Aso-4" about 90,000 years ago) (volcanic explosivity index 7) as the basis for its assumption. **The court found that it cannot conclude that the Aso-4 pyroclastic flow was very unlikely to reach Ikata NPP, and therefore judged that the Ikata NPP was not located in an appropriate location.**

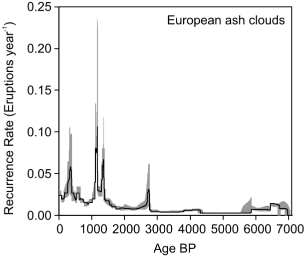
Models suggest 44 ± 7 yr for European tephra clouds

When eruption frequency is stationary, it is possible to apply univariate statistical models to estimate recurrence rates



Swindles et al. (2011) Geology.
Watson et al. (2017) EPSL.
Swindles et al. (2017) Geology.





Models suggest 44 ± 7 yr for European tephra clouds

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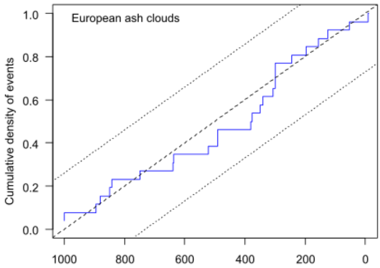
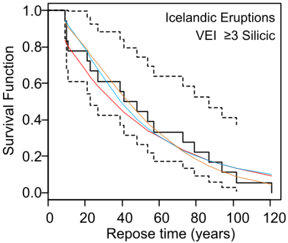
Calculate stationarity within some confidence interval:

$$\hat{\lambda} = \frac{N-1}{t_o - t_y}$$

$$CI_{95\%} = \hat{\lambda}t \pm 1.36/\sqrt{N}$$



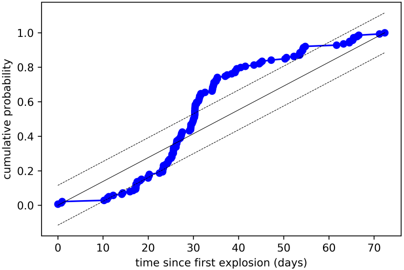


Bebbington, 2013, Connor et al. 2015, Watson et al. ,2017

$$P[N \geq 1] = 1 - \exp\left[-\lambda \Delta t\right]$$

Nonstationary eruption rates

Frequency of explosive eruptions at Momotombo volcano (Nicaragua) measured during Feb–April, 2016



Probability model must (1) use a subset of data, or (2) detrend the data, or (3) use a cluster or renewal model). One cannot apply a univariate model, like an exponential model, to nonstationary distributions (data from INETER, Armando Saballos).

A Volcano Eruption Age Model for Mars

PVHA
Background
Conceptual model
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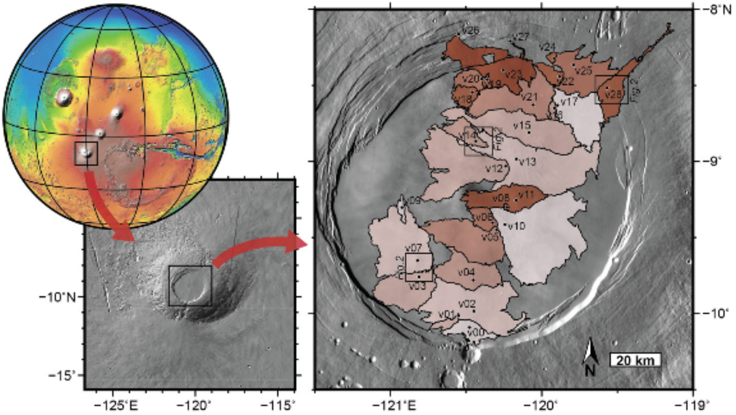
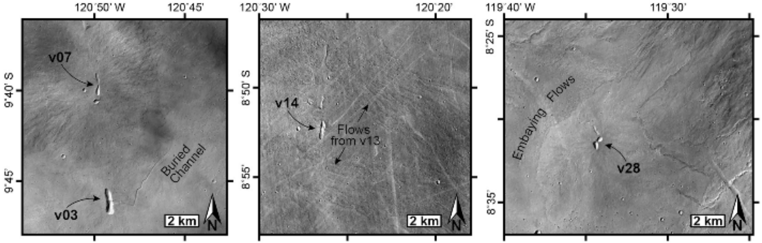


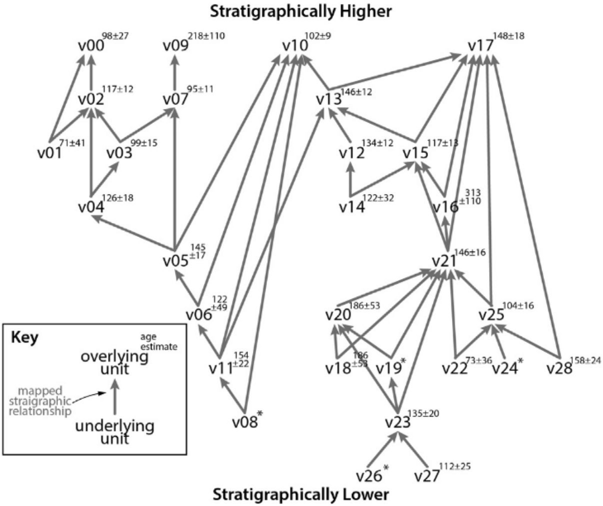
Vents and lava flows in the caldera of Arsia Mons are among Mars' youngest volcanoes. How do we constrain the timing of these eruptions? *Richardson et al., EPSL, 2017*

Map relations among lava flows reveal stratigraphy



Context Imager (CTX) datasets are used to map stratigraphic relationships within the caldera at the summit of Arsia Mons.

A directed graph of age and stratigraphic relationships



Ages estimated (with high uncertainty!) from crater density

Monte Carlo simulation of event rate

Randomly sample ages of all events using directed graph ($M = 10000$ times),
Volcano i of total N formed by event $\hat{e}_i$,
For each set of age estimates, j, for N volcanoes, the cumulative distribution is:

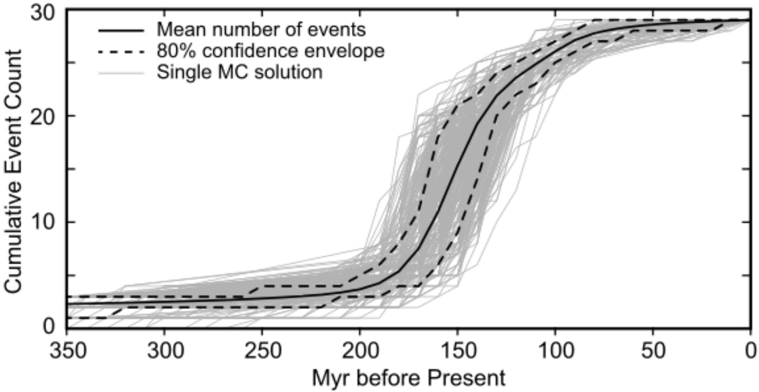
$$X_j(T) = \sum_{i=1}^{N} P\left[\hat{e}_{i,j}, t < T\right]$$

where $P\left[\hat{e}_{i,j}, t < T\right] = 0$ if $T < \hat{e}_{i,j}$ and $P\left[\hat{e}_{i,j}, t < T\right] = 1$ if $T \geq \hat{e}_{i,j}$

$$E(X) = \frac{1}{M} \sum_{j=1}^{M} X_j(T)$$

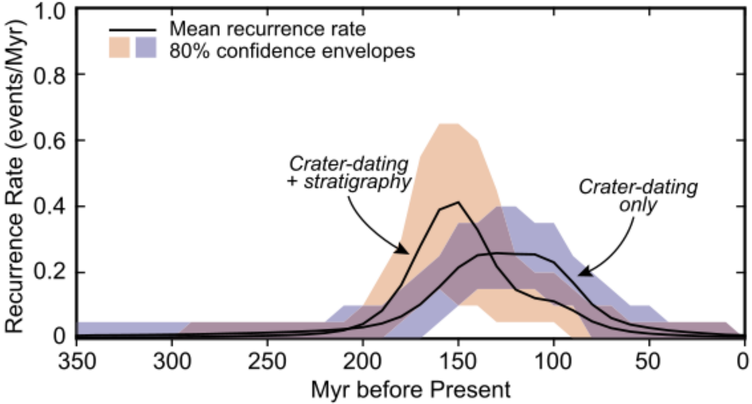
$$R(X) = \frac{\Delta E(X)}{\Delta t}$$

Monte Carlo simulation of event rate



Based on Monte Carlo simulation using age estimates and stratigraphic information

Age distribution of events is improved by using directed graph with Monte Carlo simulation



March 20, 2017

Mars Volcano, Earth's Dinosaurs Went Extinct About the Same Time

Estimating recurrence rate from the rock record

PVHA

Background

Conceptual model

Rates

Location

Magnitude

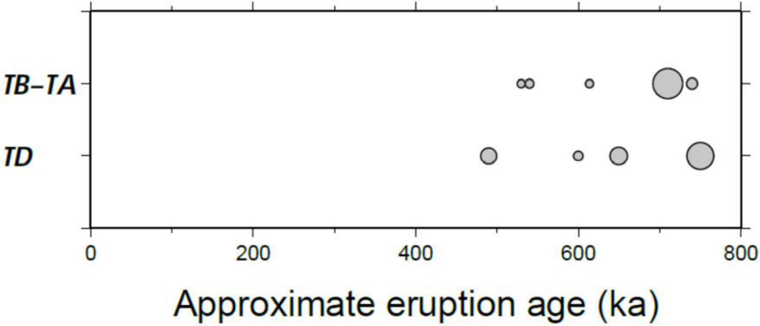
Impacts

Future

B

System	Stage	Geochronometry, Ma	Geological Unit	Age, Ma, K-Ar	Age, Ma, Ar-Ar	Stage	Decription
Quaternary	Holocene, Q_4		1. Q3-Q4, a,d,e,p				Alluvia, diluvia, eluvia, proluvia deposits, pebble, sand, sandy-loam, loam, rubble.
	Upper Pleistocene, Q_3	0.0117	2. Q3, g,fg,m				Glacial and fluvioglacial deposits, moraines
	Middle Pleistocene, Q_2	0.126	3. Q2, B-BA	0.45-0.53	0.614	IV	Basaltic trachyandesite and basaltic-andesite lava flows. Tirinkatar, Ashtarak, Dashtakar
			4. Q2, TD		0.75		Trachydacite lava flows of Cakhkasar volcano (Pokr Bogutlu
			5. Q2, g,fg,m			III	Glacial and fluvioglacial deposits, moraines
			6. Q2, TA-TD	0.73-0.54			Trachyandesites, trachydacites, of near the summit plateau
			7. Q2, Ig,A				Tuffs (ignimbrites) of Artik horizon
			8. Q2, B-BA				Basaltic and basaltic-andesite lava flows of Kakavasar, SW slopes o Aragats
			9. Q2, B-BA				Basaltic and basaltic-andesite lava flows of Sharailier (Golgat) group of volcanoes (N. Aragats)
			10. Q2, TB-TBA	0.74-0.90			Trachybasaltic and basaltic trachyandesite lava flows of Mantash plateau , K-Ar).
			11. Q2, D,P,Ig		0.49		Irind volcano and Ashnak plateau. Dacite lava flows, Plinian eruption pumice fallout deposits, hyaloclastite ignimbrites.
			12.Q2, Ig,YG-BS		0.65-0.66		Ignimbrite tuffs of Yerevan-Gyumri type and Byurakan-Shamiram subtype.
			13. Q1-2, B-BA				Basalts, Basaltic-andesites covering Ani type tuff.
			14.Q1-2, P-Ig			II	Pumice ignimbrite tuffs of Ani type
	Lower Pleistocene, Q_1	0.781	15. Q1-2, TA-TD,P				Trachyandesites, trachydacites of slopes of Aragats, in South part covered by Irind dacites, Plinian eruption fallout deposits of Pemzashen.
			16. Q1-2, A-D				Andesites, dacites of Dsoran and Byurakan type
			17. Q1-2, LS				Upper unit of lake sediments deposits of Ararat and Shirak valleys and Aparan depression.
			18a-b.Q1-2, TBA-TA	0.91-1.10	0.71-1.32 0.809		Basaltic-andesites, basaltic-trachyandesites, andesites and trachyandesites of Shamiram and Eghvard plateaus, Bazmaberd, Greako and other cinder cones.
			19. Q1-2, A-D	0.92-0.99	0.902		Basaltic trachyandesites of Sardarapat structure
			20. Q1, TD-Rh	1.45-1.60			Trachydacites and rhyolites of Arteni volcano
	...er ...ene	1.806	21. N_2^2-Q1, B-BA			I	Basalts and basaltic-andesites of S and SW Aragats
			22. N_2^2, B-BA (D)	2.20-2.50			Dolerite basalts and basaltic andesite.

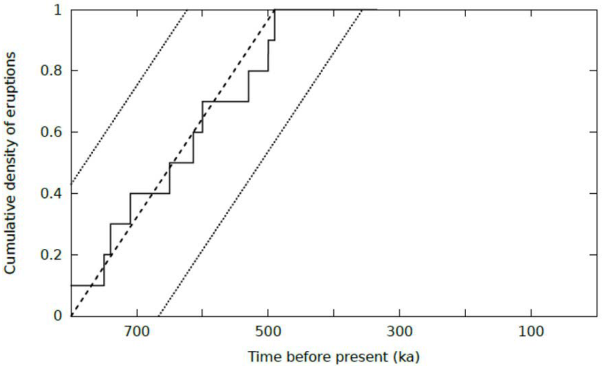
Recurrence rate: Known eruptions by volume



- TB-TA: trachy-basalt trachy-andesite
- TD: trachy-dacite

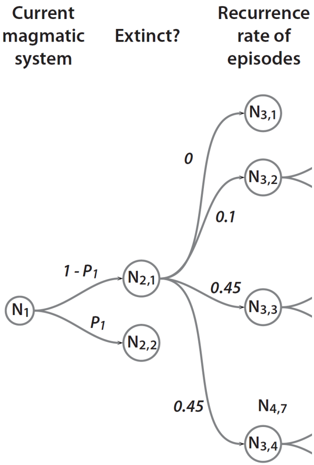
Main concern: is there no activity in the last 400 ka? Or is there a lack of preservation of smaller eruptions?

Recurrence rate



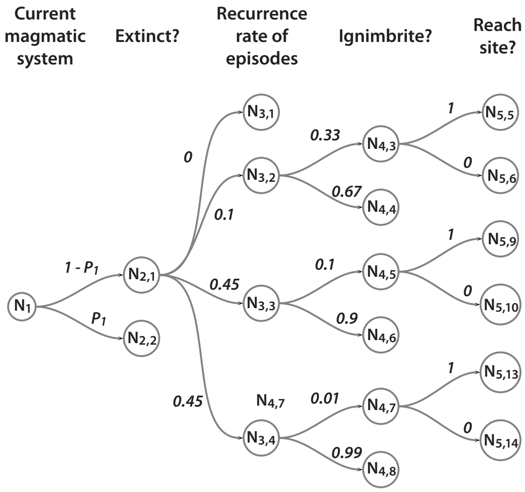
- Cumulative distribution function of Aragats eruptions.
- Steady-state activity until about 0.5 Ma, after which no eruptions are identified.

Recurrence rate: weighting alternative models with expert judgment



Node	Recurrence Rate (yr^{-1})	Wt
$N_{3,1}$	$> 5 \times 10^{-5}$	0
$N_{3,2}$	$> 0.5 - 5 \times 10^{-5}$	0.1
$N_{3,3}$	$0.9 - 5 \times 10^{-6}$	0.45
$N_{3,4}$	$< 9 \times 10^{-7}$	0.45

logic tree for pdcs impacting the site

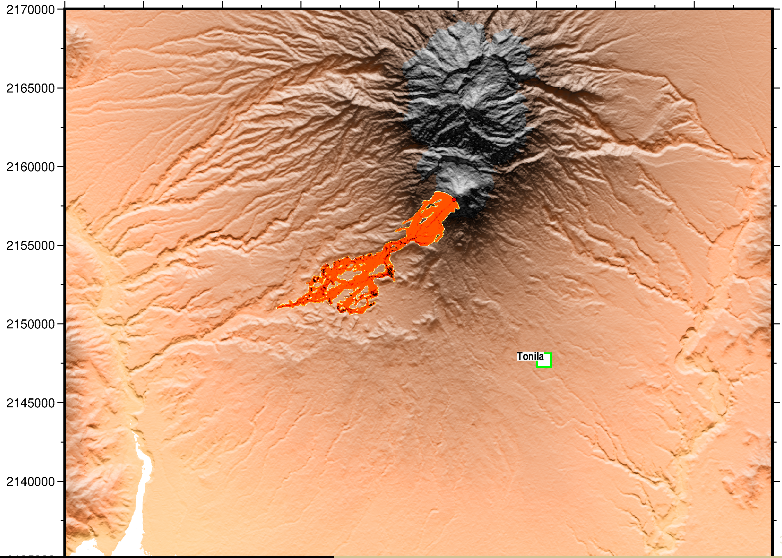


Aggregate Probability for pdcs impacting the site

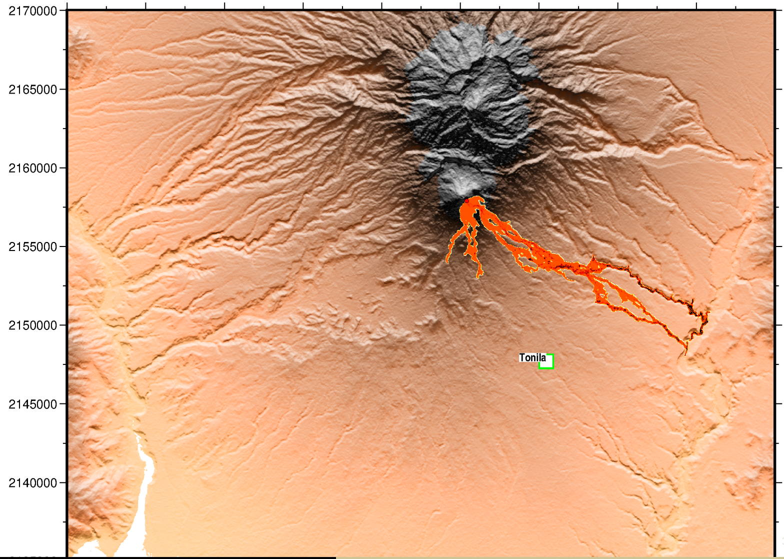
Range (High/Low)	**Weight** ($w_{2,1-4}$)	**RR** (yr^{-1})	**Weight** ($1 - w_{3,1-3}$)	**Weight** ($1 - w_4$)	**Weighted Probability**
H	0.10	5e-05	0.67	1	3.3×10^{-6}
L	0.10	5e-06	0.33	1	1.6×10^{-7}
H	0.45	5e-06	0.10	1	2.2×10^{-7}
L	0.45	9e-07	0.10	1	4×10^{-8}
H	0.45	9e-07	0.01	1	4×10^{-9}

Aggregate Annual Probability $= 2 \times 10^{-7} – 3.5 \times 10^{-6}$

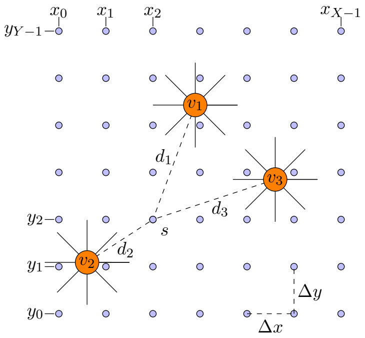
Forecasting location matters



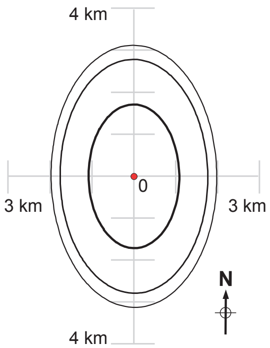
Forecasting location matters



spatial density of volcanic vents

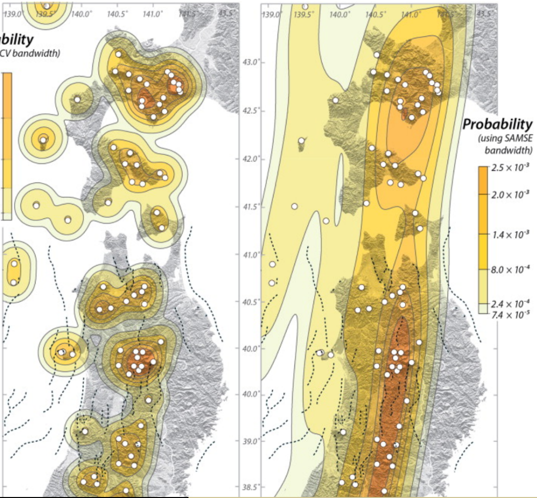


$$\hat{\lambda}(\mathbf{s}) = \frac{1}{2\pi\sqrt{|\mathbf{H}|}} \sum_{i=1}^{N} \exp\left[-\frac{1}{2}\mathbf{b}^{\mathbf{T}}\mathbf{b}\right]$$

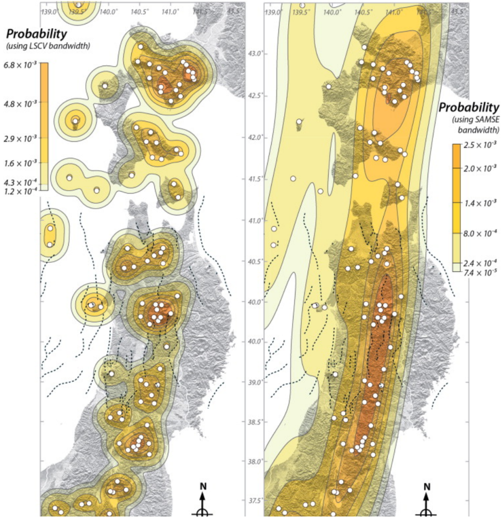


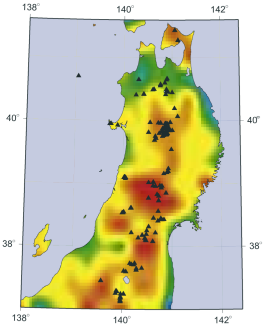
Along-arc variations in volcano spatial density

Alternative probability density models for volcanism along the Tohoku arc



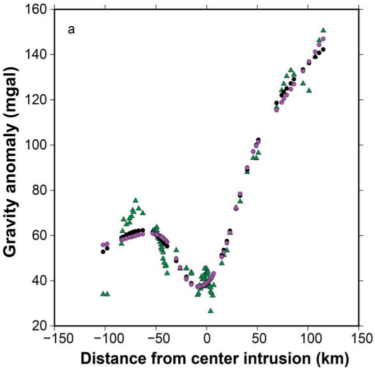
Along arc tomographic anomalies





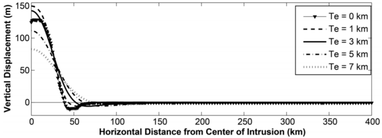
Slowness, $\Delta V_p/V_p$ at 40 km, Zhao (2001), Martin et al. (2004)

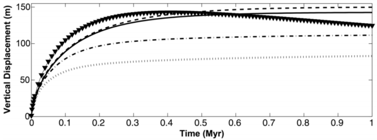
Sengan volcano cluster



George et al., 2016

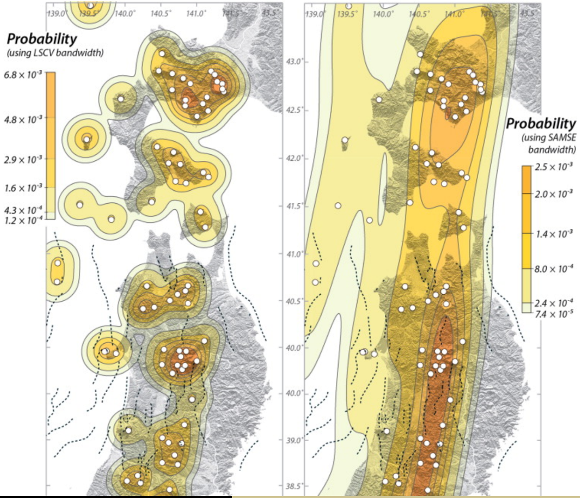
gravity anomalies indicate a large mid-crustal reservoir, which accounts for observed basement uplift and deformation rate.



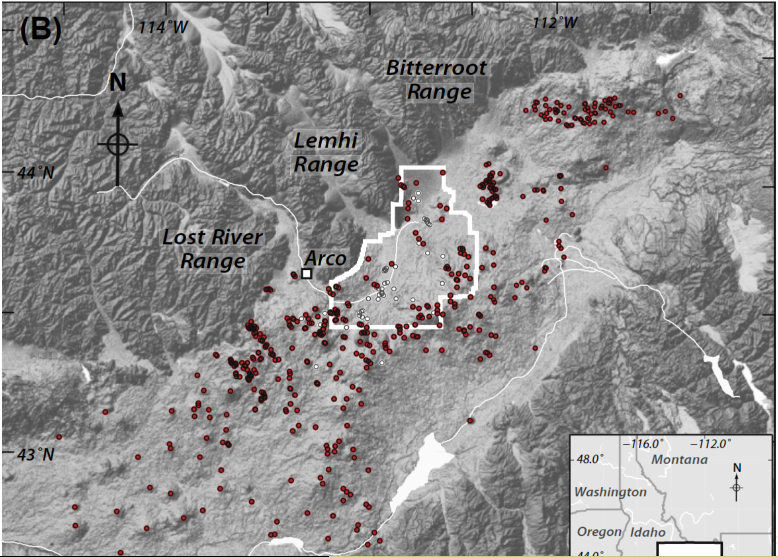


Along-arc variations in volcano spatial density

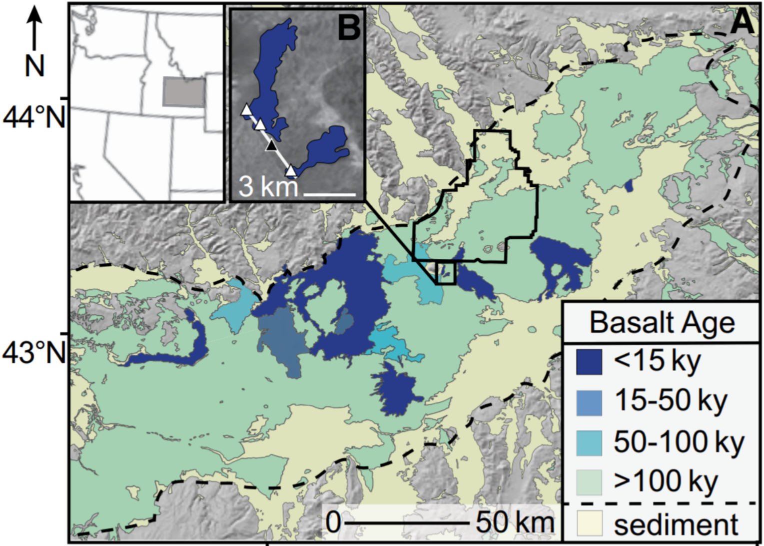
Alternative probability density models for volcanism along the Tohoku arc



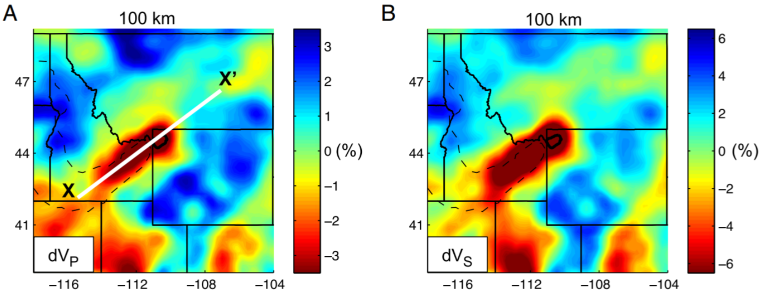
ESRP


(B)
114°W
112°W
N
44°N
43°N
Bitterroot Range
Lemhi Range
Lost River Range
Arco
−116.0°
−112.0°
48.0°
Montana
Washington
Oregon
Idaho
N

ESRP

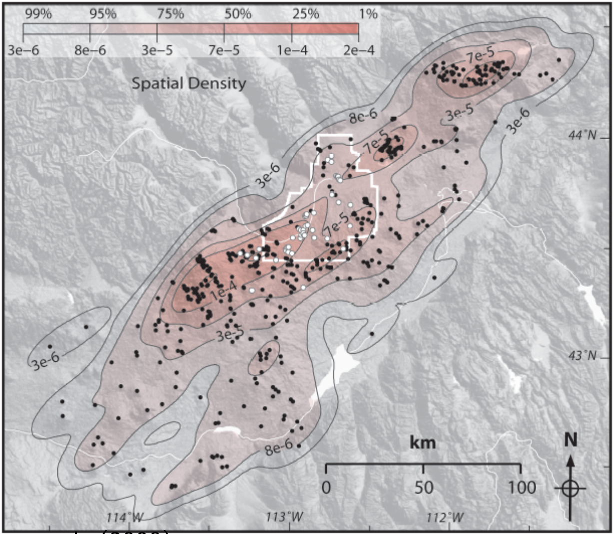

N
44°N
43°N
B
3 km
A
Basalt Age
<15 ky
15-50 ky
50-100 ky
>100 ky
sediment
0
50 km

ESRP



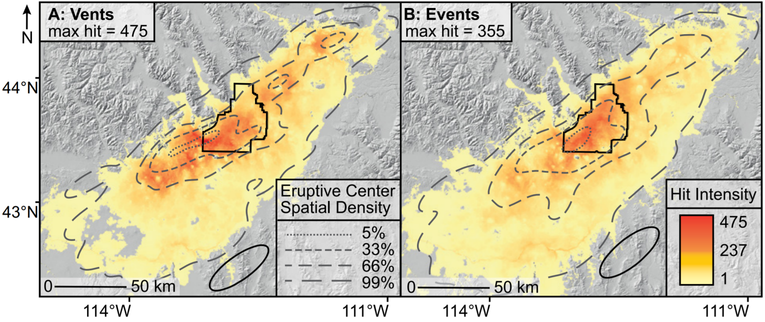
Schmandt et al. (2012)

spatial density of volcanic vents



Wetmore et al. (2009)

Probability of Opening of New Vents and Lava Inundation

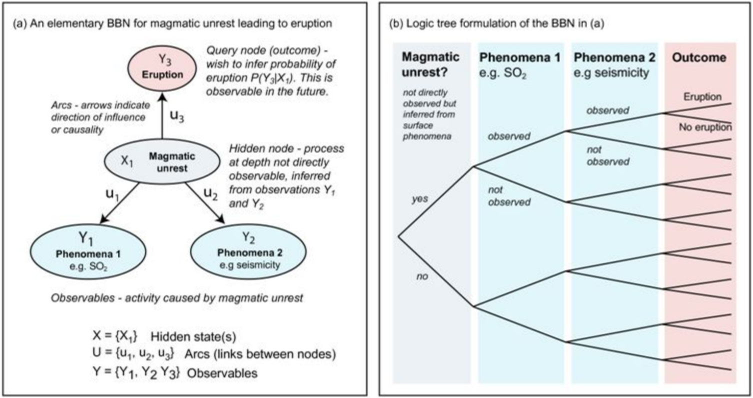


Hazard	Annual Probability (vents)	Annual Probability (Events)
Eruption on the ESRP	5.7×10^{-4}	2.6×10^{-4}
Eruption in INL	1.2×10^{-4}	6.2×10^{-5}
Lava Inundation of INL	1.8×10^{-4}	8.4×10^{-5}

see Gallant et al (2018)

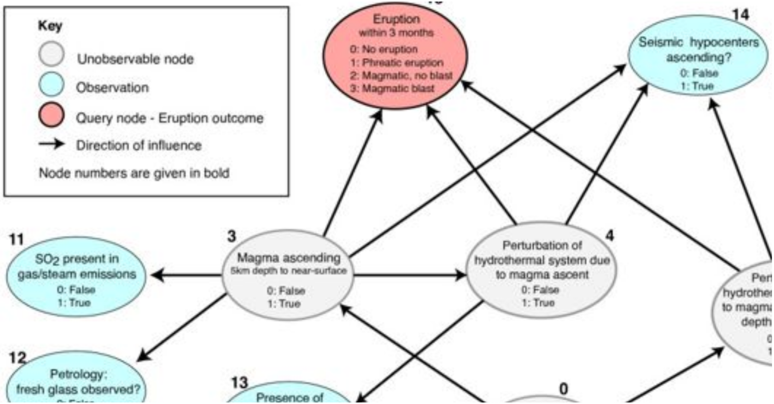
probability networks

Development of Bayes' network, or Bayesian belief network:
P[magma unrest | increase in SO_2] $\neq$ P[increase in SO_2 | magma unrest]



from Hincks et al. (2014)

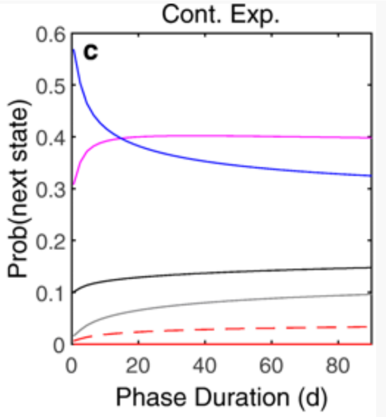
A BNN for Martinique "crisis" of 1979

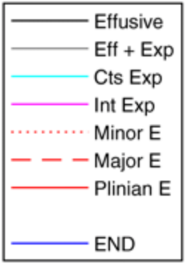


from Hincks et al. (2014)

probability networks

Markov model (MCMC) forecasting changes in eruption style





classification and probabilities based on GVP reports for > 7000 eruptions

from Jenkins and Bebbington, 2019)

Challenges

- Long-term volcanic hazard assessment must become more widespread to plan for volcanic activity, in all its forms, before it affects communities and infrastructure.
- Probabilistic volcanic hazard assessment relies on a simple hierarchical structure (e.g., logic trees). What new structures should emerge?
- PVHA places a premium on geologic data collection, especially radiometric age determinations and mapping, and numerical models of volcanic processes.
- Major challenge is to improve monitoring to identify potentially active volcanic systems before "unrest".

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- Jacob Richardson, Lis Gallant, Graeme Swindles, Elizabeth Watson, Armando Saballos, Kristy Murphy, Mike Sheridan,