University of BRISTOL

The unknown unknowns. Uncertainty in volcanic hazard assessment

Dr Pete Rowley

What is uncertainty?

Why do we care about it?

Where are the uncertainties in volcanic forecasting?

What does the future hold?

Current activity (11:00 GMT 5/12/23

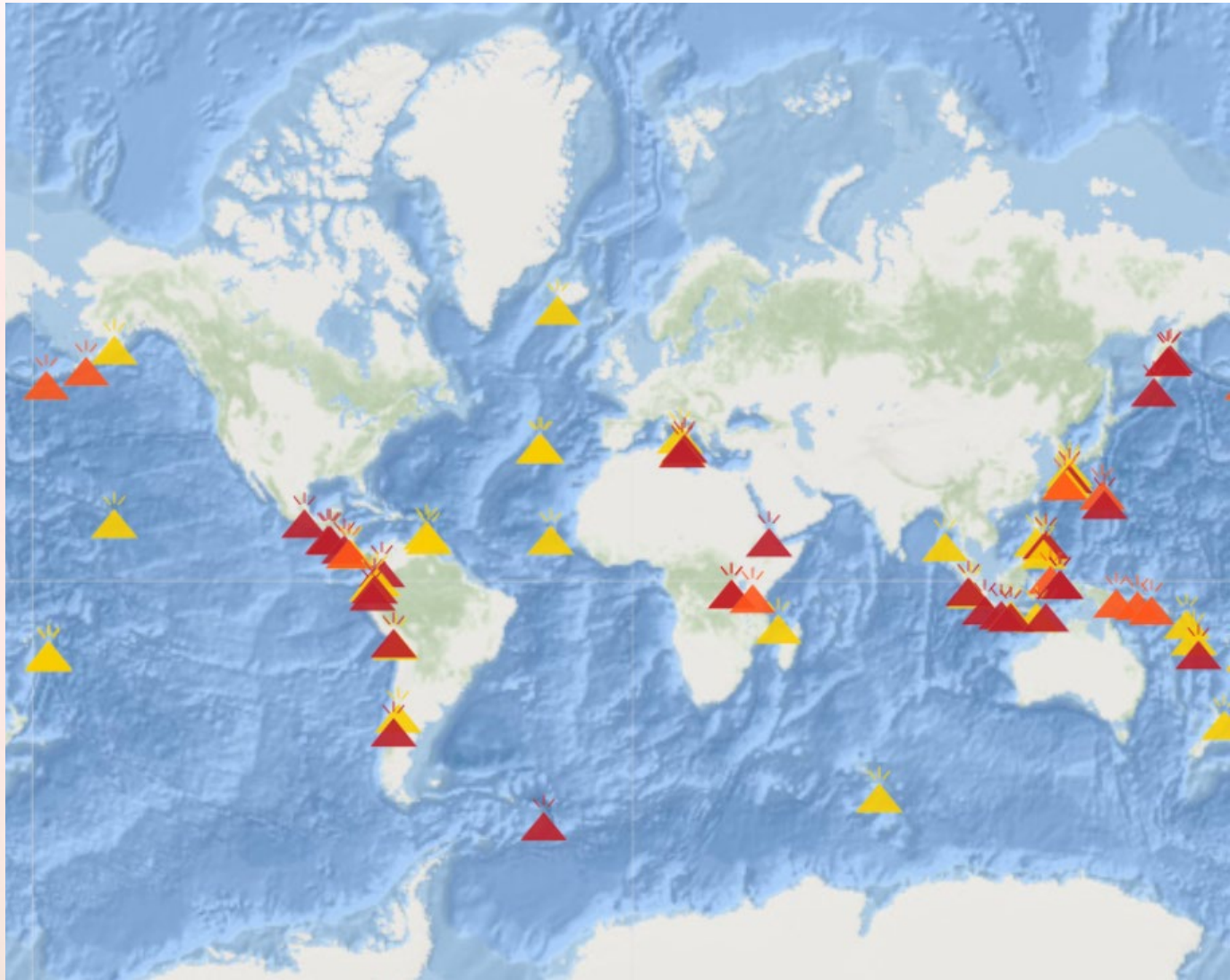
40-50 ***active*** volcanoes at any one time

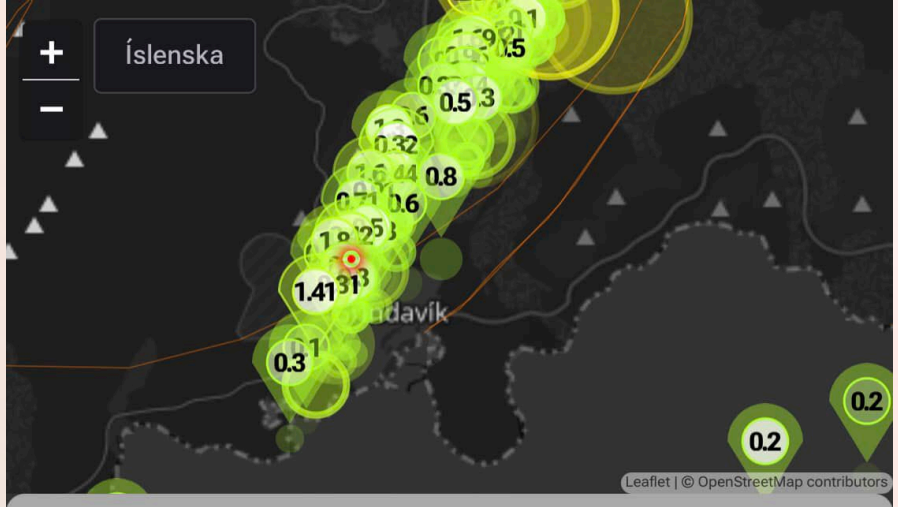
10-30 erupting

Red – erupting

Amber – warning / minor activity

Yellow – Heightened unrest



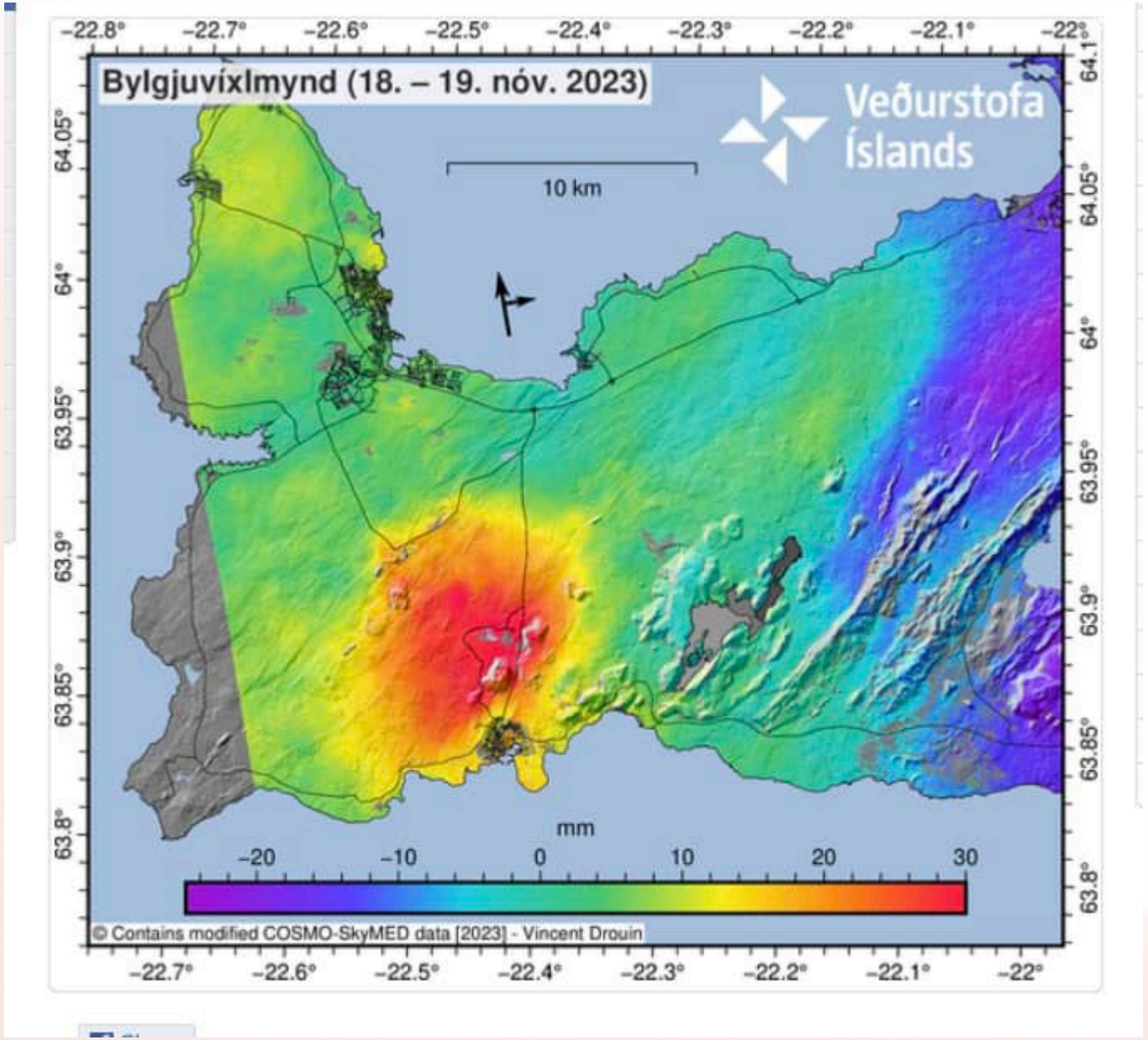


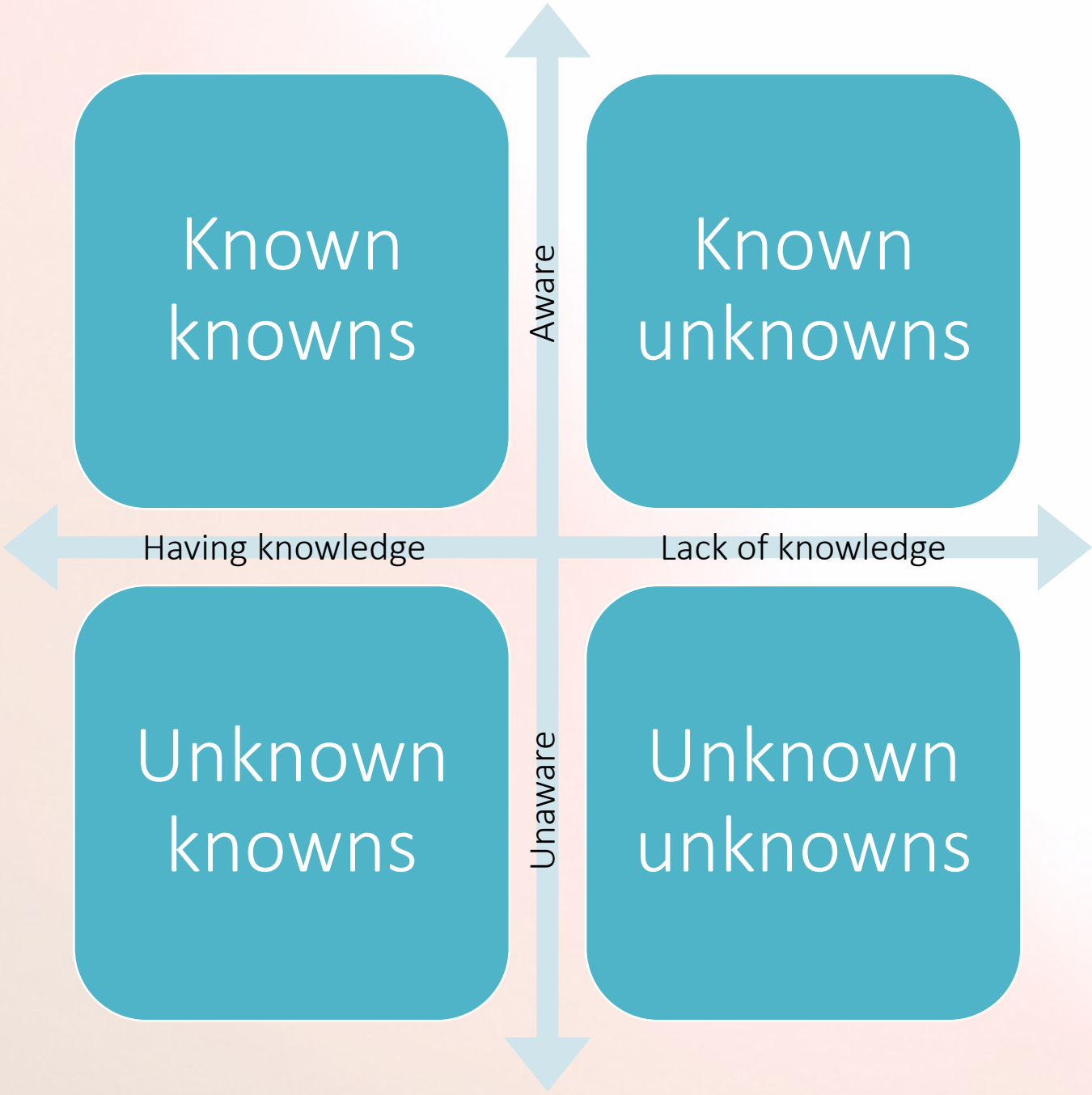
QUAKES LAST 6 HOURS (115)

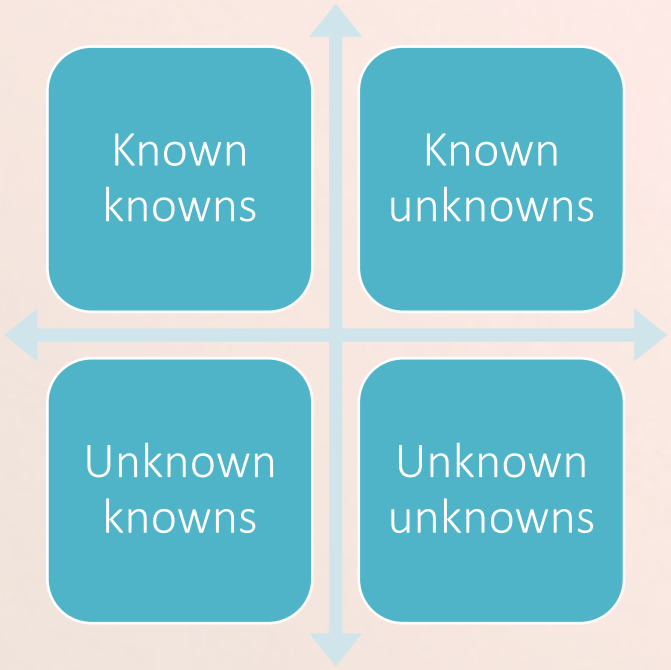
LIVE FROM ICELAND

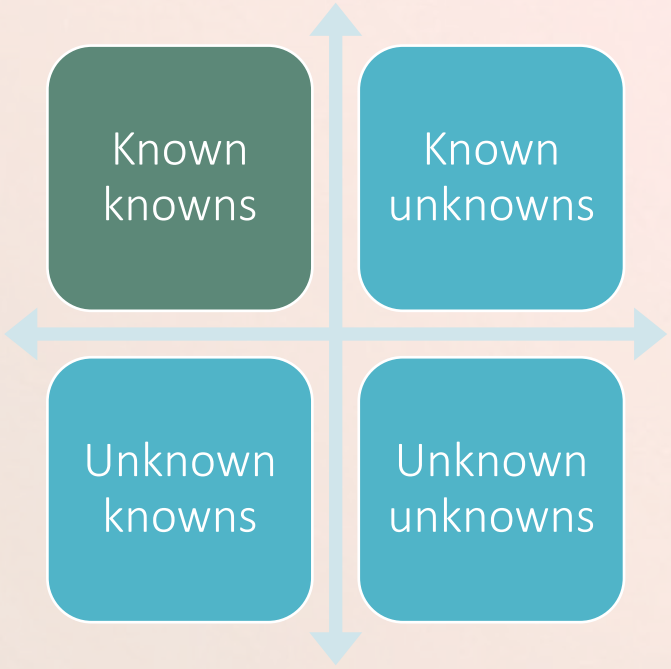
TIME	MAG.	DEPTH	ALERT AREA
21:30:21	0.5 aM	4.4 km	Svartsengi
21:27:18	0.5 aM	5.9 km	Svartsengi
21:25:09	0.5 aM	7.1 km	Reykjanesskagi
21:23:10	0.3 aM	1.1 km	Ísland
21:22:51	0.5 aM	5.8 km	Svartsengi
21:20:33	1.3 aM	5.0 km	Svartsengi
21:15:48	0.7 aM	17.2 km	Reykjanes-hryggur
21:15:26	0.1 aM	1.0 km	Svartsengi
21:02:14	0.3 aM	1.1 km	Svartsengi
20:57:37	0.8 aM	5.9 km	Svartsengi
20:52:14	0.3 aM	1.1 km	Ísland
20:51:40	0.5 aM	5.0 km	Svartsengi
20:43:51	1.3 aM	1.1 km	Vestra gos-beltið

AUTOMATIC DATA UPDATES

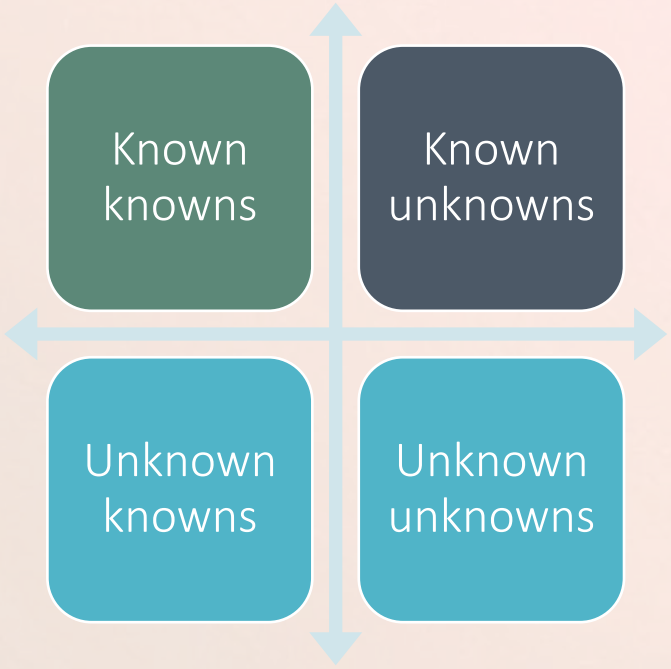



Known knowns
Known unknowns
Unknown knowns
Unknown unknowns
Aware
Unaware
Having knowledge
Lack of knowledge


Known knowns
Known unknowns
Unknown knowns
Unknown unknowns

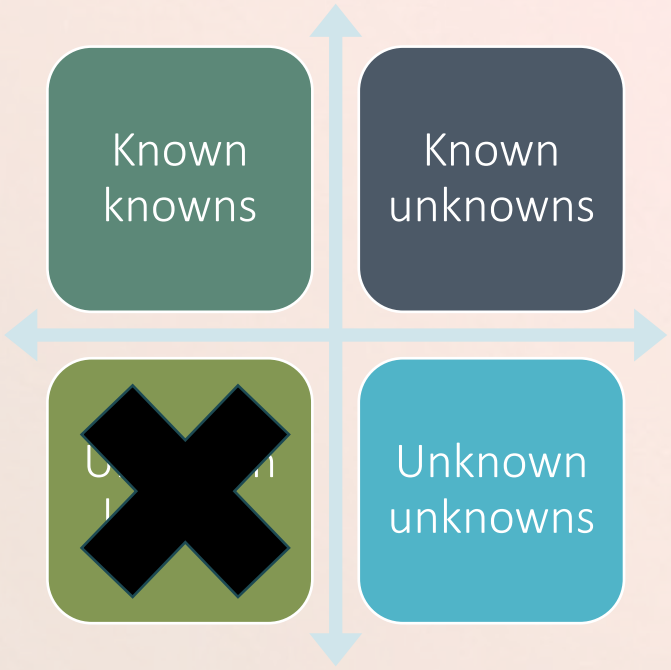


Things we are confident that we already understand



Things we are confident that we already understand

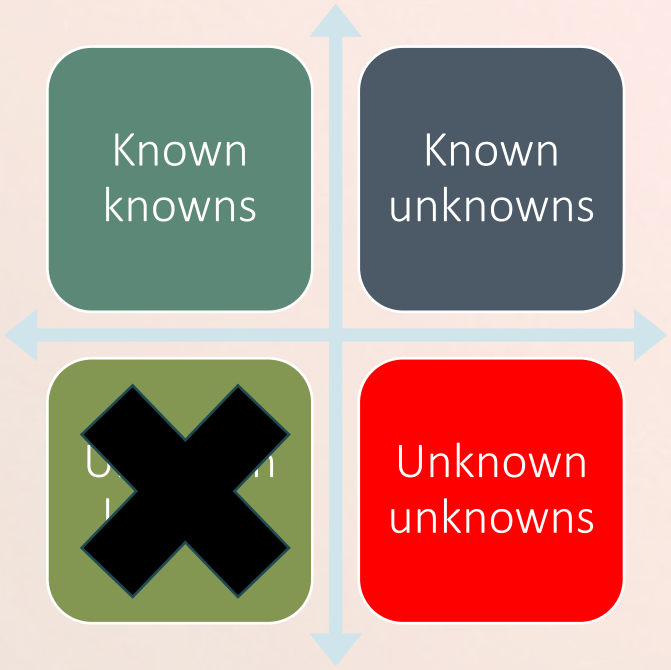
Things we know that we don’t understand



Things we are confident that we already understand

Things we know that we don't understand

Things we don't realise that we already know



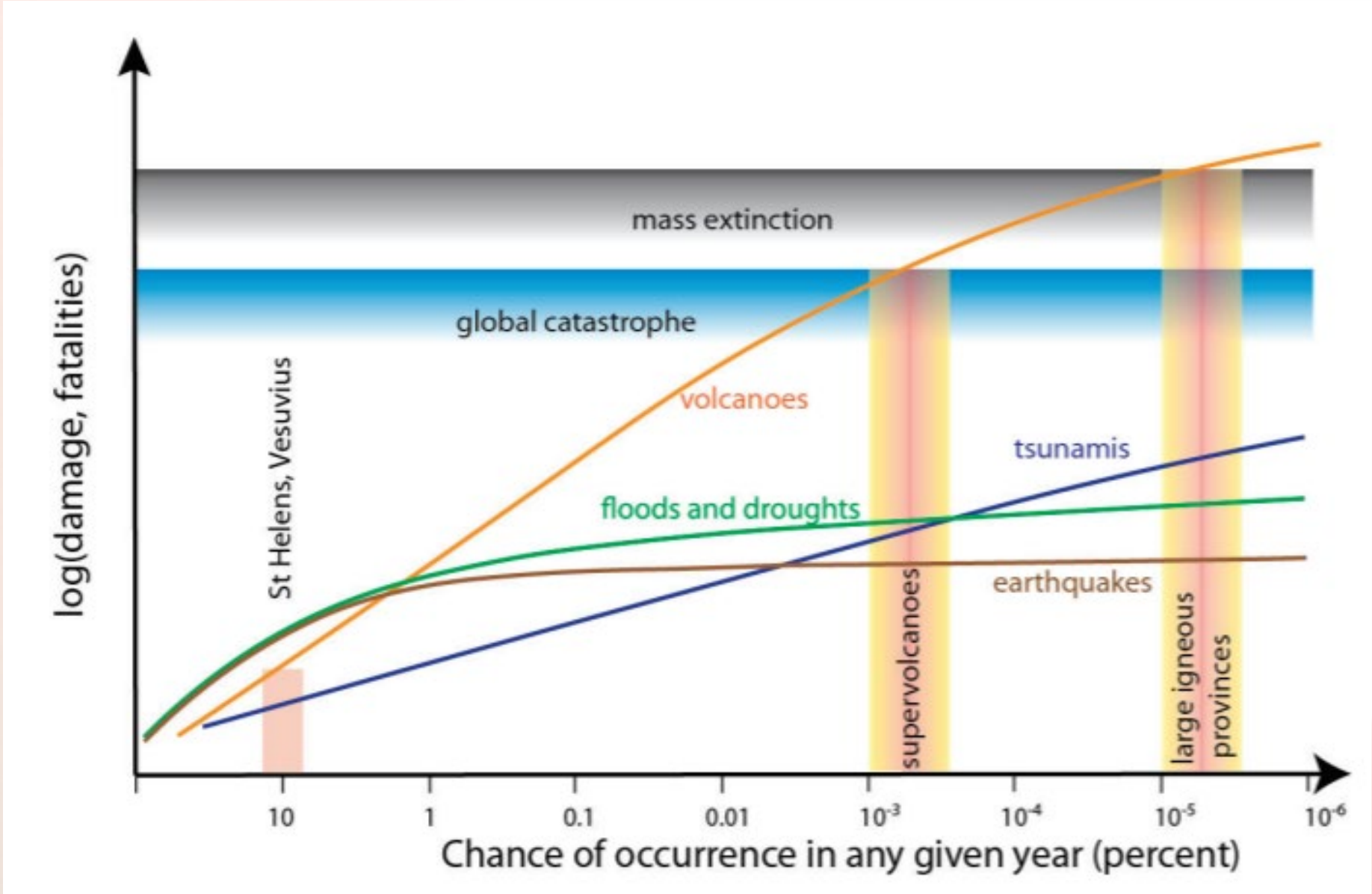
Things we are confident that we already understand

Things we know that we don't understand

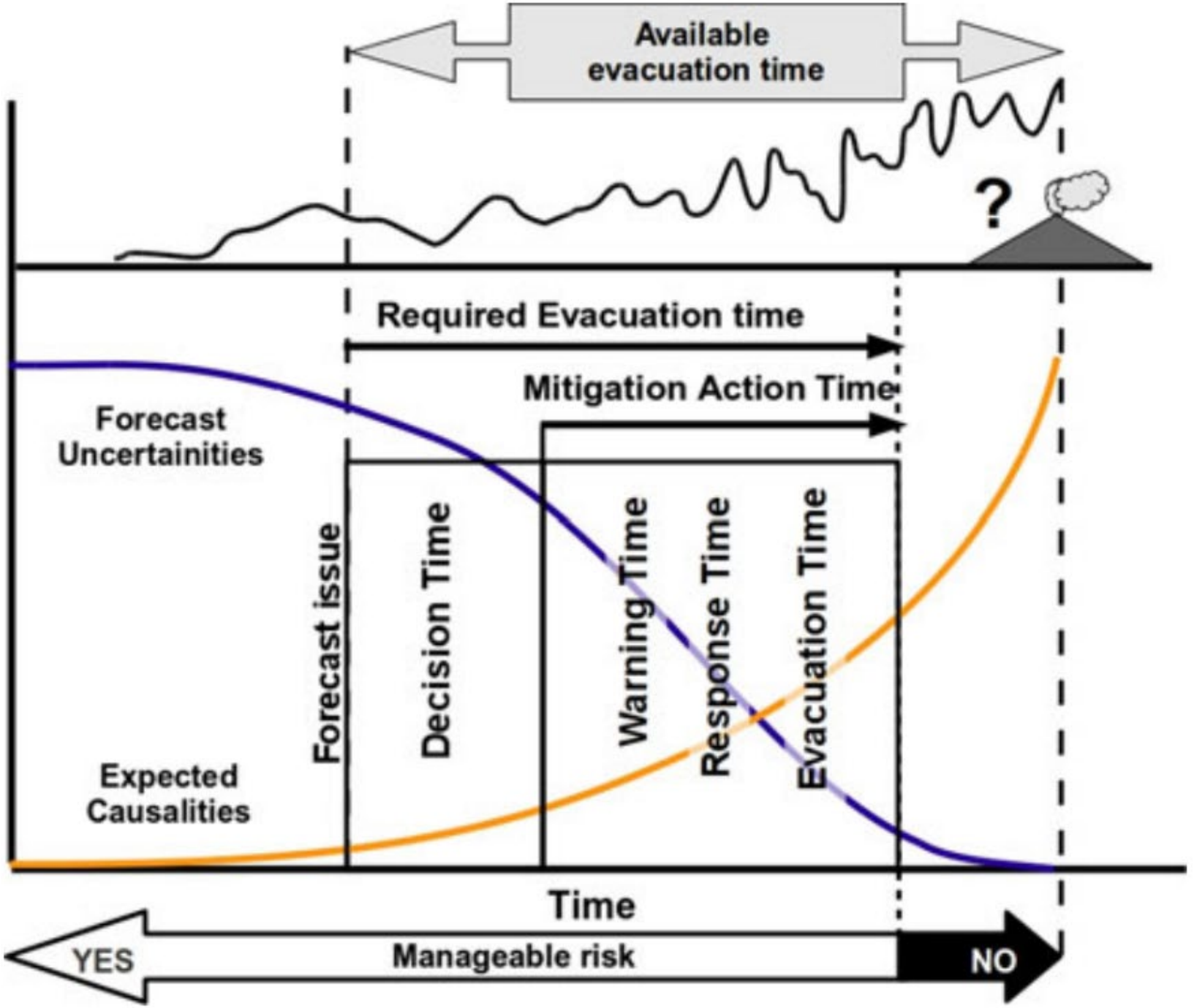
Things we don't realise that we already know

Things that we don't know that we don't know

Why do we care?



National Academy of Sciences (2017)



Marrero et al. 2013

What is a volcano?

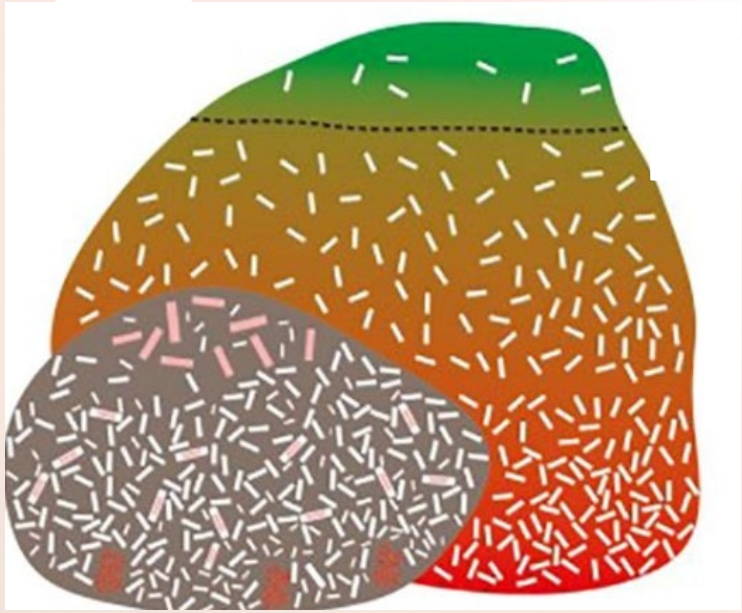
A source of magma

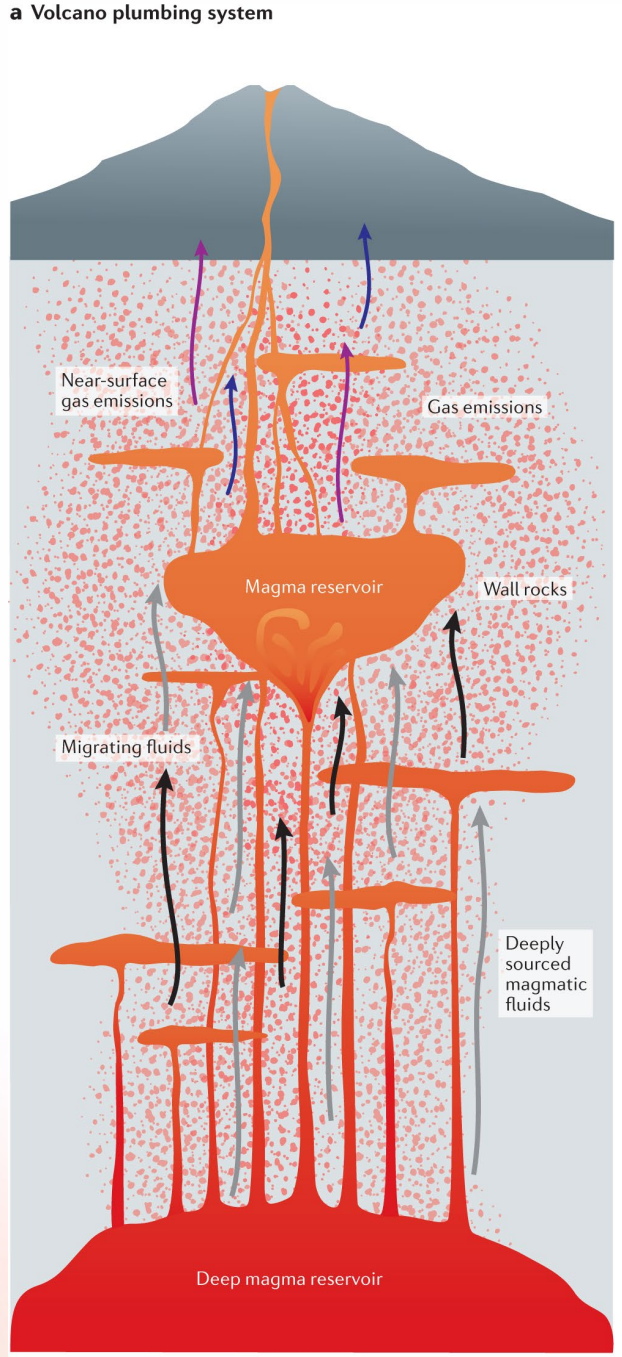
Crustal transport (buoyancy)

Crustal storage (reservoirs, dykes, sills)

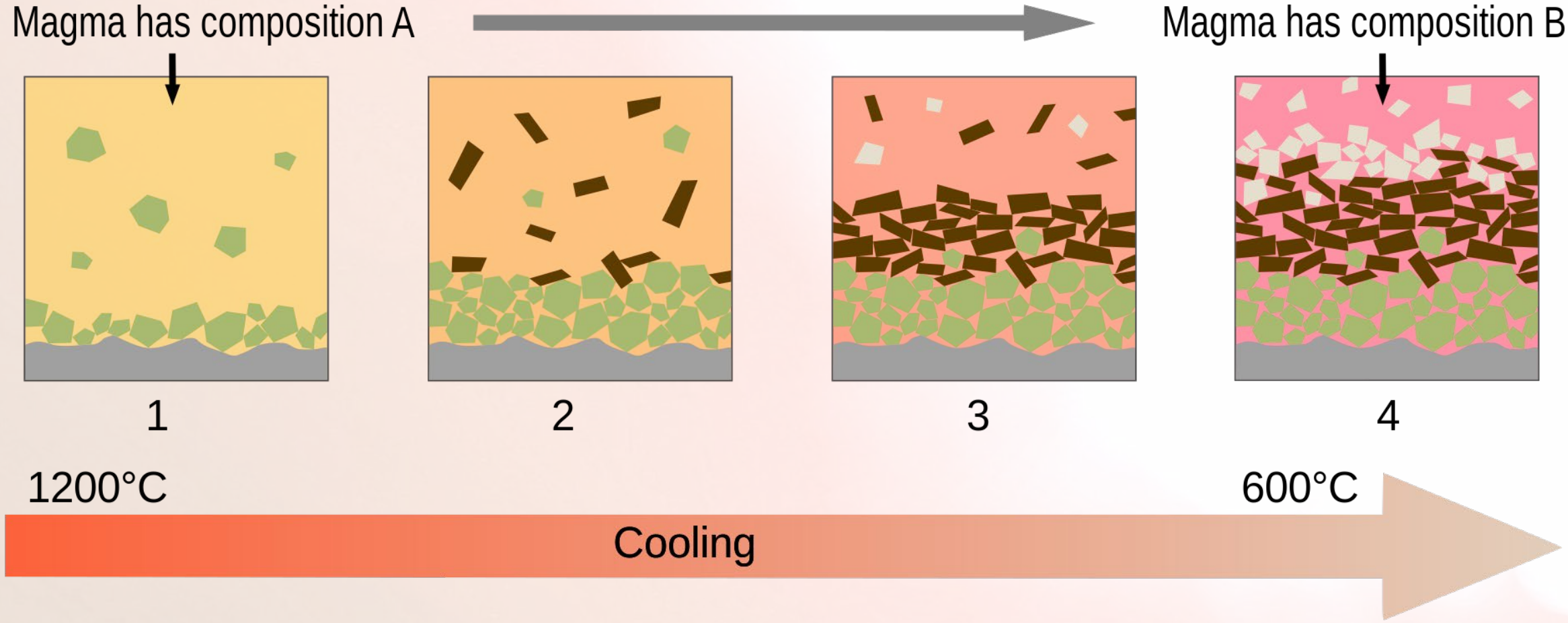
- Mixing/mingling
- Cooling
- Crystallisation
- Assimilation
- Degassing

Vent





Carrichi et al 2021


Magma has composition A
Magma has composition B
1
2
3
4
1200°C
600°C
Cooling

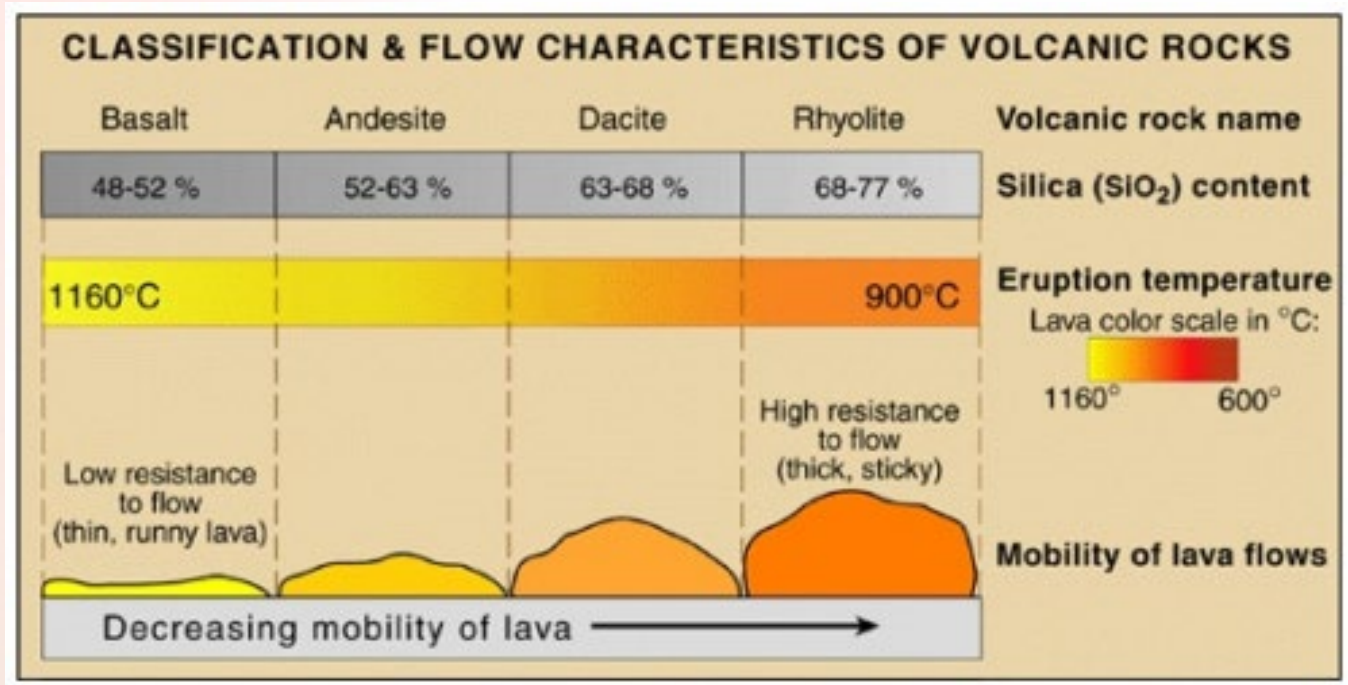
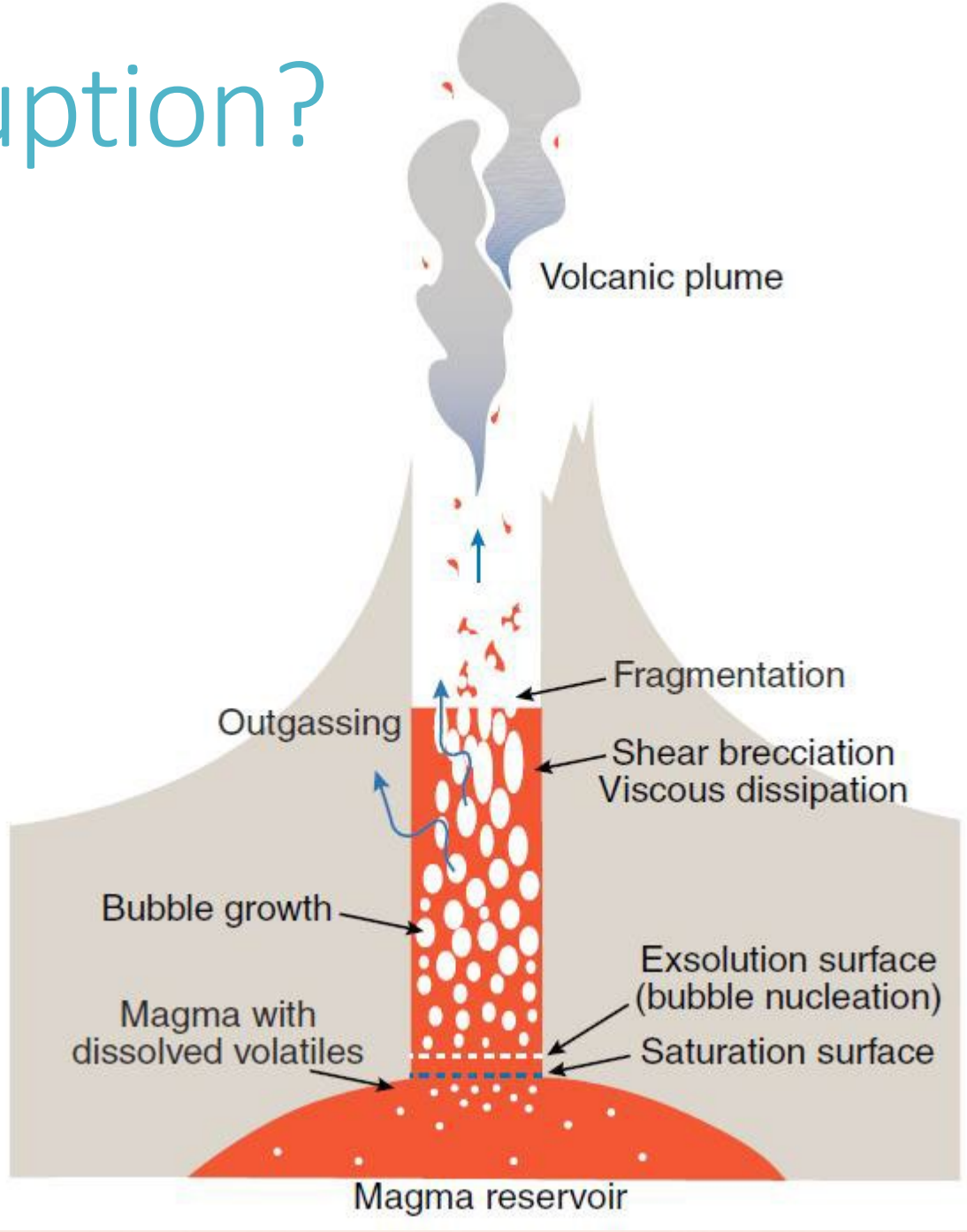
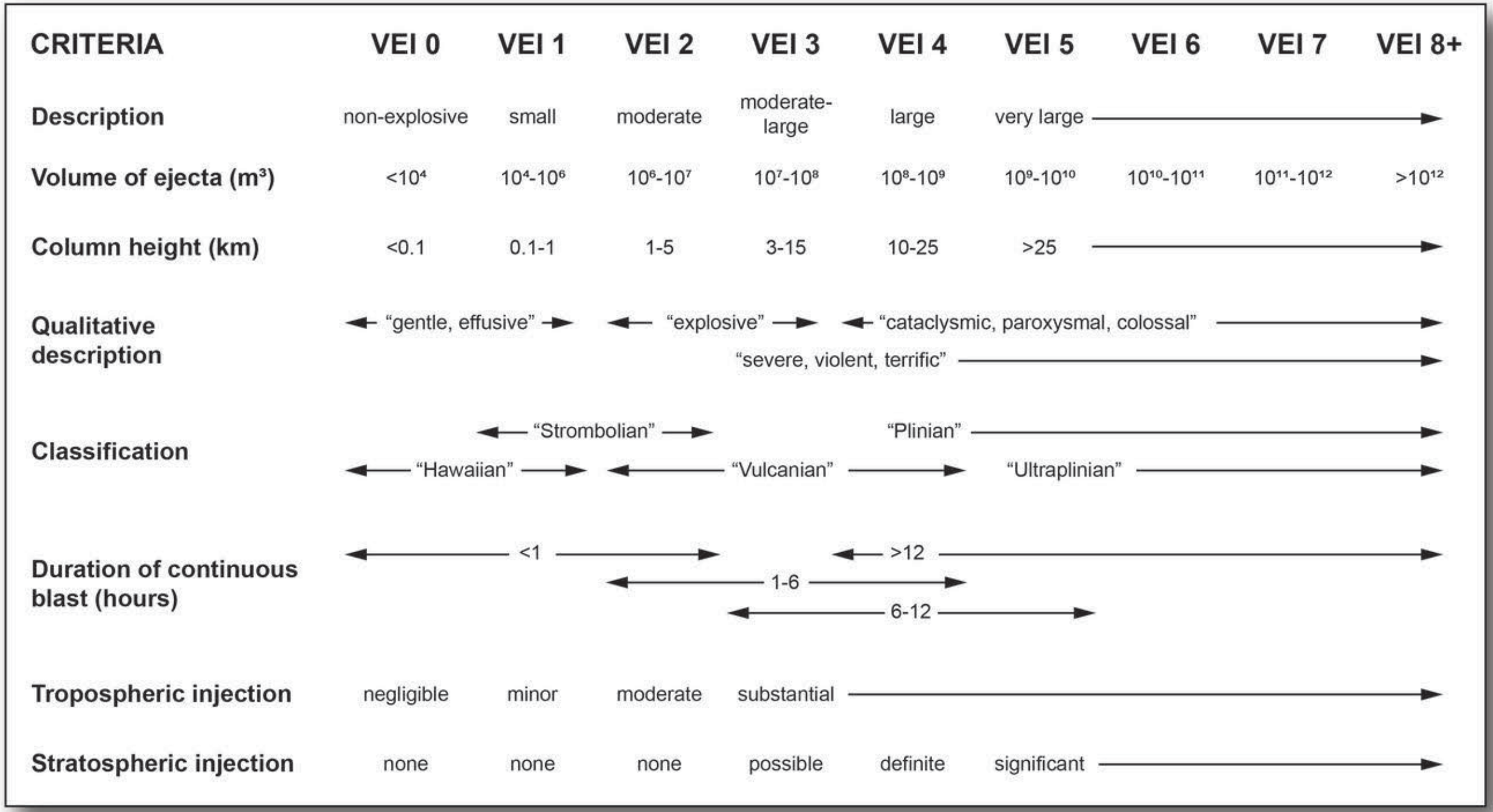


Illustration by J. Johnson

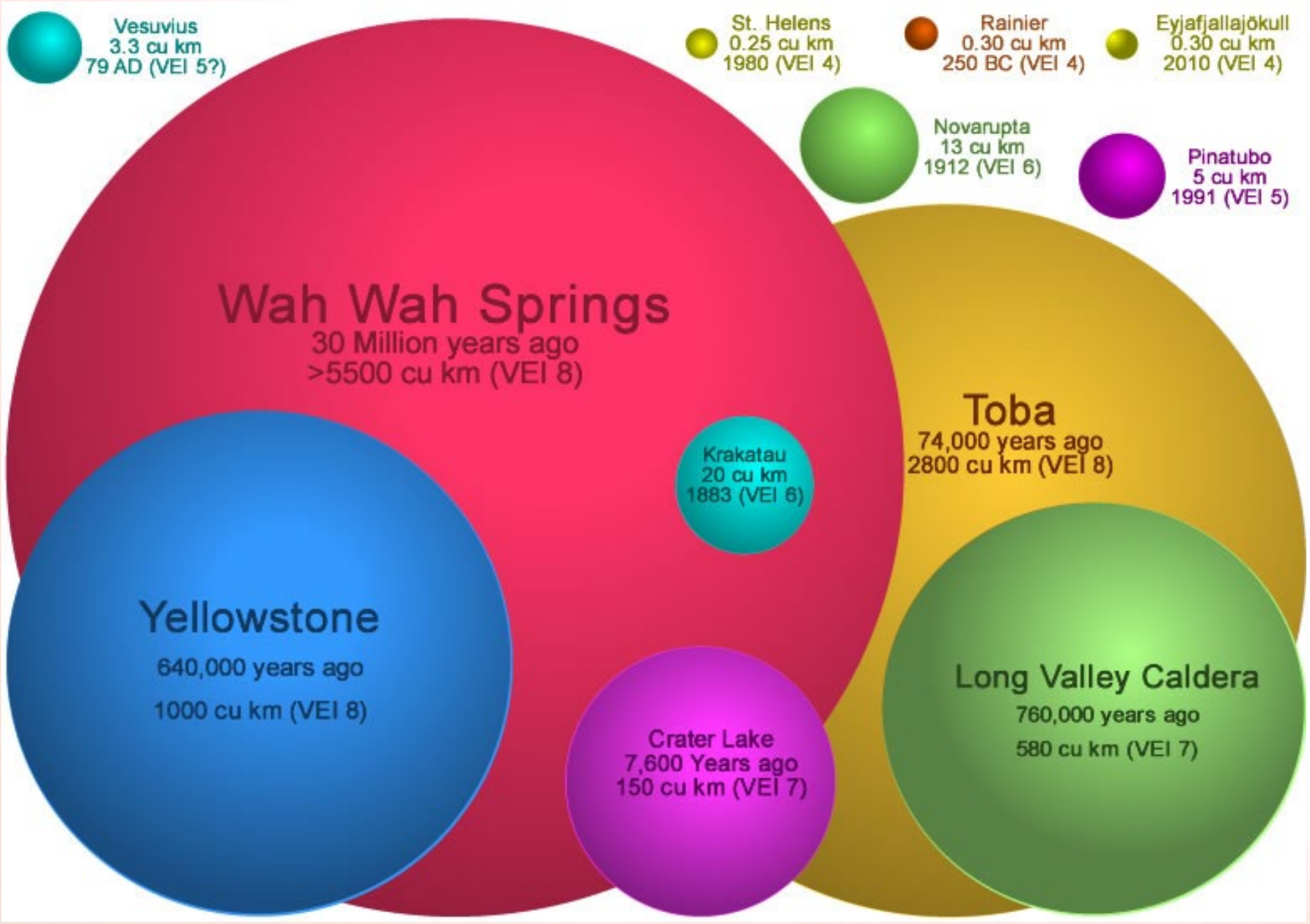
So what's a volcanic eruption?

The 4 December 2015 paroxysm plume from Mount Etna's Voragine crater, as seen from Cesarò, Messina, at 9:27 Greenwich Mean Time. Credit: G. Famiani




CRITERIA
VEI 0
VEI 1
VEI 2
VEI 3
VEI 4
VEI 5
VEI 6
VEI 7
VEI 8+
Description
non-explosive
small
moderate
moderate-large
large
very large
Volume of ejecta (m³)
<10⁴
10⁴-10⁶
10⁶-10⁷
10⁷-10⁸
10⁸-10⁹
10⁹-10¹⁰
10¹⁰-10¹¹
10¹¹-10¹²
>10¹²
Column height (km)
<0.1
0.1-1
1-5
3-15
10-25
>25
Qualitative description
"gentle, effusive"
"explosive"
"cataclysmic, paroxysmal, colossal"
"severe, violent, terrific"
Classification
"Strombolian"
"Plinian"
"Hawaiian"
"Vulcanian"
"Ultraplinian"
Duration of continuous blast (hours)
<1
>12
1-6
6-12
Tropospheric injection
negligible
minor
moderate
substantial
Stratospheric injection
none
none
none
possible
definite
significant

VEI Eruption Frequency	
VEI	**Frequency**
0	frequent
1	frequent
2	tens per year
3	several per year
4	tens per decade
5	one per decade
6	several per century
7	several per millennium
8	two per 100,000 years



What controls a volcanic eruption?

Viscosity (chemistry, temperature)

Gas content (chemistry, storage time/ascent rate)

Rate of eruption (Volume of tapped storage, pressure conditions, structure/strength of vent and substructure, gas content, viscosity)

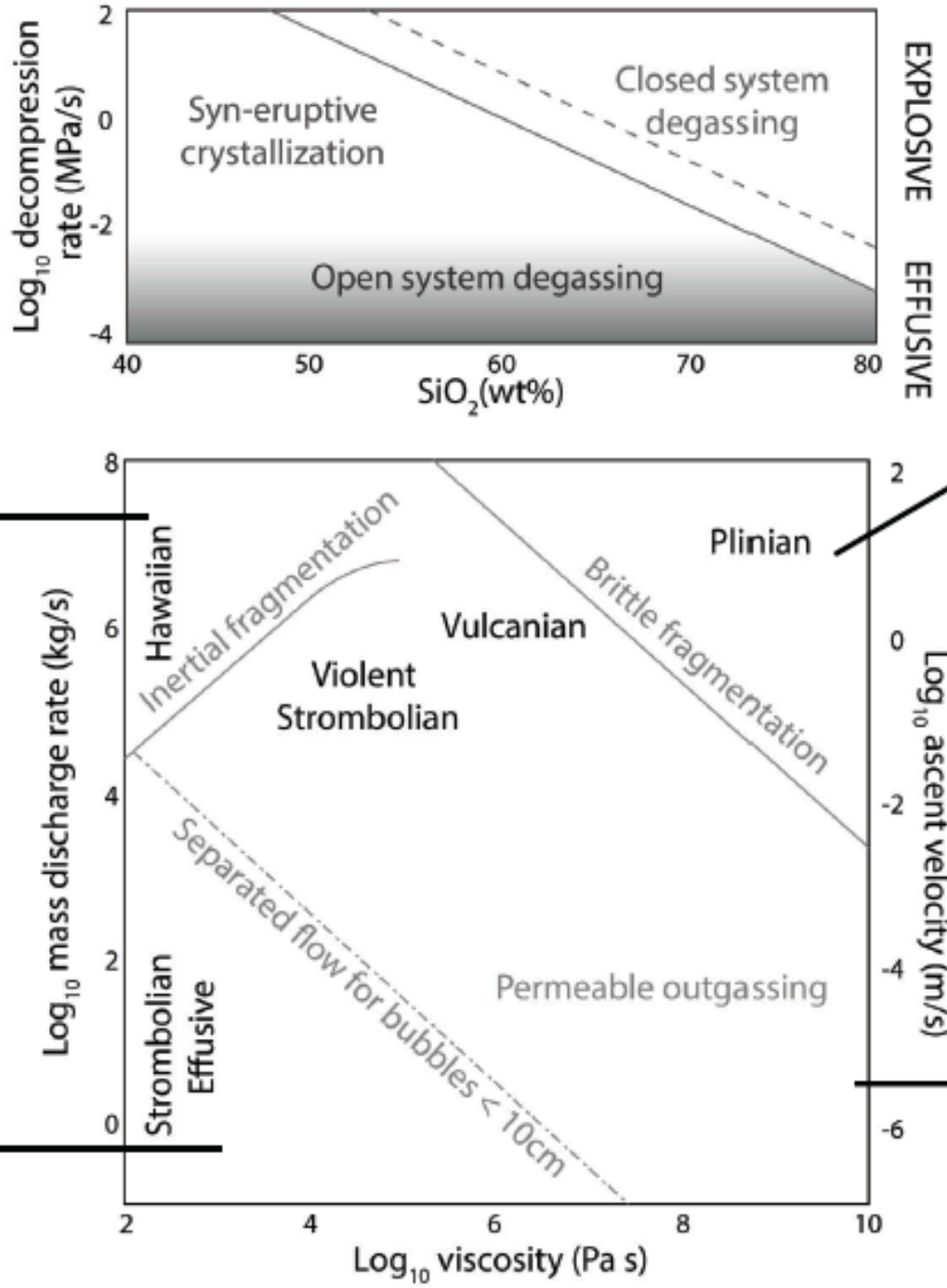
Volume of eruption (Volume of tapped storage, availability of connected storage, overpressure in different reservoirs)

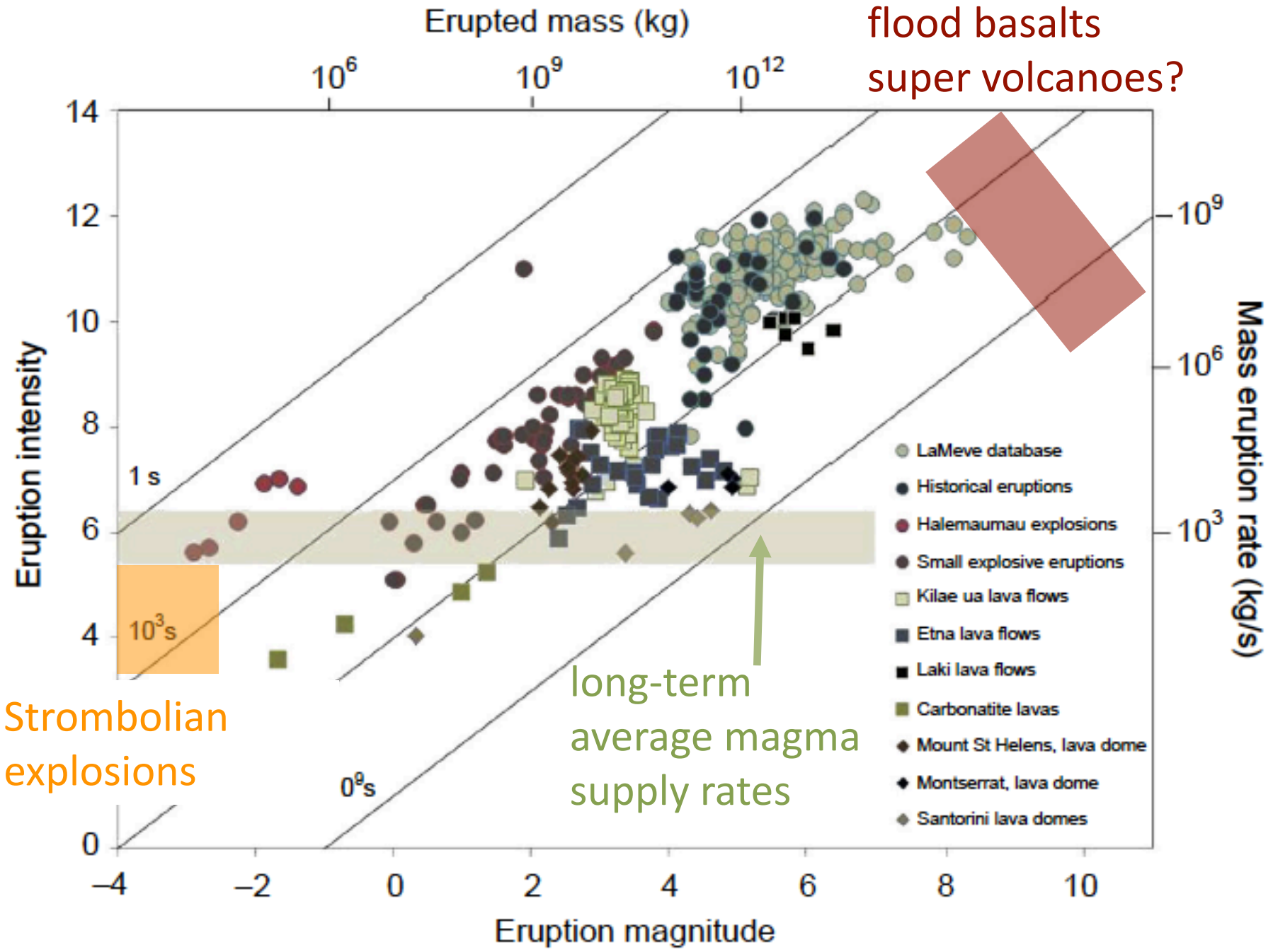
Kilauea Iki 1959

Kilauea 1983-present

St Helens 1980

St Helens 2004-2008




Erupted mass (kg)
10^6
10^9
10^{12}
flood basalts
super volcanoes?
Eruption intensity
14
12
10
8
6
4
0
1 s
10^3s
10^9s
10^9
10^6
10^3
Mass eruption rate (kg/s)
LaMeve database
Historical eruptions
Halemaumau explosions
Small explosive eruptions
Kilae ua lava flows
Etna lava flows
Laki lava flows
Carbonatite lavas
Mount St Helens, lava dome
Montserrat, lava dome
Santorini lava domes
Strombolian explosions
long-term average magma supply rates
–4
–2
0
2
4
6
8
10
Eruption magnitude

What makes volcanoes dangerous?

	Fatalities since 1500 CE
Pyroclastic density currents	(60,000)
Tsunami	(57,000)
Lahaars	(46,000)
Ash fall	(4,300)
Debris avalanche	(3,500)
Gas emissions	(2,300)
Lava flows	(660)
Ballistics	(370)
Hydrothermal	(60)
Volcanic Lightning	(9)

St Pierre, Martinique

8th May 1902

"...I looked back and the whole side of the mountain, facing towards the town, seemed to open and topple down on the screaming people. I was burned ... by the stones and ashes that came flying ..., but I got to the cave,..."

Havivra Da Ifrile


Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image © 2023 Maxar Technologies
Image © 2023 CNES / Airbus
Data LDEO-Columbia, NSF, NOAA
Google Earth

What can we use to forecast?

Underlying process	Thing we can observe
Magma movement	Deformation of the volcano
	Noises made as the magma fractures its pathway upward (seismicity)
Magma production and evolution	Gases emitted
	Size/fluid content of the plumbing system

Imaging the plumbing system

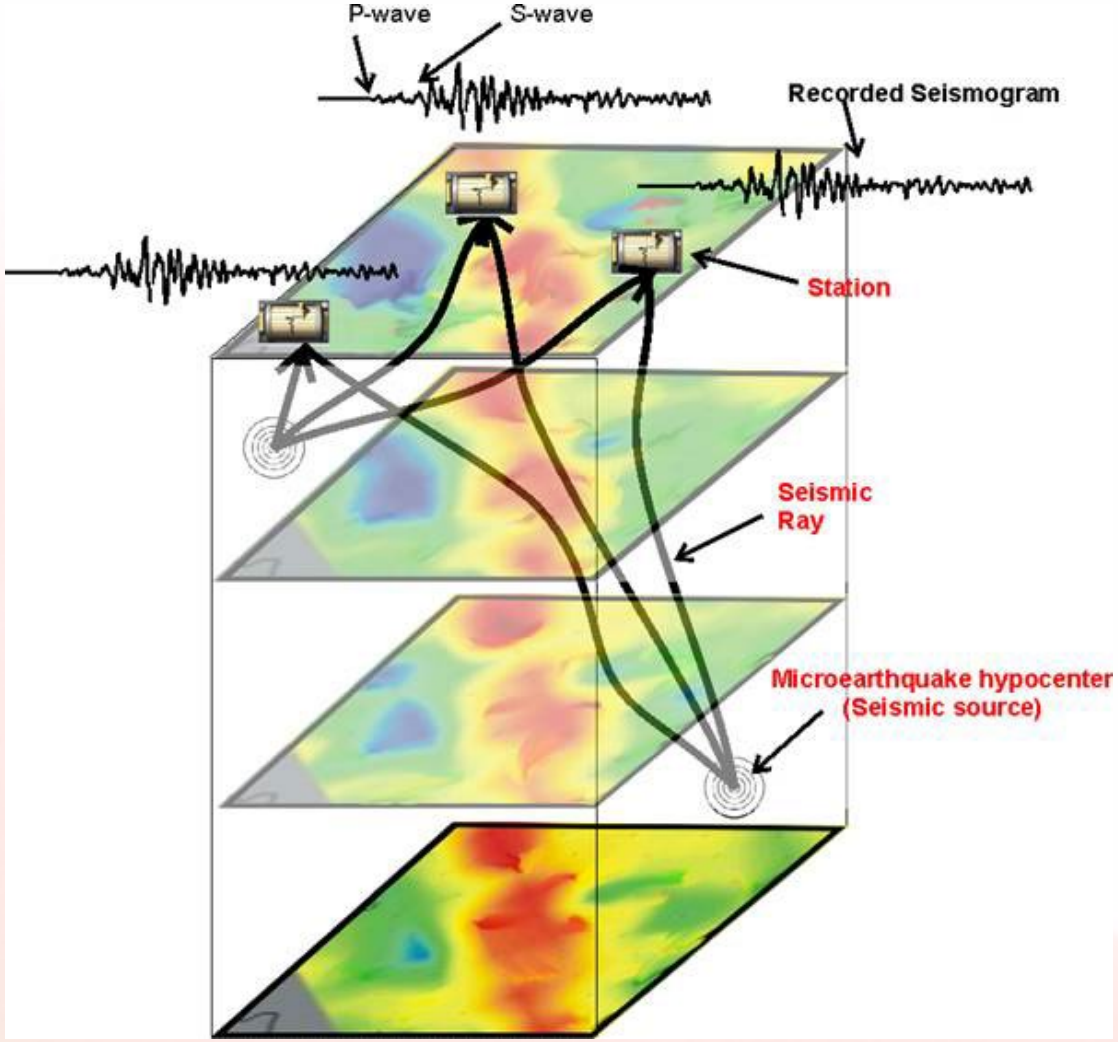
Identify rigid and soft regions by how fast seismic waves travel though the material

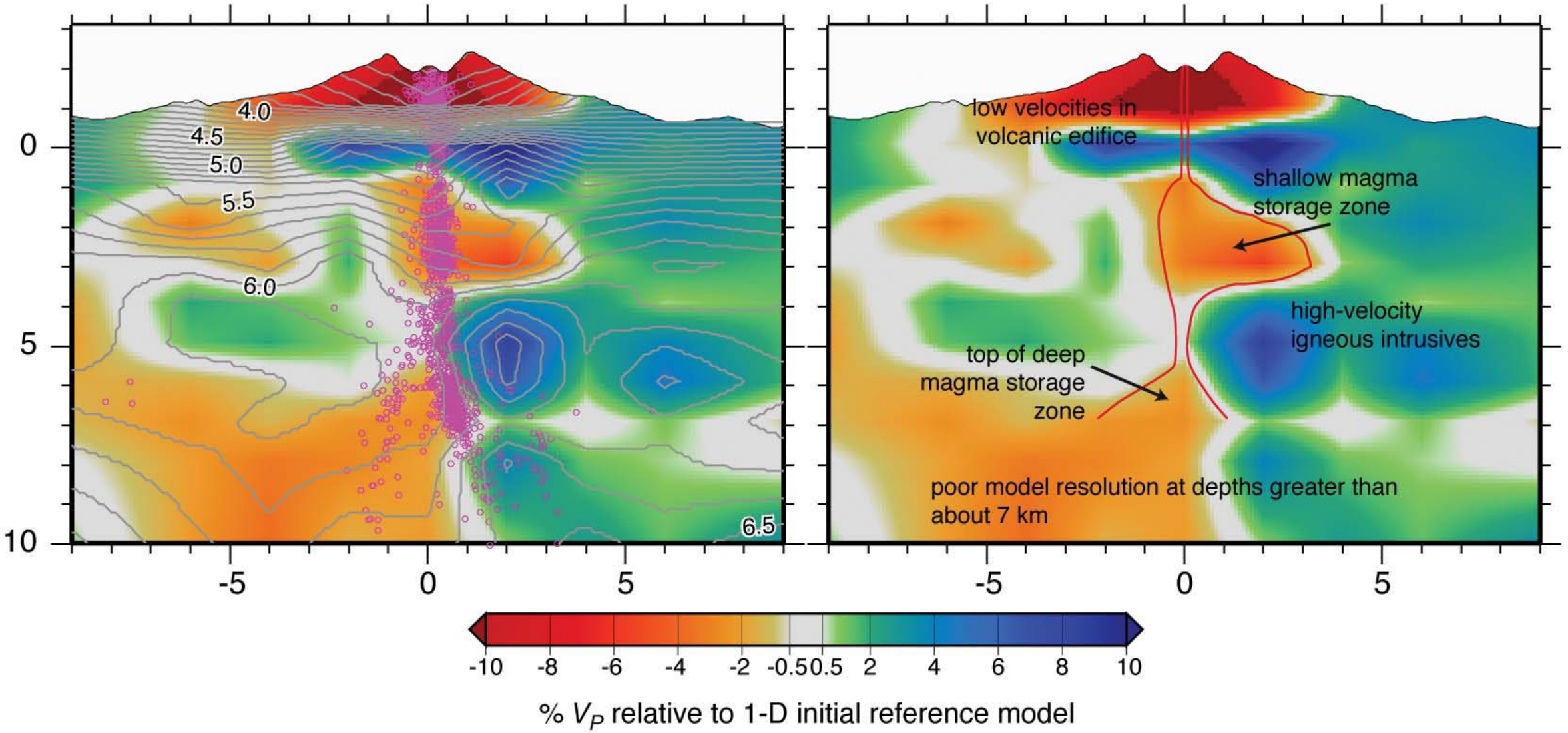
Needs lots of sensors

Needs lots of earthquakes

Low resolution

Not responsive – long timescale information



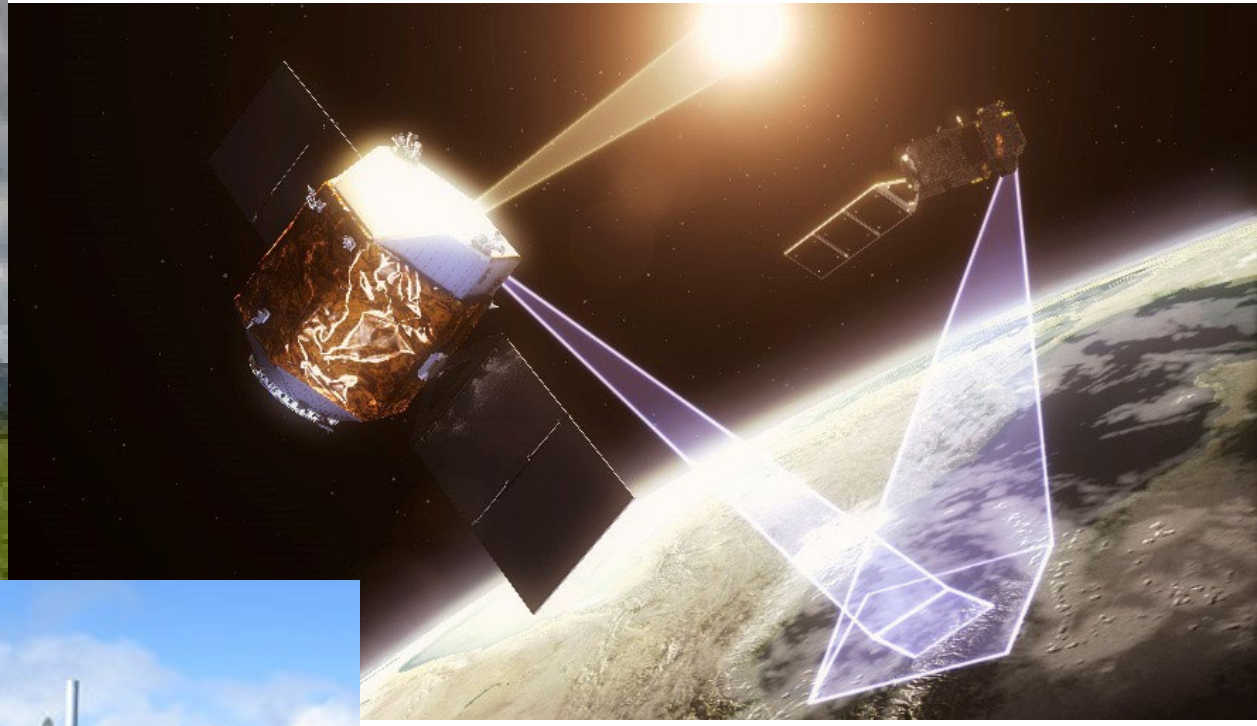

4.0
4.5
5.0
5.5
6.0
6.5
low velocities in volcanic edifice
shallow magma storage zone
high-velocity igneous intrusives
top of deep magma storage zone
poor model resolution at depths greater than about 7 km
0
5
10
-5
0
5
-10
-8
-6
-4
-2
-0.5
0.5
2
4
6
8
10
% V_P relative to 1-D initial reference model

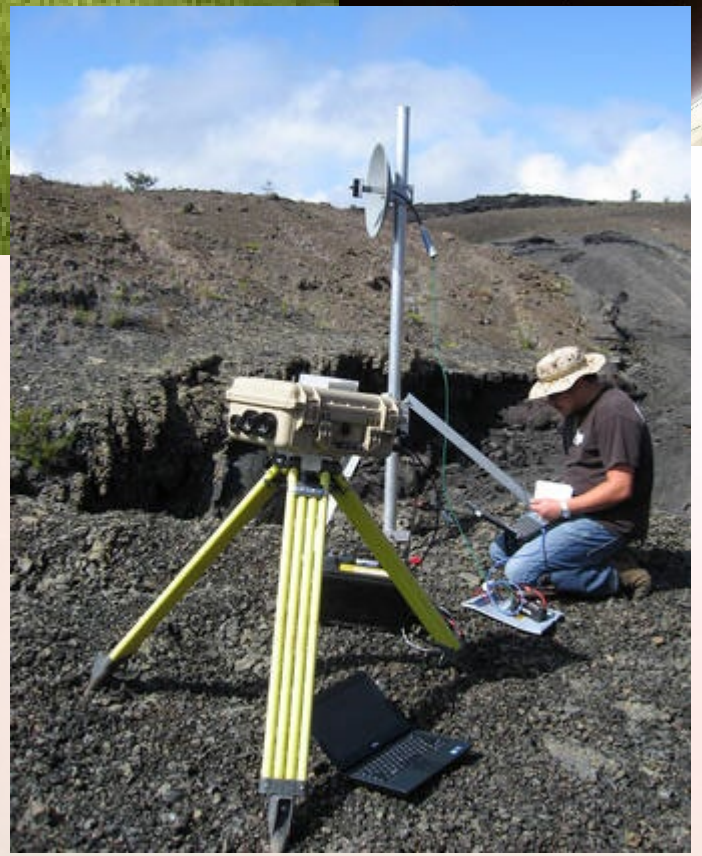
Gas emission

Gases present in all magma

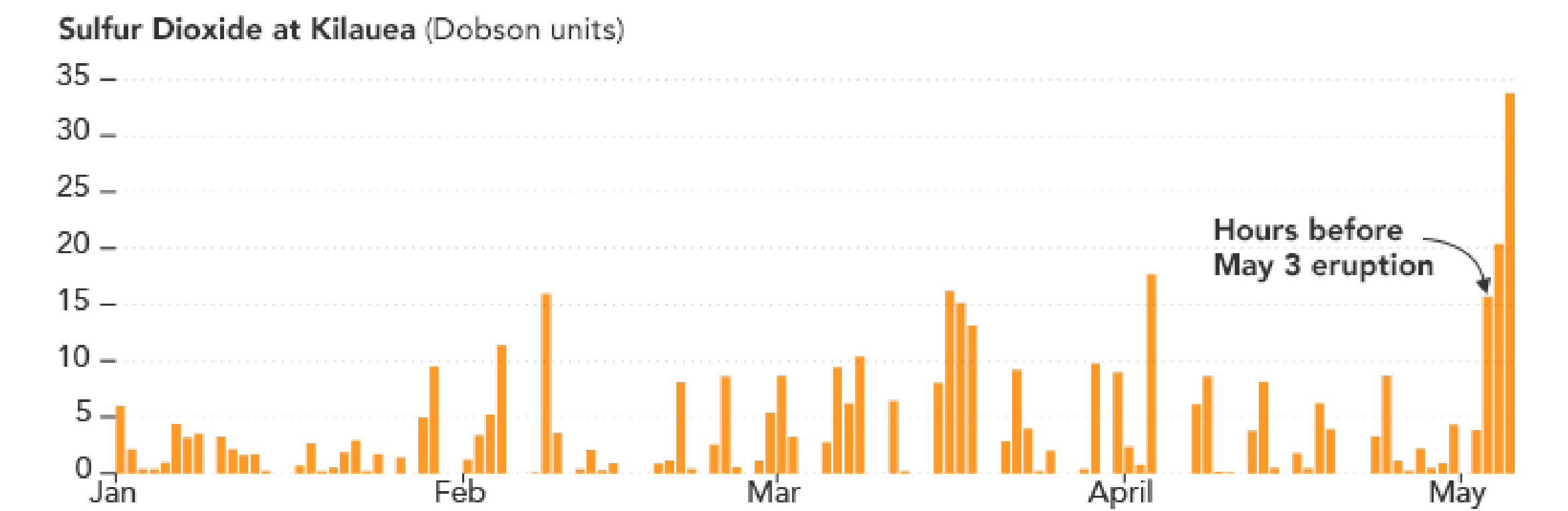
As magma rises, pressure decreases, solubility of gas in magma changes.

Gas escapes through the crust much faster than magma travels





Hawaii 2018

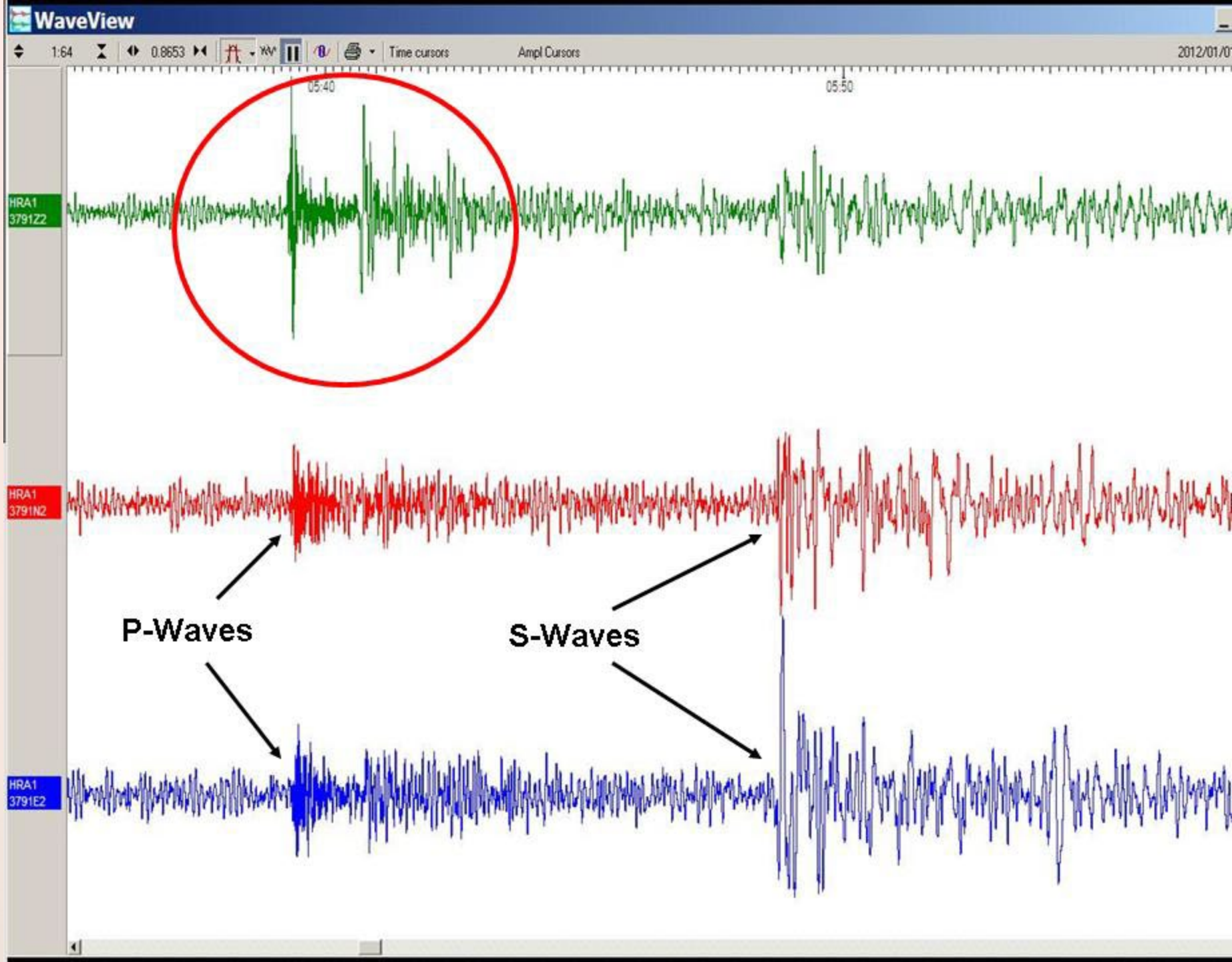

Sulfur Dioxide at Kilauea (Dobson units)
35
30
25
20
15
10
5
0
Jan
Feb
Mar
April
May
Hours before
May 3 eruption

Seismicity

Type

Rate

Location



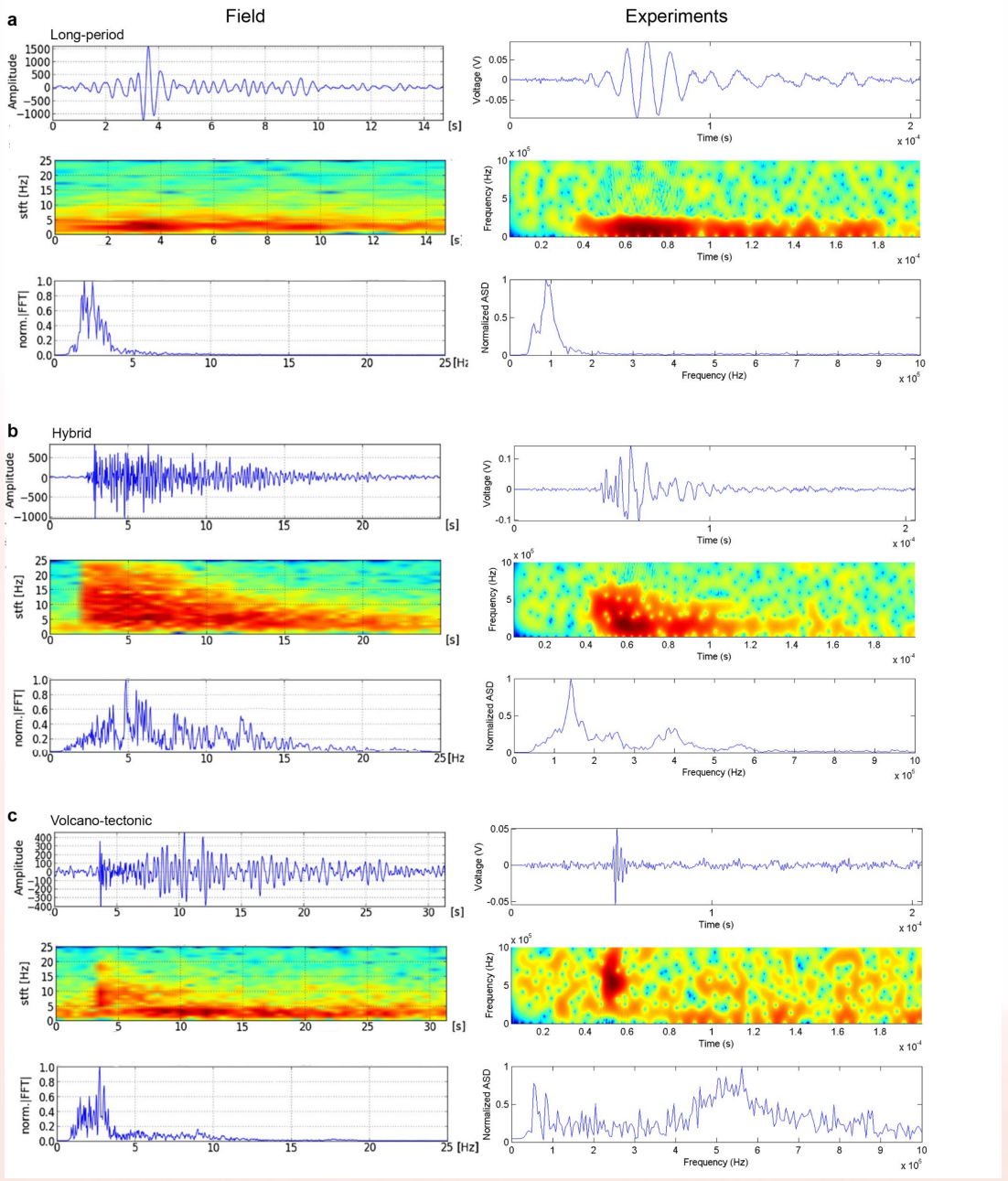
Type

Different frequency characteristics

Different timescales

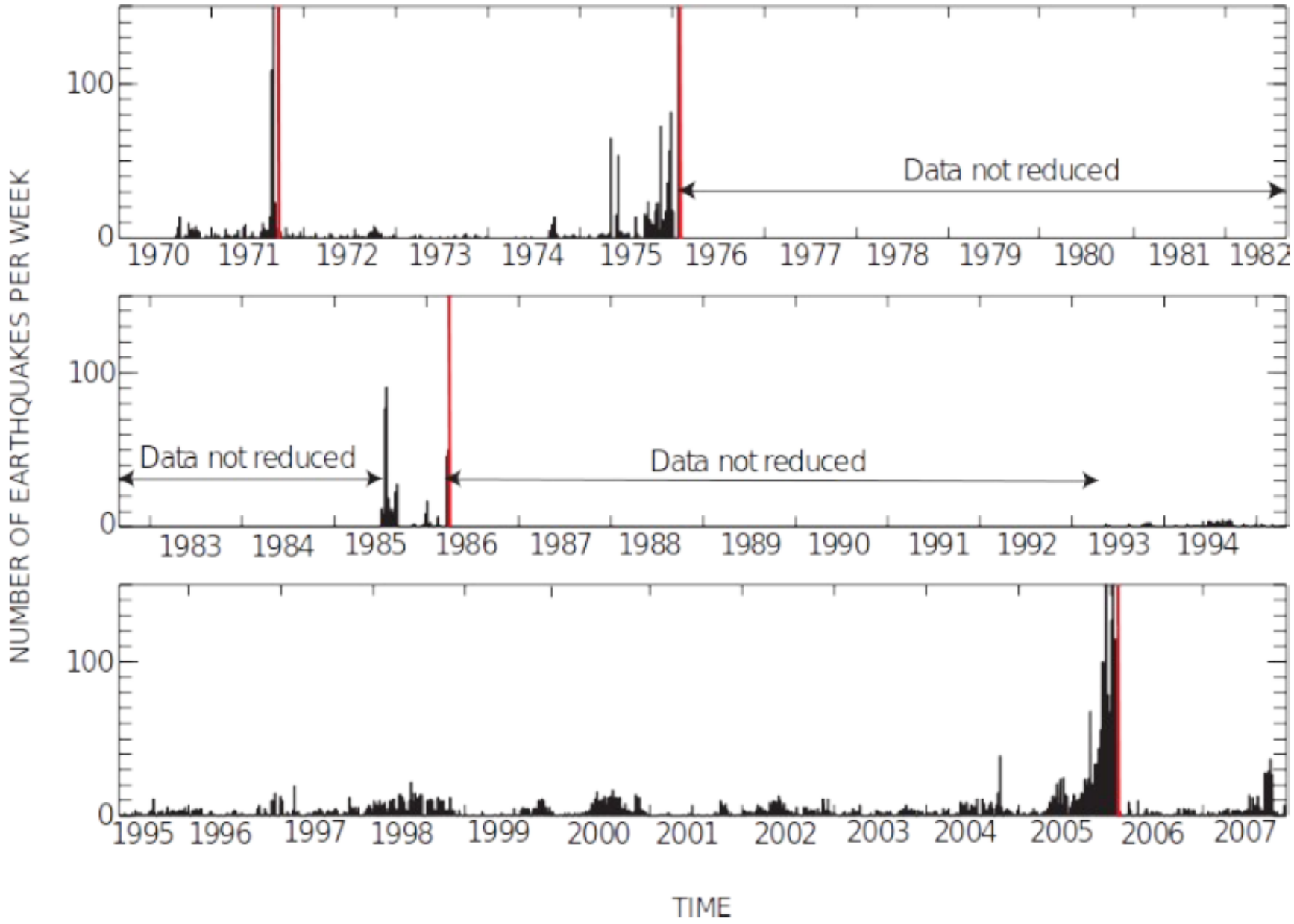
Different causes!

But what process causes what signal?

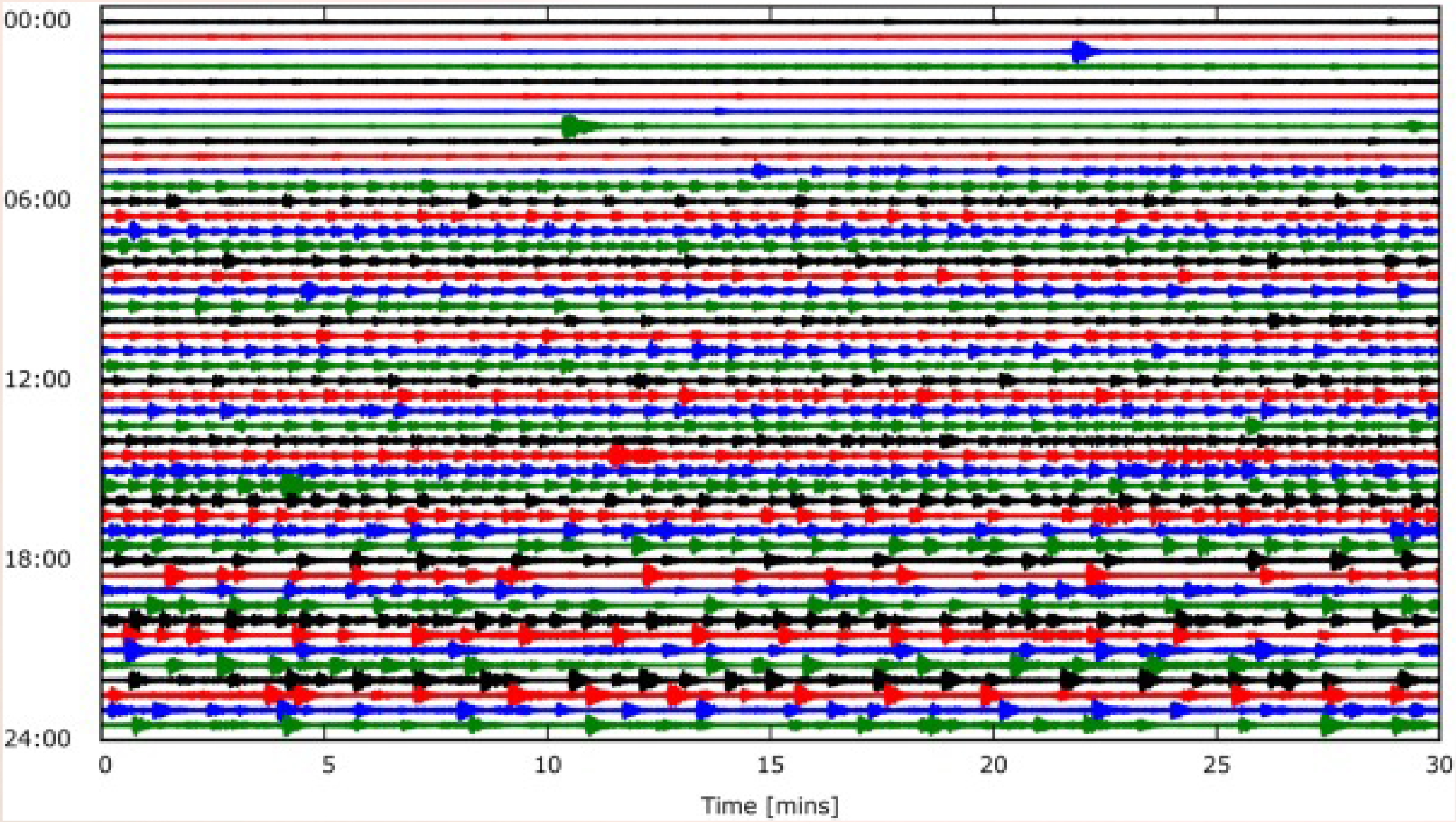


Rate

Augustine 1970-1



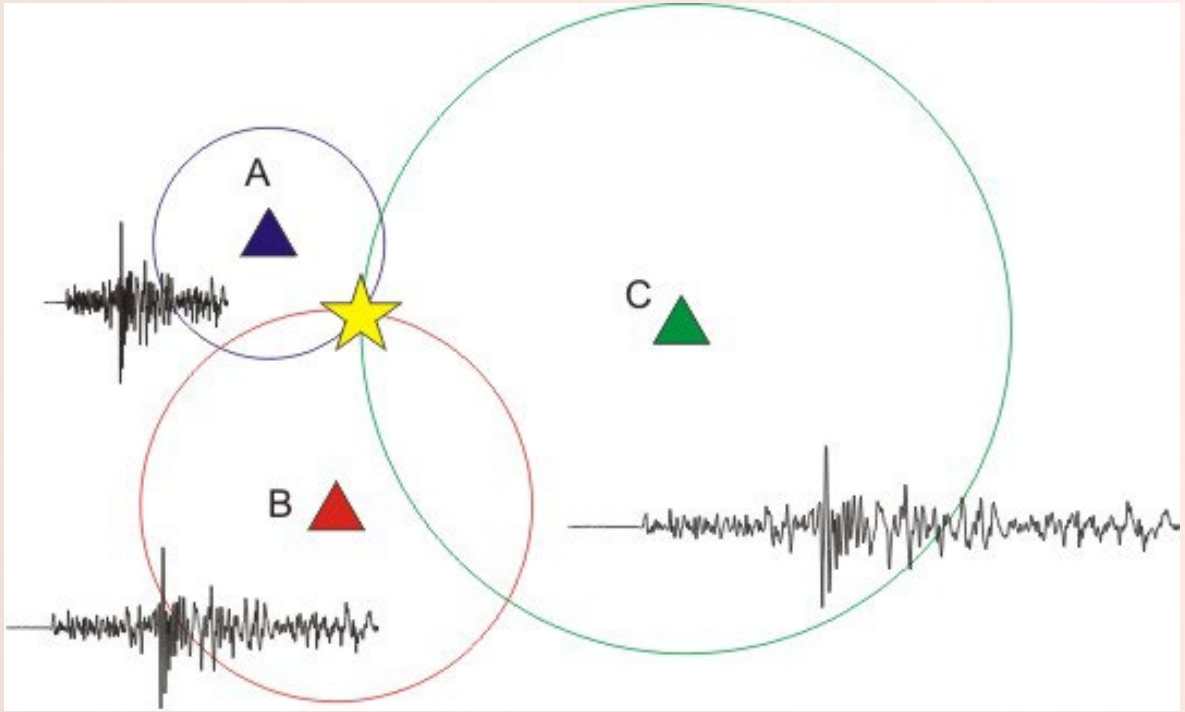
Power et al. 2010

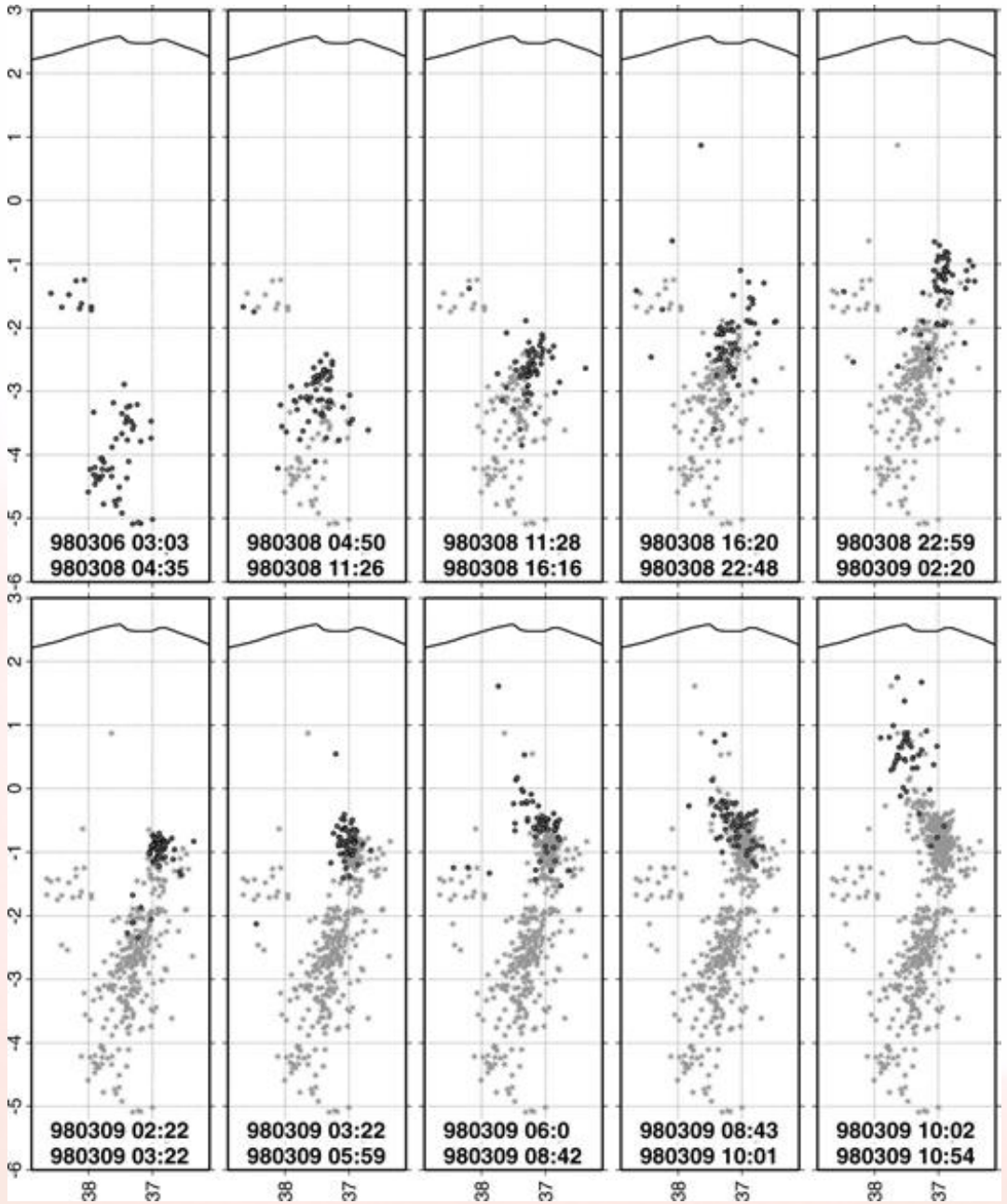


Tungurua, 10/4/15

Location

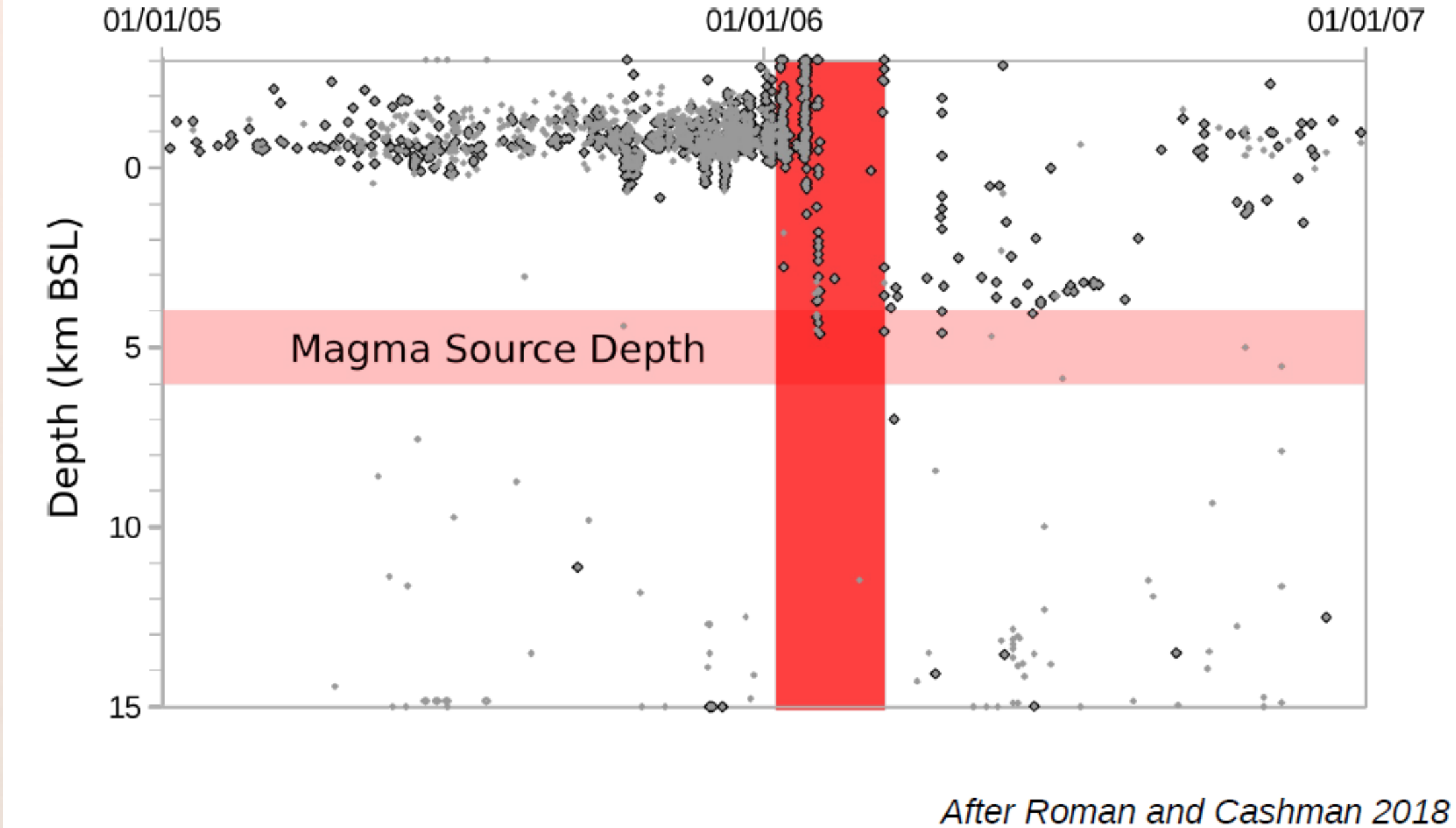
Piton de la Fournaise, 1998





Battaglie et al 2005

Augustine, 2006



After Roman and Cashman 2018

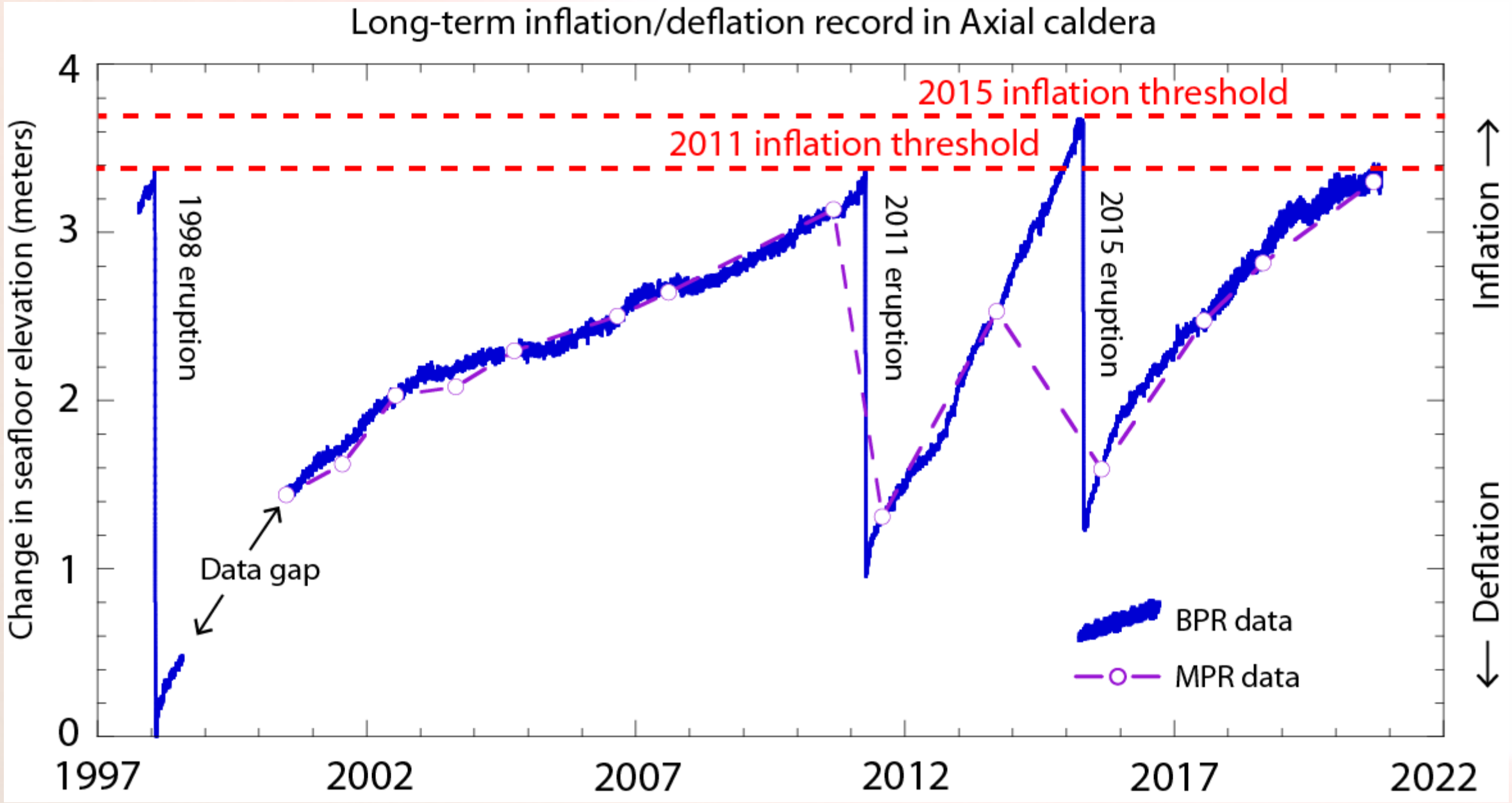
Deformation

Tiltmeters

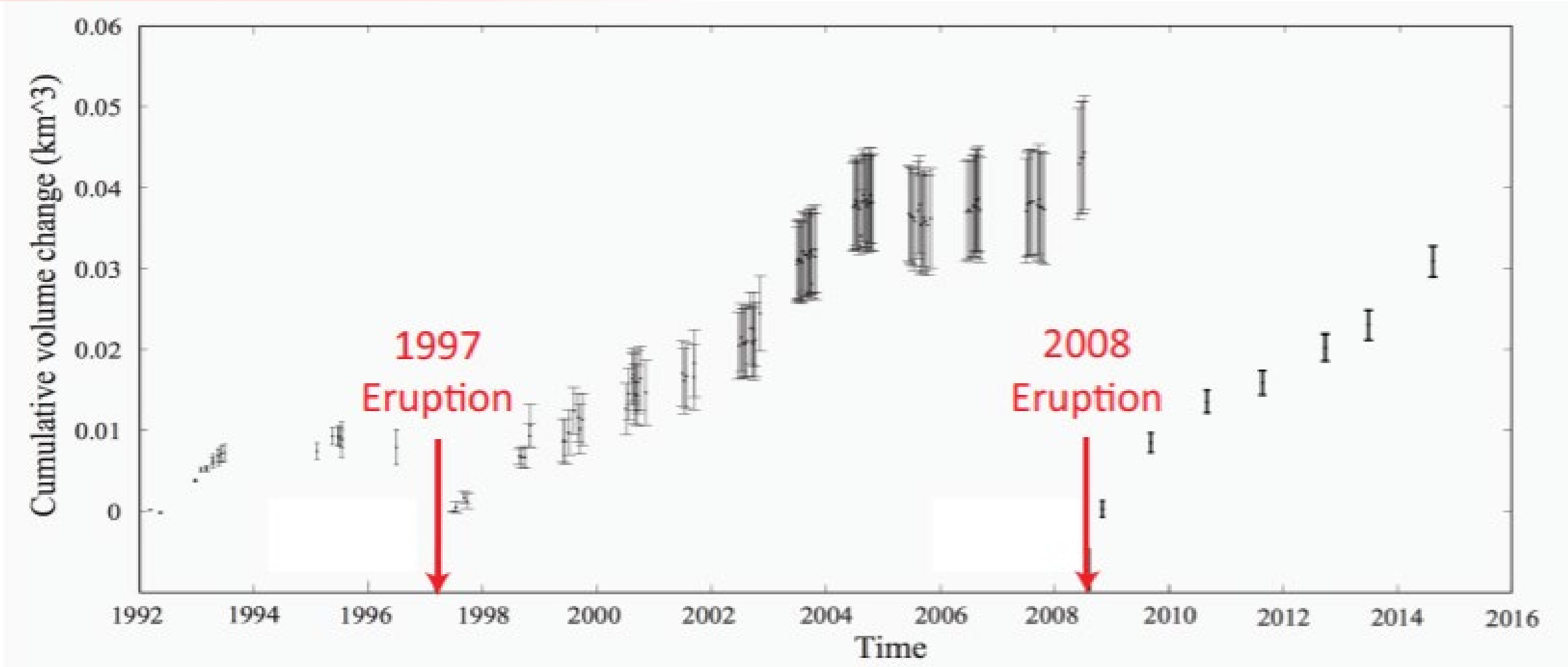
GPS

Laser Ranging

INSAR

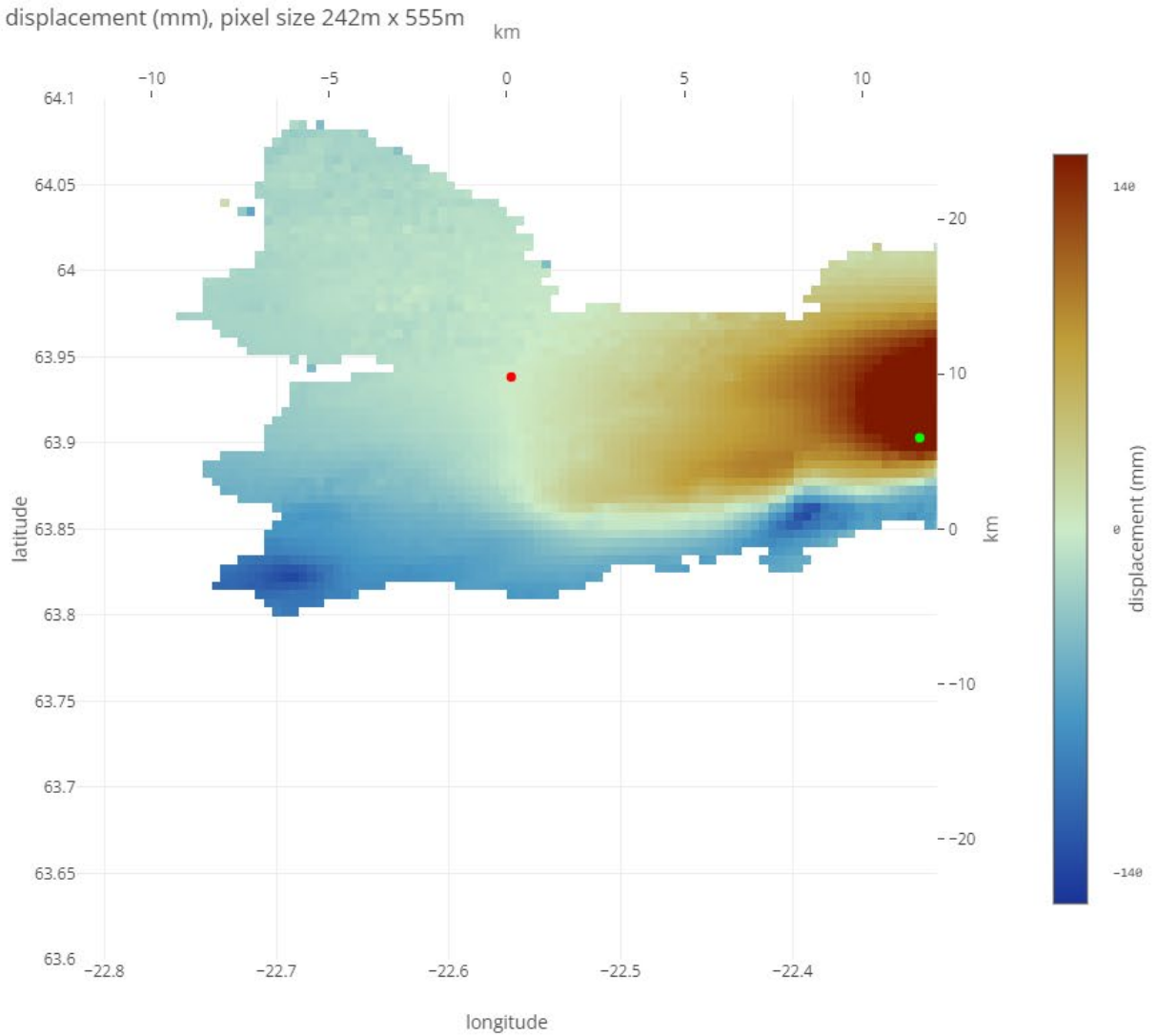


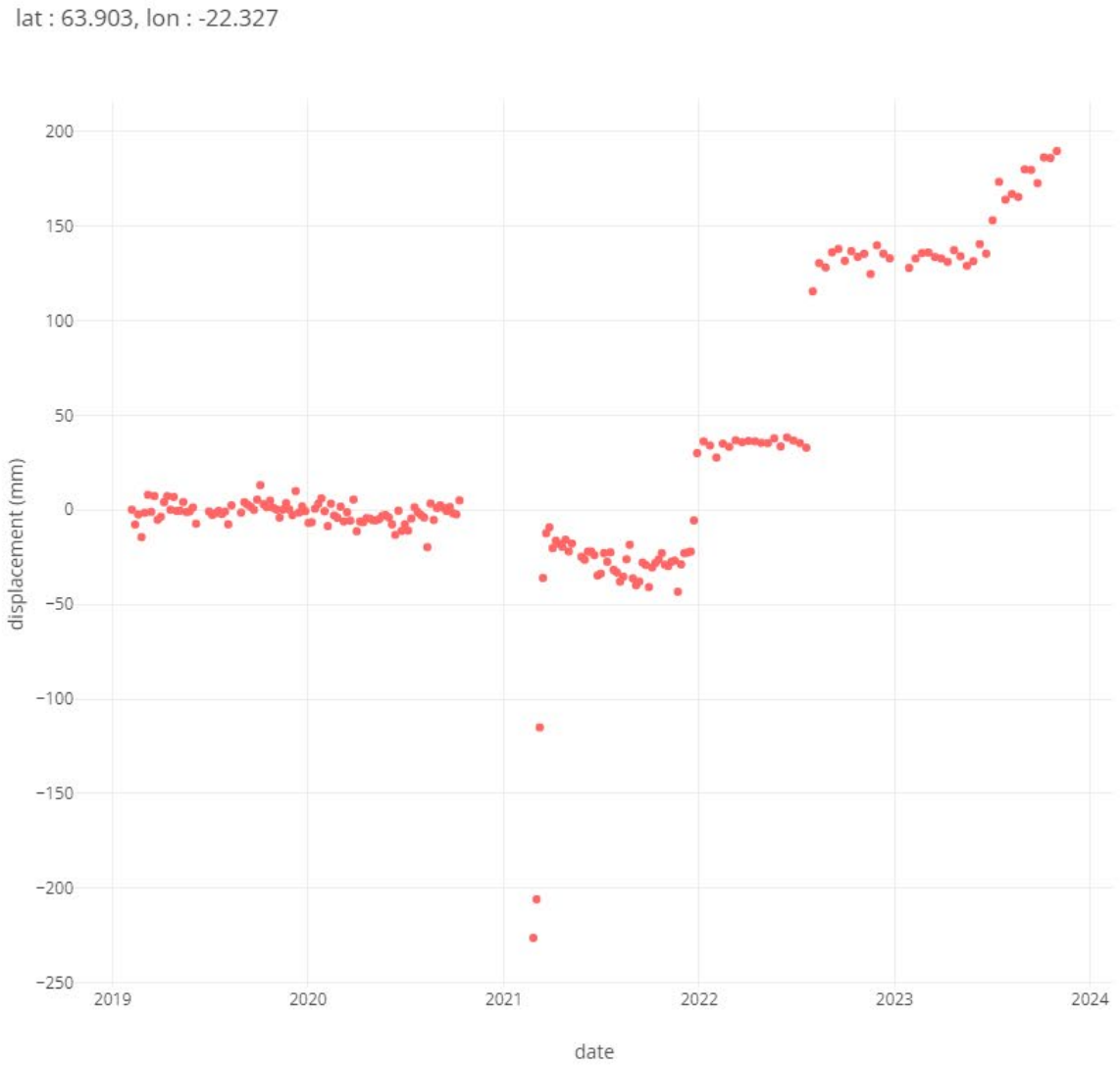
https://www.pmel.noaa.gov/eoi/axial_blog.html



Okmok

National Academy of Sciences (2017)





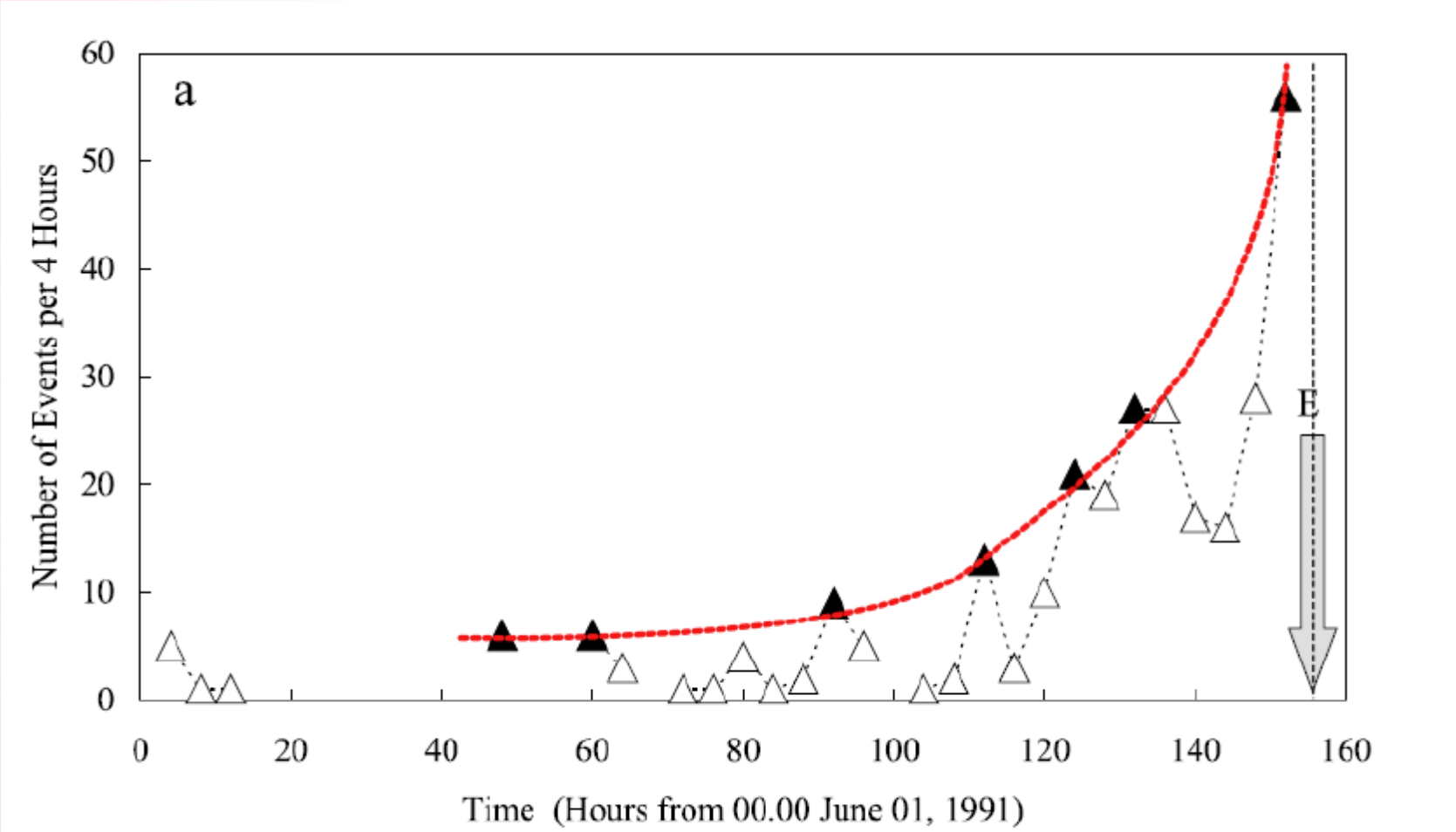
COMET

sentinel-1

The problem with forecasting …

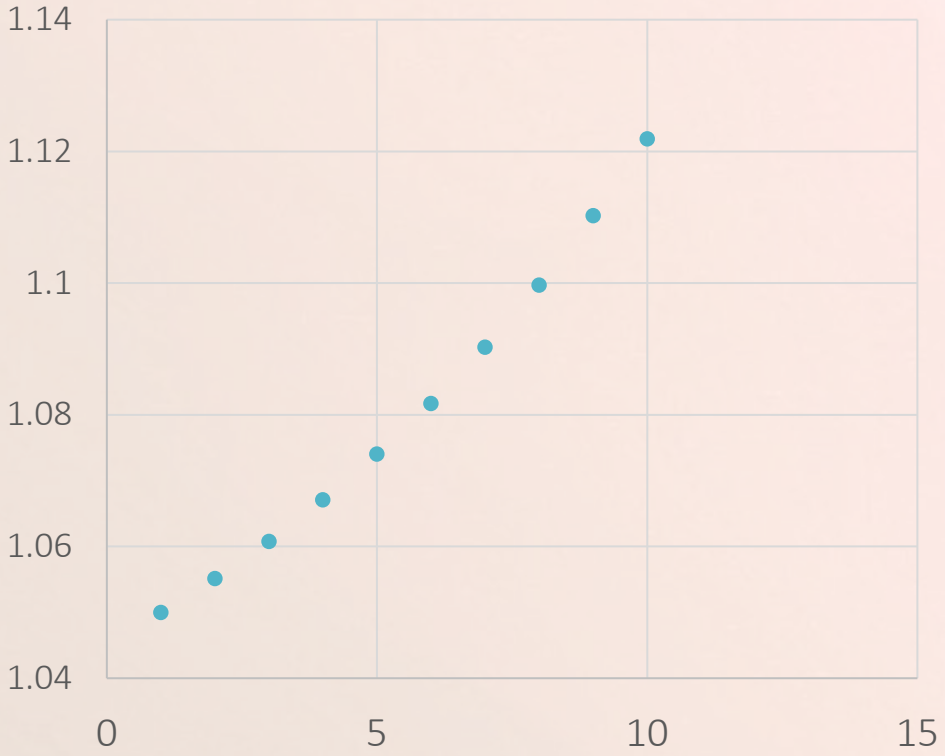
We've seen increasing patterns of activity in all these data…

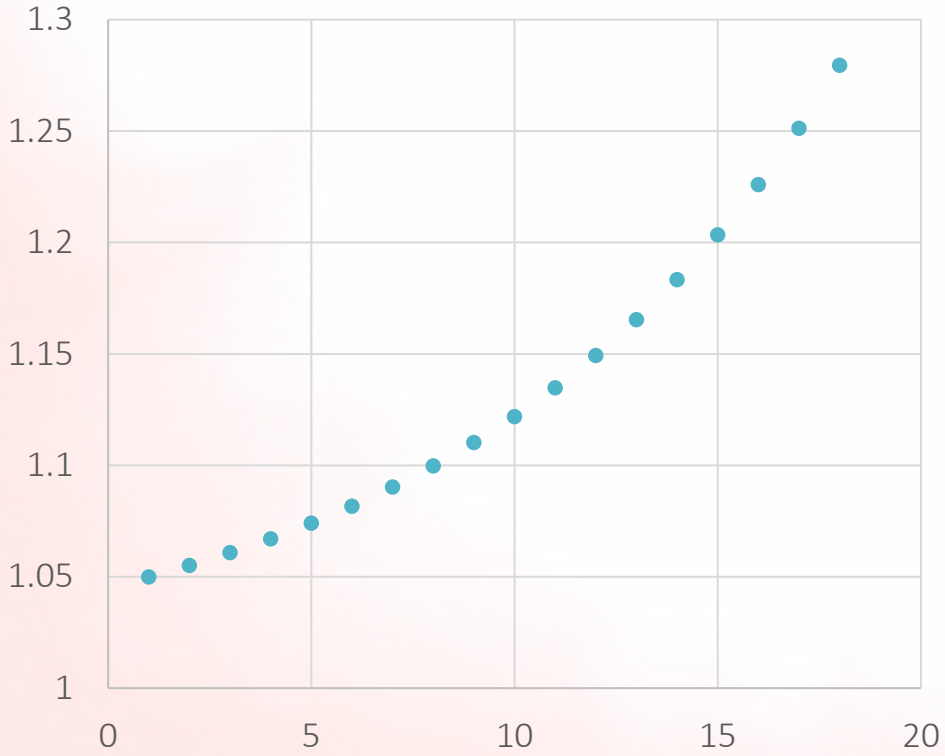
…But it's only useful retrospectively



After Kilburn (2003)

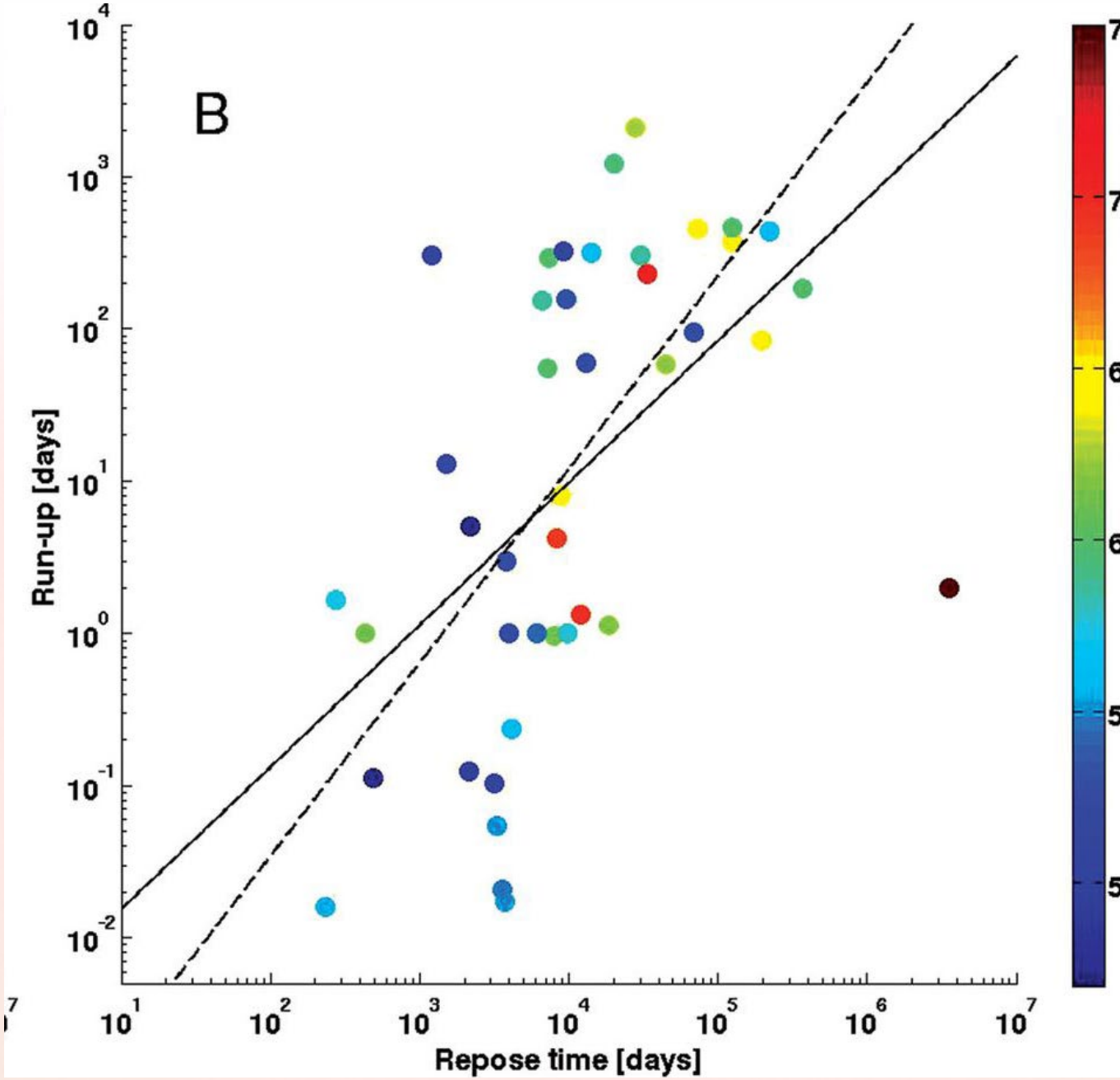
Growth curves are not predictive of failure points





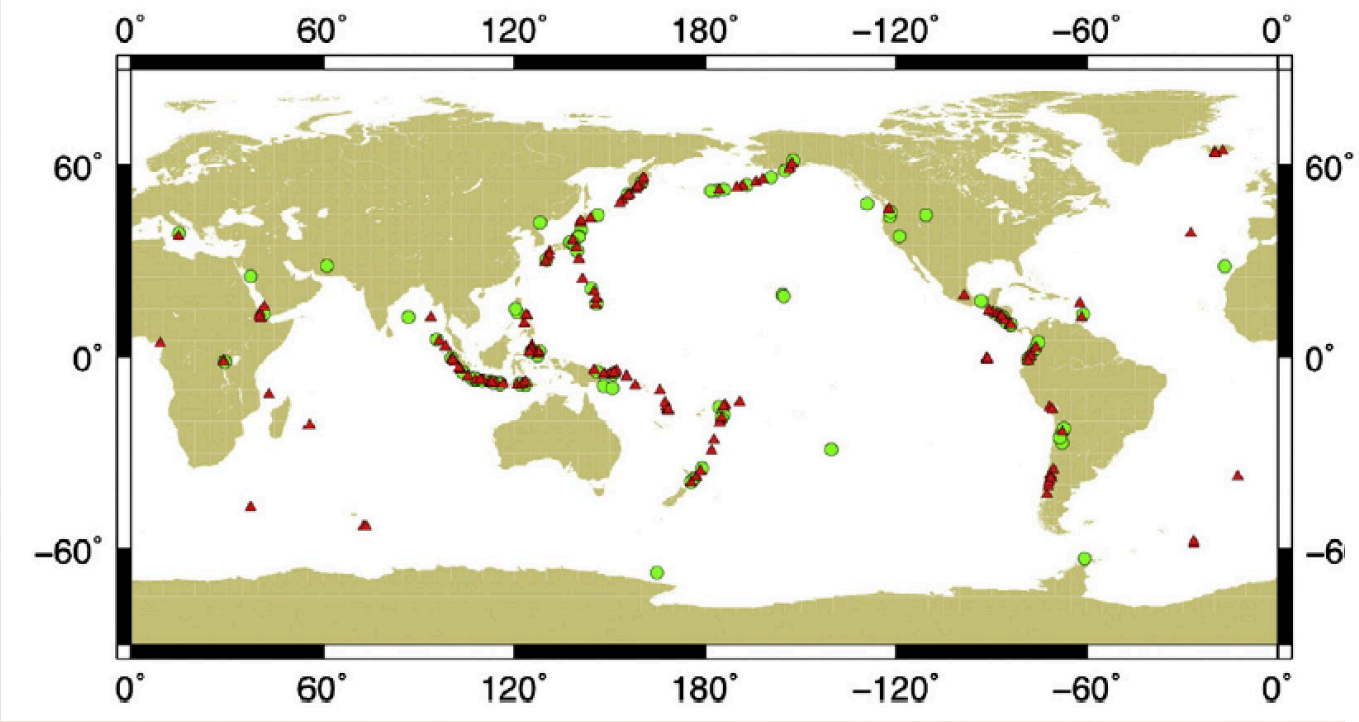
There is no pattern

Eruptions after similar repose times, with the same kind of magma involved, at the same volcano, can have totally different “run up” periods of unrest.



Passarelli & Brodski 2012

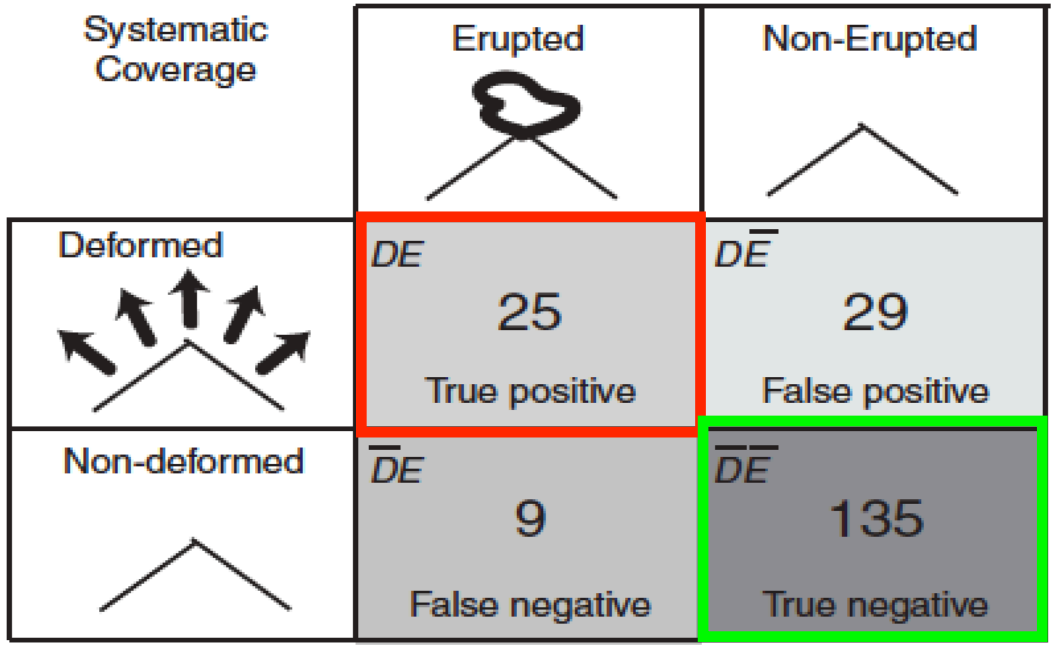
Even if there was a pattern…

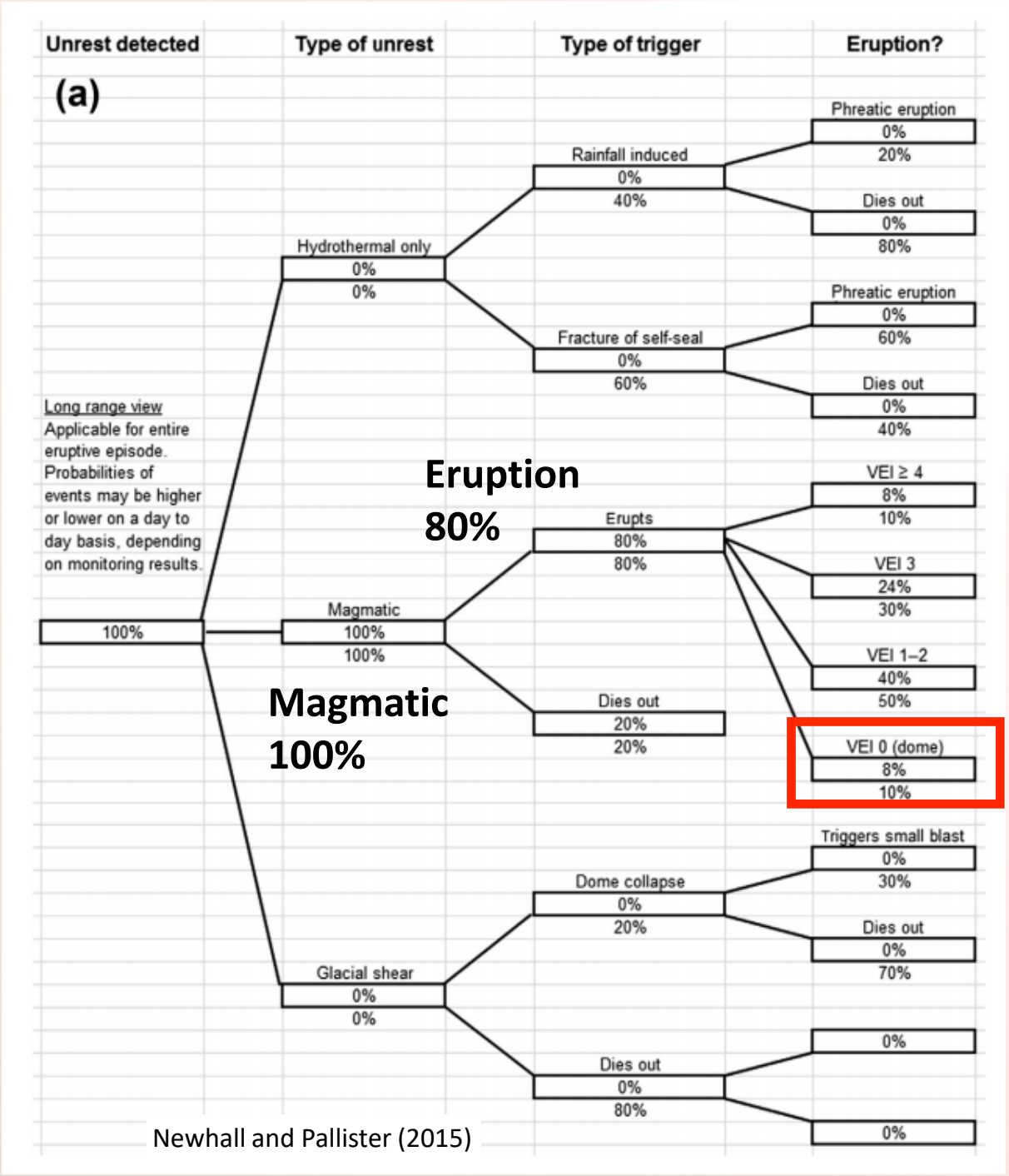


Global Volcanic Unrest 2001-2011

47% of restless volcanoes eventually erupted

53% didn't!





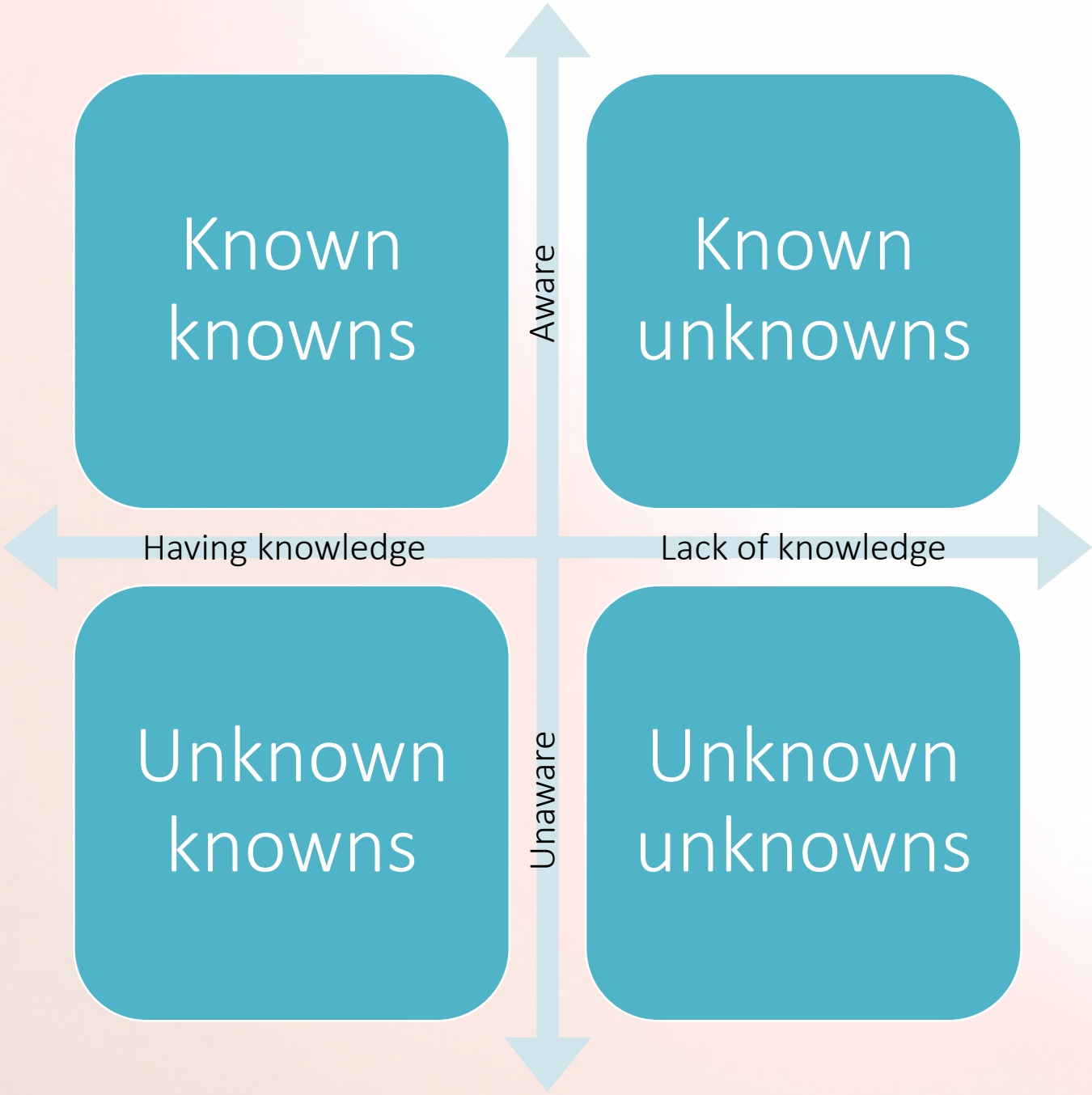
Newhall and Pallister (2015)

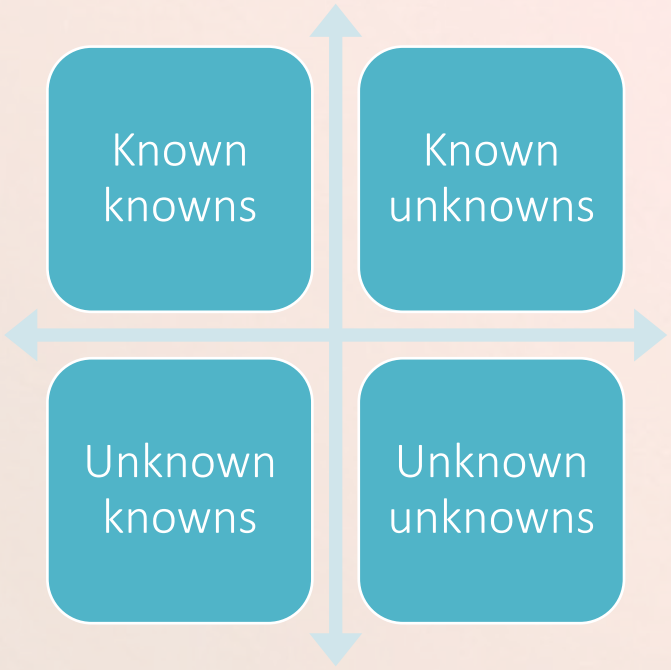
Example:
Mount St. Helens 2004

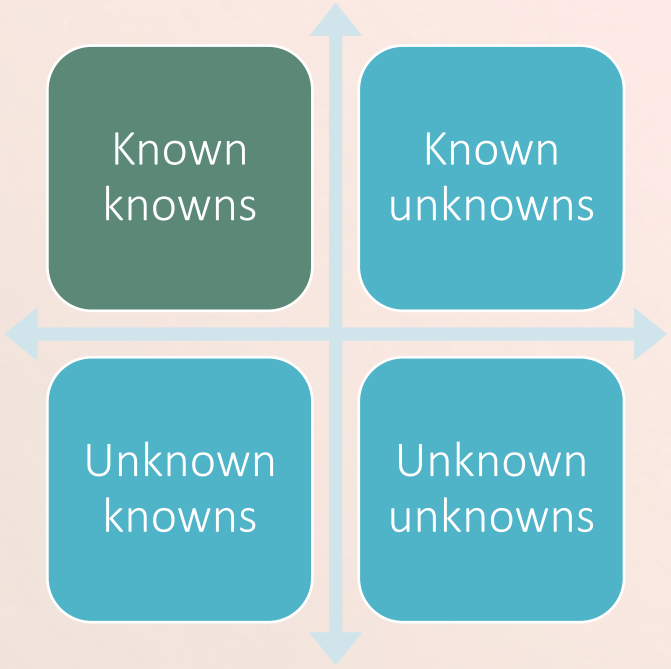
Important because of the media frenzy and memories of 1980 eruption

VEI 1-2 most likely (50%)

Actual outcome (dome) 8%


Known knowns
Known unknowns
Unknown knowns
Unknown unknowns
Aware
Unaware
Having knowledge
Lack of knowledge


Known knowns
Known unknowns
Unknown knowns
Unknown unknowns

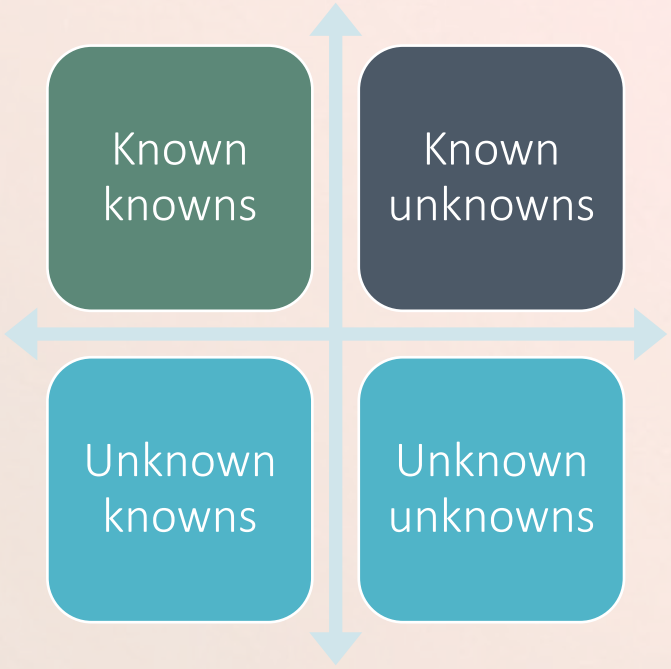


Things we are confident that we already understand

How to measure gas, seismic emissions and deformation around volcanoes

How viscosity and gas content impact eruptive behaviour

What causes some seismic, gas and deformation signals



Things we know that we don't *fully* understand

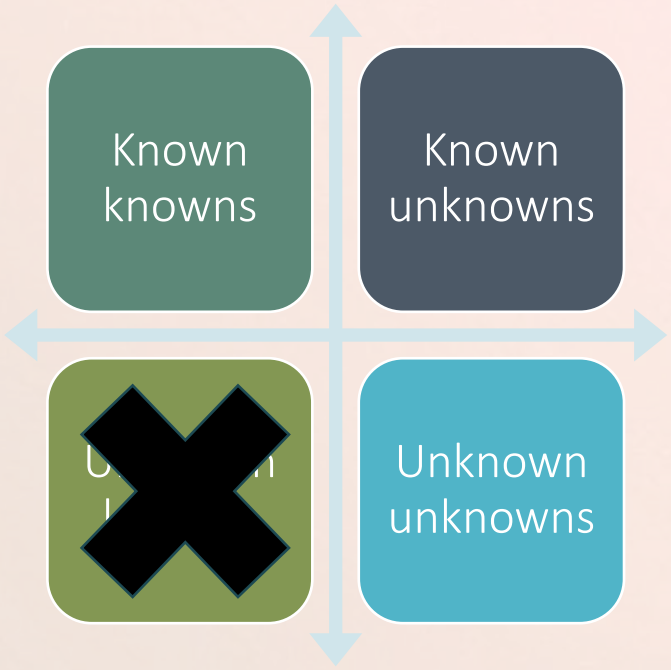
What causes some seismic signals

What causes some deformation signals

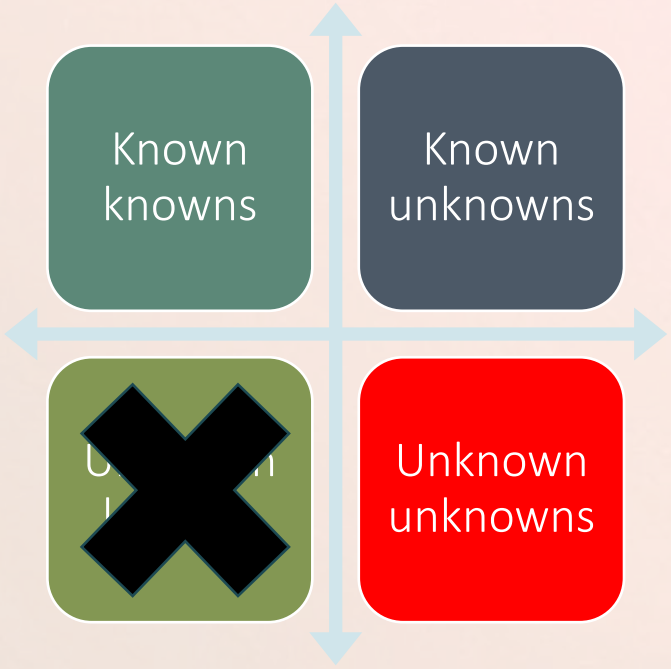
What causes some gas signals

What's going on at depth in detail

How close to triggering an eruption any given system is



Things we don’t realise that we already know

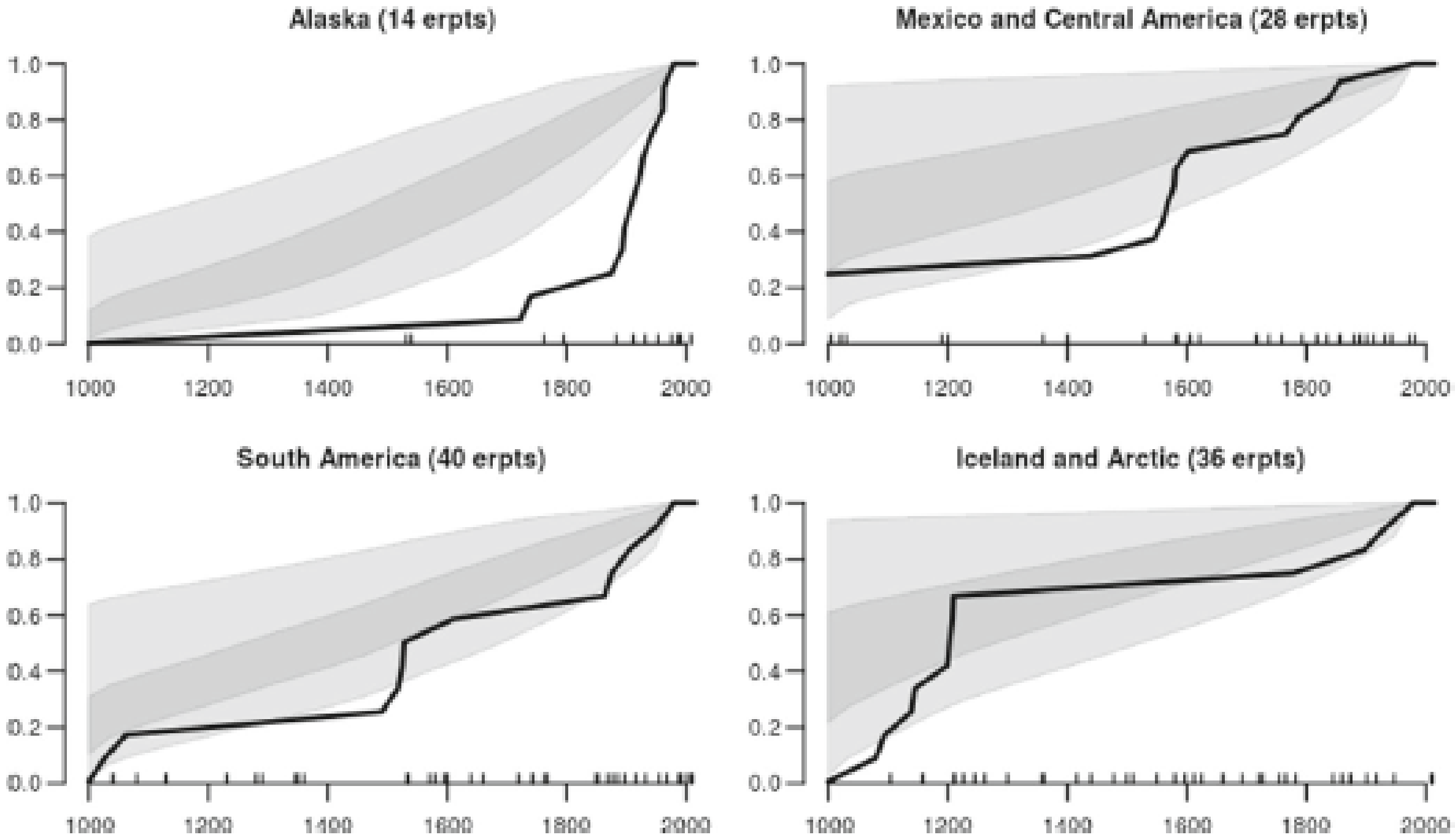


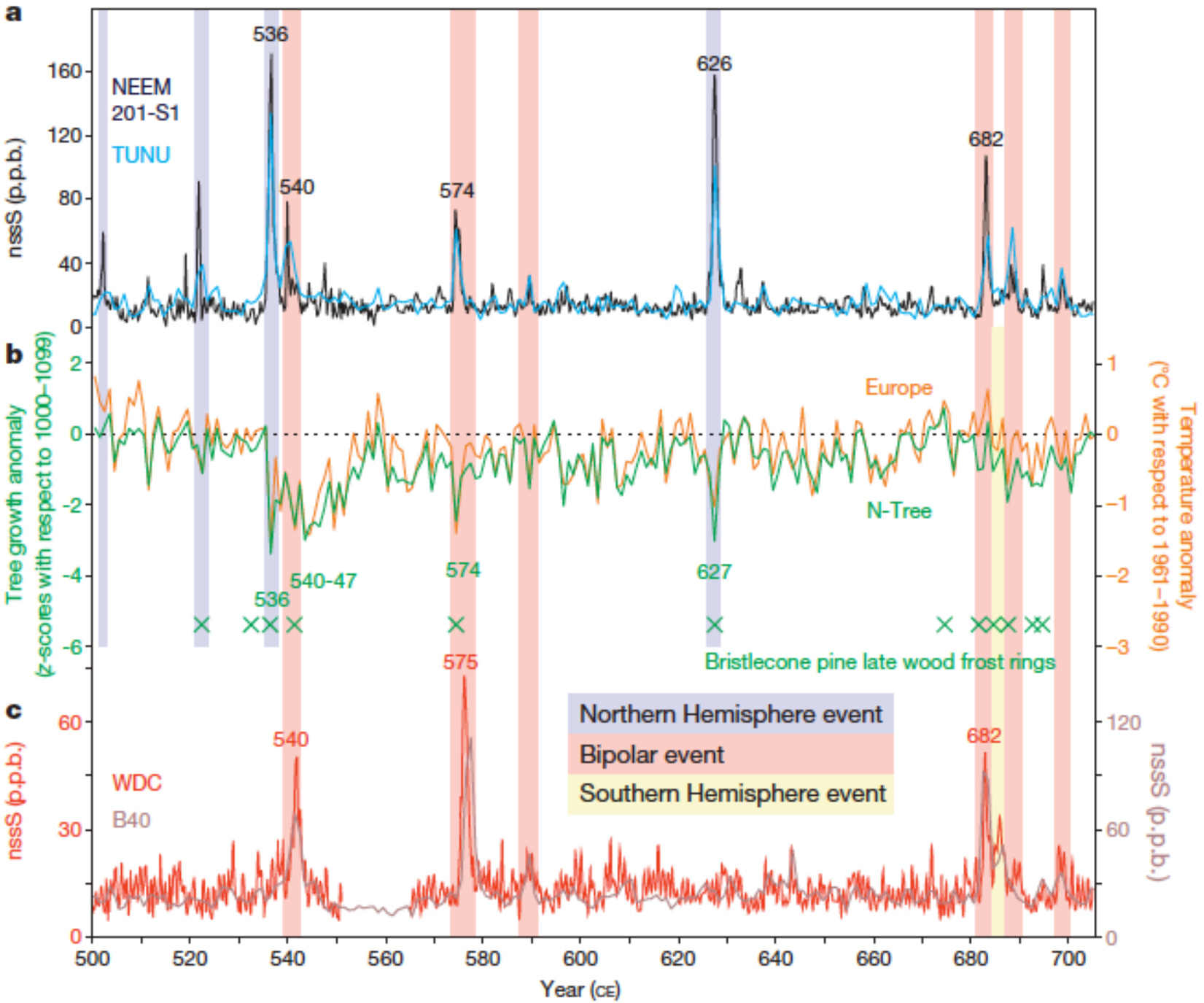
Things that we don't know that we don't know

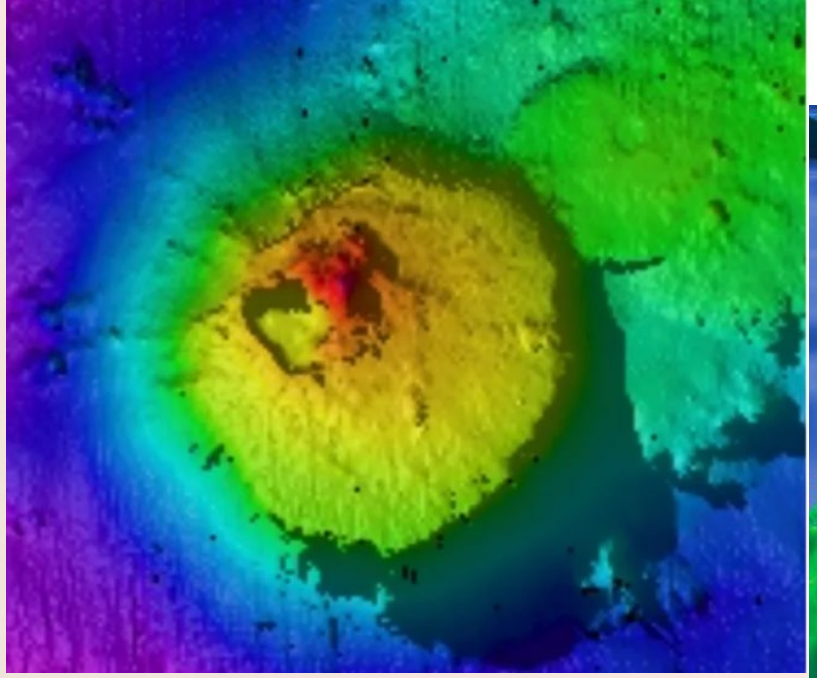
???

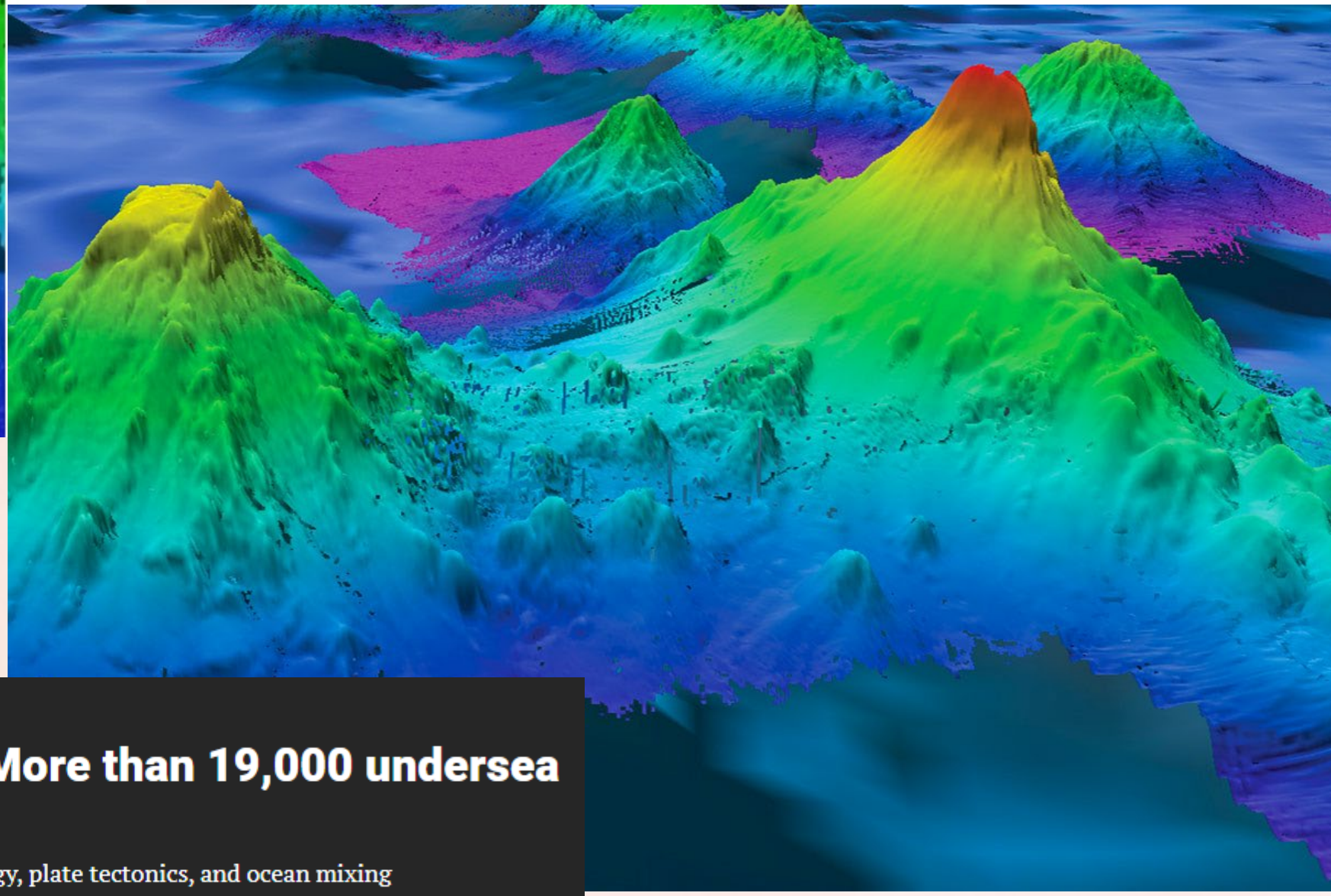
Some things to reflect on:

1. Are the mechanisms at all volcanoes the same?
2. Are there physical processes happening at depth we don't know about?
3. How confident are we that the records we have are statistically useful?
4. **What about the volcanoes we can't see or haven't looked at properly?**


Alaska (14 erpts)
Mexico and Central America (28 erpts)
South America (40 erpts)
Iceland and Arctic (36 erpts)
1.0
0.8
0.6
0.4
0.2
0.0
1000
1200
1400
1600
1800
2000


a
NEEM
201-S1
TUNU
nssS (p.p.b.)
536
540
574
626
682
b
Tree growth anomaly
(z-scores with respect to 1000–1099)
Europe
N-Tree
Temperature anomaly
(°C with respect to 1961–1990)
536
540-47
574
627
Bristlecone pine late wood frost rings
c
nssS (p.p.b.)
WDC
B40
540
575
682
Northern Hemisphere event
Bipolar event
Southern Hemisphere event
Year (CE)





Science

NEWS | OCEANOGRAPHY

“It’s just mind boggling.” More than 19,000 undersea volcanoes discovered

New seamount maps could aid in studies of ecology, plate tectonics, and ocean mixing

19 APR 2023 • 1:10 PM ET • BY PAUL VOOSEN

Even for the things we do know…

We don’t have consistency.

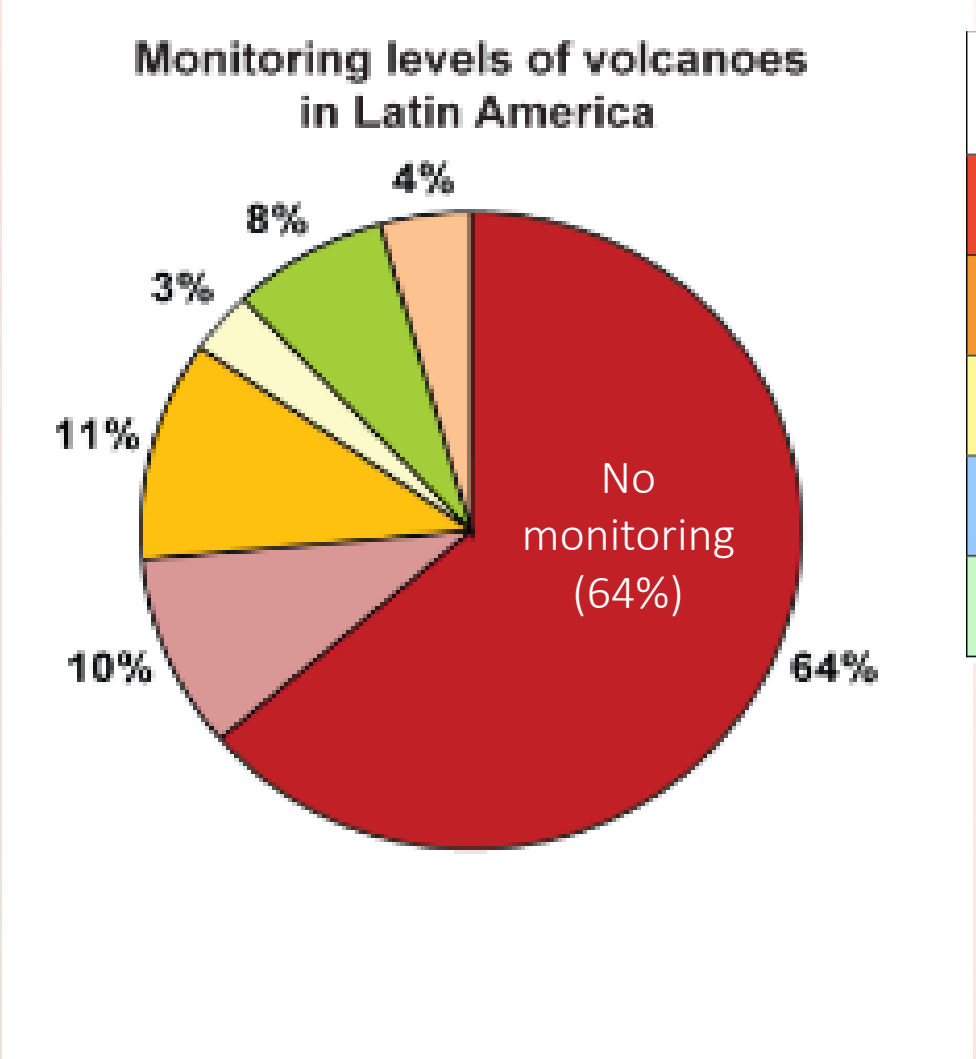
About 1500 potentially active volcanoes globally*

500 million people living on the flanks of these volcanoes.

Monitoring is not uniform.

~ 100 volcano observatories, but not all have the same capacity

Lack of Ground-Based Monitoring

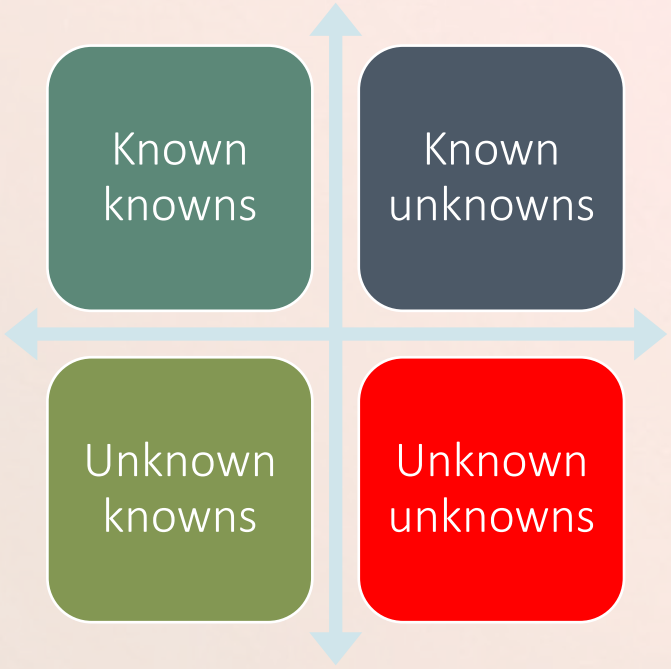


Volcano Monitoring in the US

	Level 4 Well monitored	Level 3 Basic real time	Level 2 Limited	Level 1 Minimal	Level 0 No ground based
Very High Threat (N=18)	17%	33%	39%	11%	0%
High Threat (N=37)	0%	54%	22%	11%	13%
Moderate Threat (N=48)	0%	11%	29%	27%	33%
Low Threat (N=34)	0%	6%	9%	32%	53%
Very Low Threat (N=32)	0%	0%	0%	69%	31%

"It would take at least 20 years to finish installing and making fully operational all instrumentation on "high-threat" and "very high-threat" volcanoes if funding does not increase"

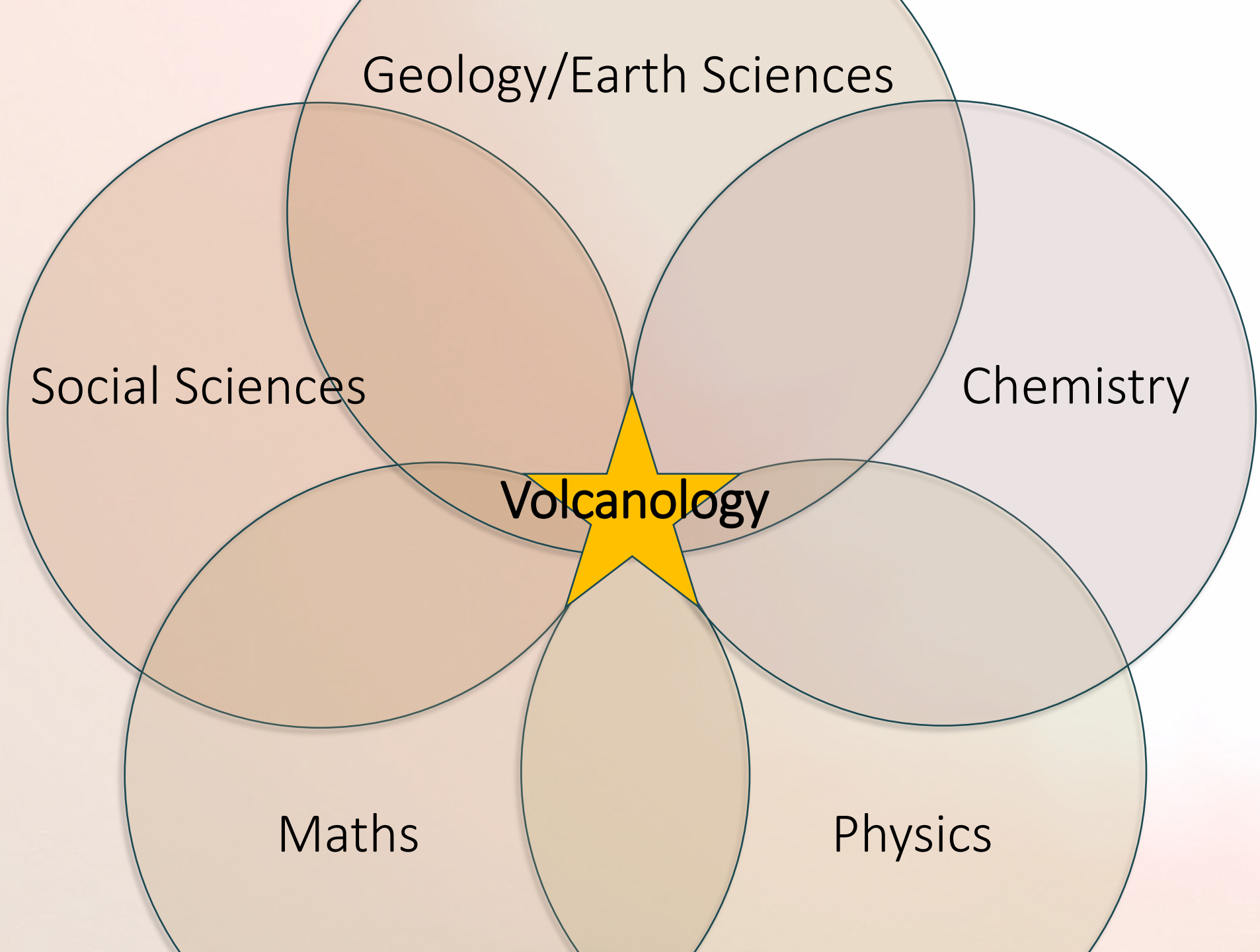
U.S. Geological Survey Volcano Hazards Program Coordinator Dr. Charles Mandeville to Congressional Hearing, 19 Nov 2014

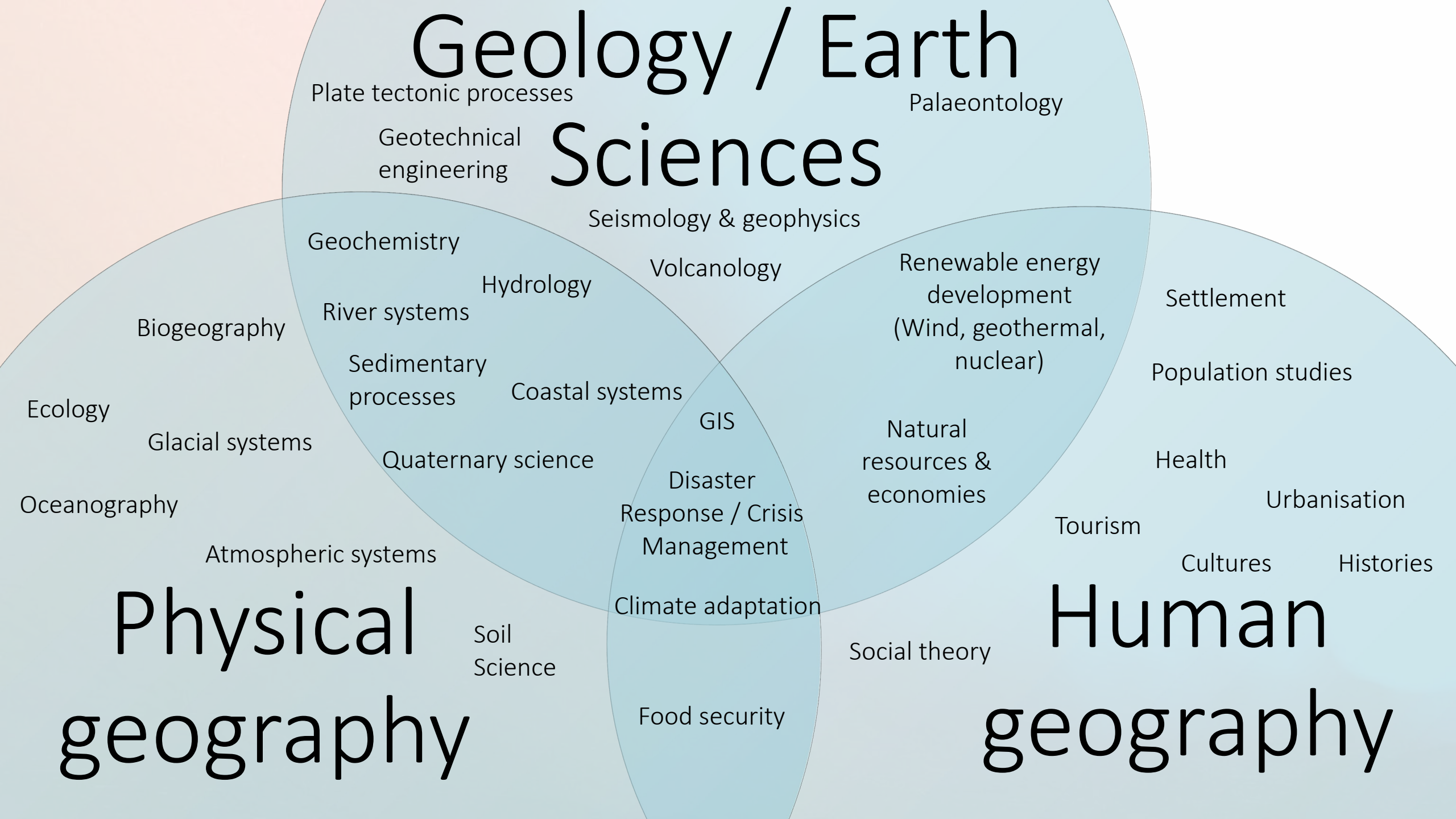


For individual volcanoes the unknown-unknowns are far greater.

- If we don't know it's eruptive history, we don't know how it has behaved in the past.
- If we don't know the structure of the plumbing system, we don't know how it might behave in the future.
- If we don't have any monitoring we don't know how it *is* behaving right now.


Volcan de Agua, Antigua Guatemala, Pop 46,054
~250,000 within 15 km of Agua.


Geology/Earth Sciences
Social Sciences
Chemistry
Volcanology
Maths
Physics


Geology / Earth Sciences
Plate tectonic processes
Palaeontology
Geotechnical engineering
Seismology & geophysics
Geochemistry
Volcanology
Hydrology
River systems
Biogeography
Sedimentary processes
Coastal systems
Ecology
Glacial systems
Quaternary science
Oceanography
Atmospheric systems
Physical geography
Soil Science
Food security
GIS
Disaster Response / Crisis Management
Climate adaptation
Renewable energy development (Wind, geothermal, nuclear)
Settlement
Population studies
Natural resources & economies
Health
Urbanisation
Tourism
Cultures
Histories
Social theory
Human geography

Thank you!

University of BRISTOL

GEOLOGY EARTH SCIENCE

https://earth-science.org.uk/teach-earth/