

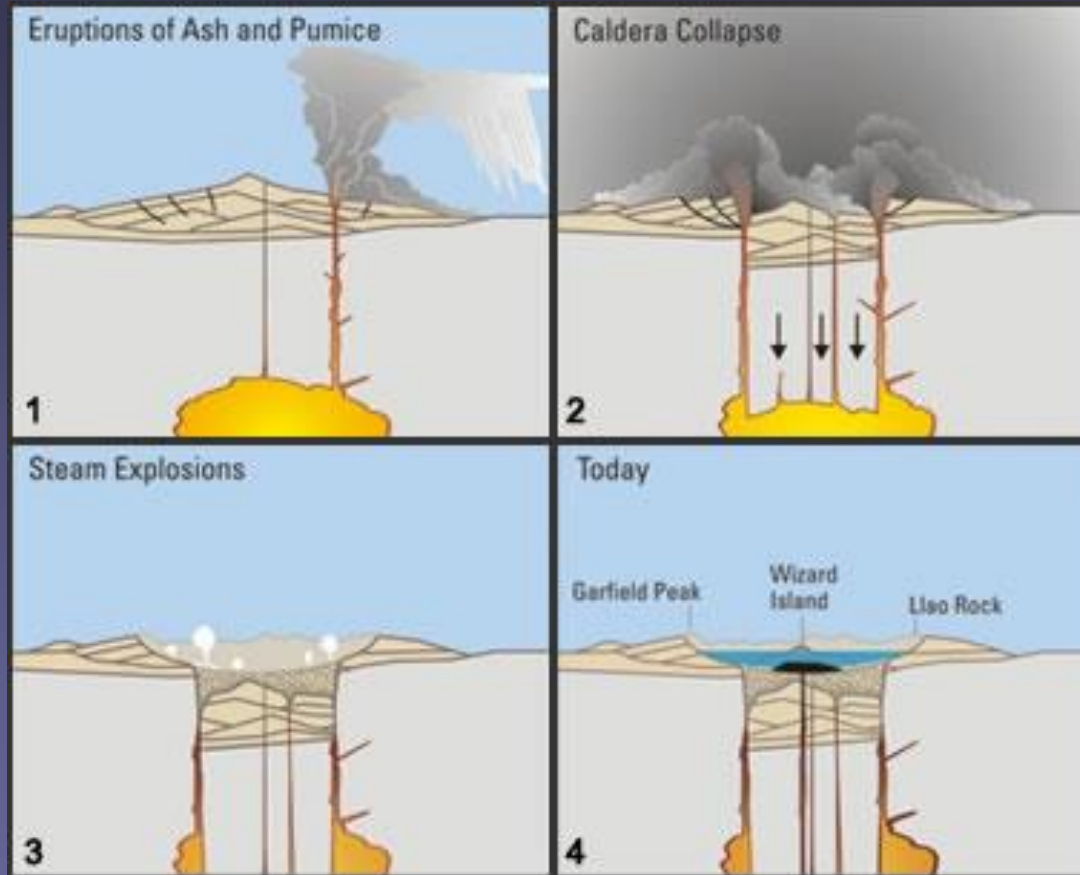
An aerial photograph of a caldera, showing a large, roughly circular depression in the ground. The surrounding landscape is covered in dense, colorful vegetation, primarily in shades of green and purple. A large, solid black silhouette of the caldera's rim is overlaid on the image, creating a stark contrast with the natural colors. The text is centered within this black area.

CALDERAS

the most devastating,
the least understood

Paolo Papale, INGV

Caldera formation mechanisms



Example from Crater Lake caldera, OR, US

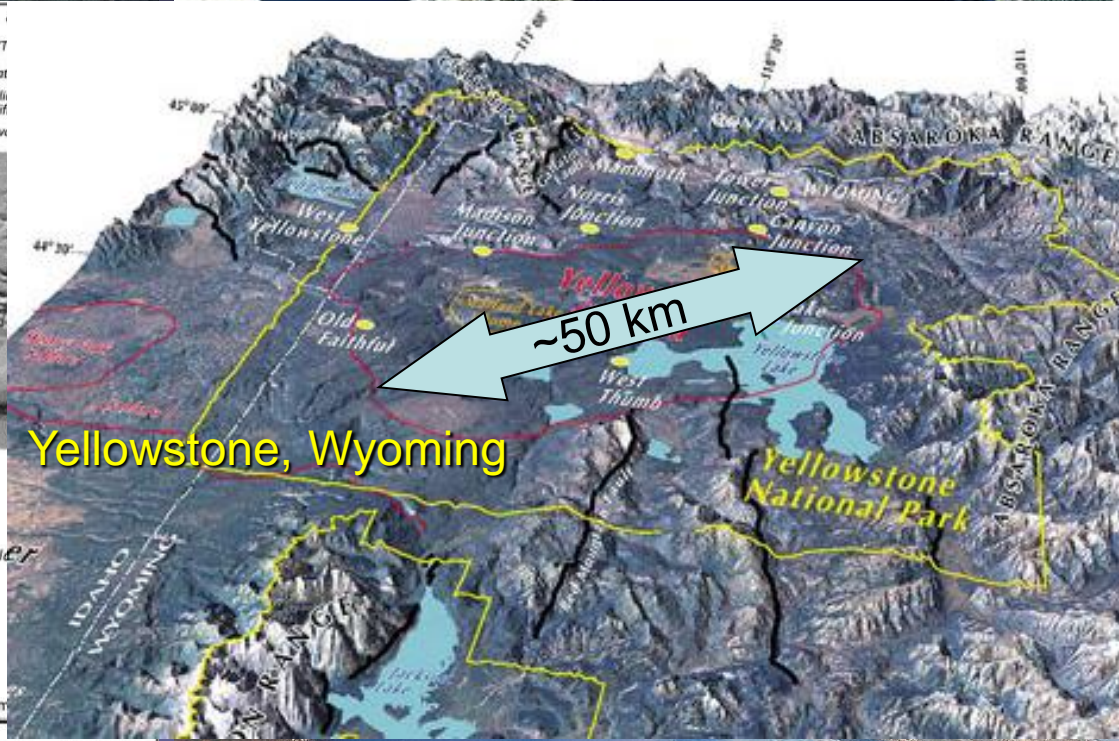
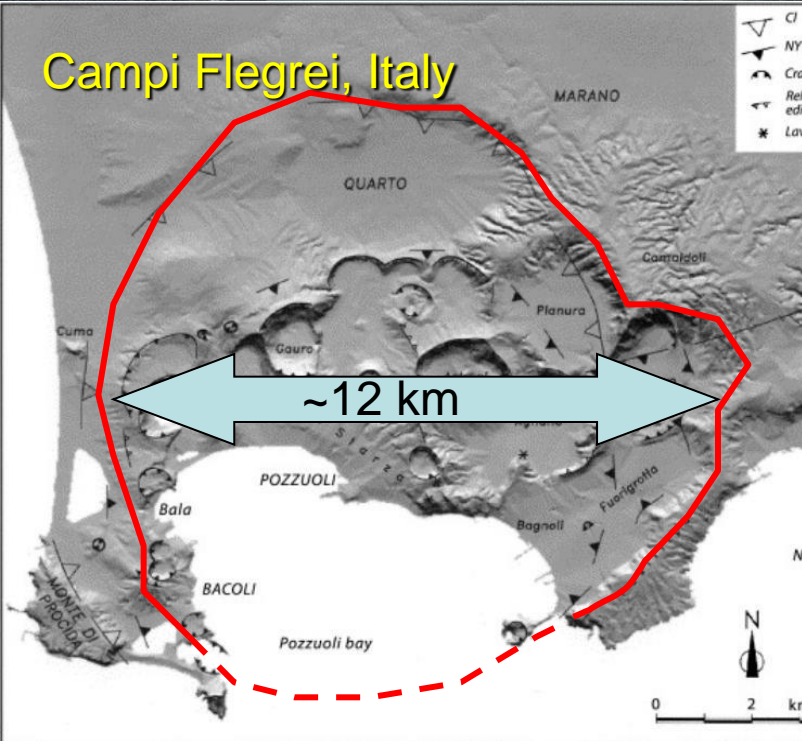
source: USGS



Aso, Japan



Crater Lake, Oregon



Kaguyak, Alaska



Santorini, Greece

Kanaga, Alaska



Fujii, Japan



STRATOVOLCANOES

Rainier, Washington

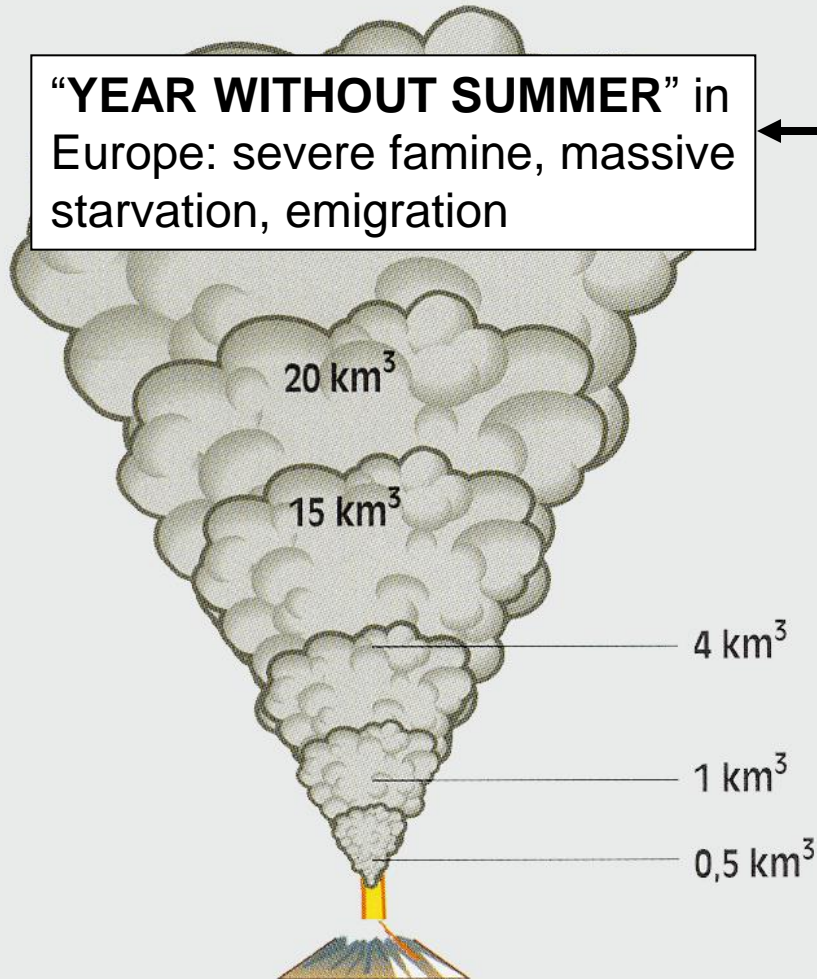


Cotopaxi, Ecuador



Erupted magma volumes in historical eruptions

“YEAR WITHOUT SUMMER” in Europe: severe famine, massive starvation, emigration



CALDERA formation

Tambora (*Indonesia*) 1815
Santorino (*Grecia*) 1500 a.C.

Krakatoa (*Indonesia*) 1883

Katmai (*Alaska*) 1912

Vesuvio (*Italia*) 79 d.C.
Pinatubo (*Filippine*) 1991

St.Helens (*USA*) 1980

Vesuvio (*Italia*) 1631
Mt.Pelè (*Martinica*) 1902
Etna (*Italia*) 1991-93

Plinian eruptions



Eyjafjallajökull, Iceland, 2010



Grimsvotn, Iceland, 2011



Puyehue, Chile, 2011



Puyehue, Chile, 2011



Kurili Islands, 2009



2800 km³

Toba, Indonesia, ~75,000 BP

> 2450 km³

Huckleberry Ridge Tuff, Yellowstone (WY), US, 2.1 My ago

> 500 km³

Taupo, New Zealand, 26,500 BP

300 km³

Campanian Ignimbrite, Campi Flegrei, Italy, 39,000 BP

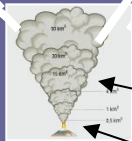
SUPER-ERUPTIONS

(>1000 km³)

Tambora, Indonesia, 1815

Piñatubo, Philippines, 1991

Eyjafjallajökull, Iceland, 2010

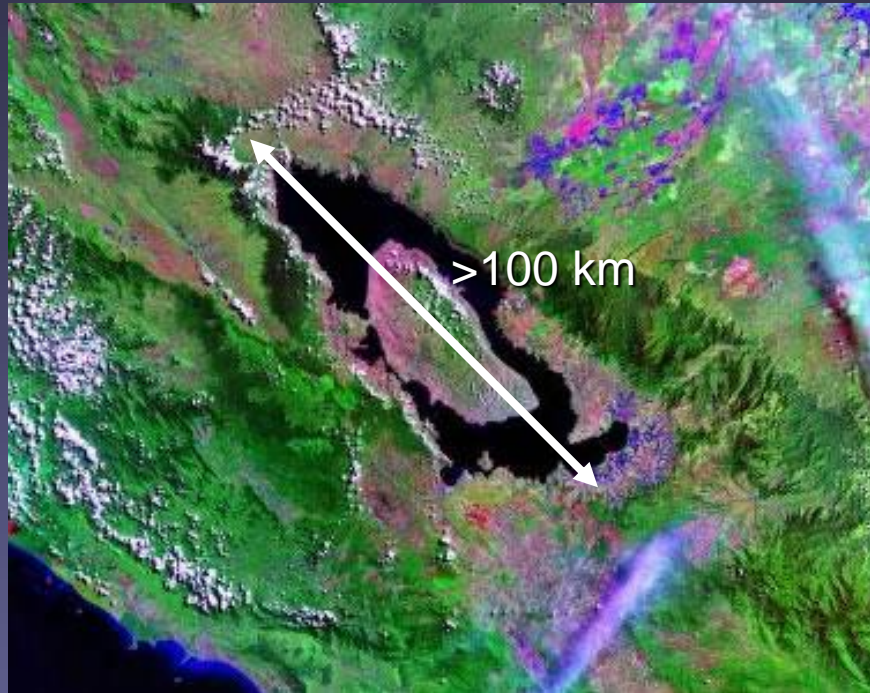


Landsat image of Toba caldera, Sumatra island, Indonesia

2800 km³ of magma

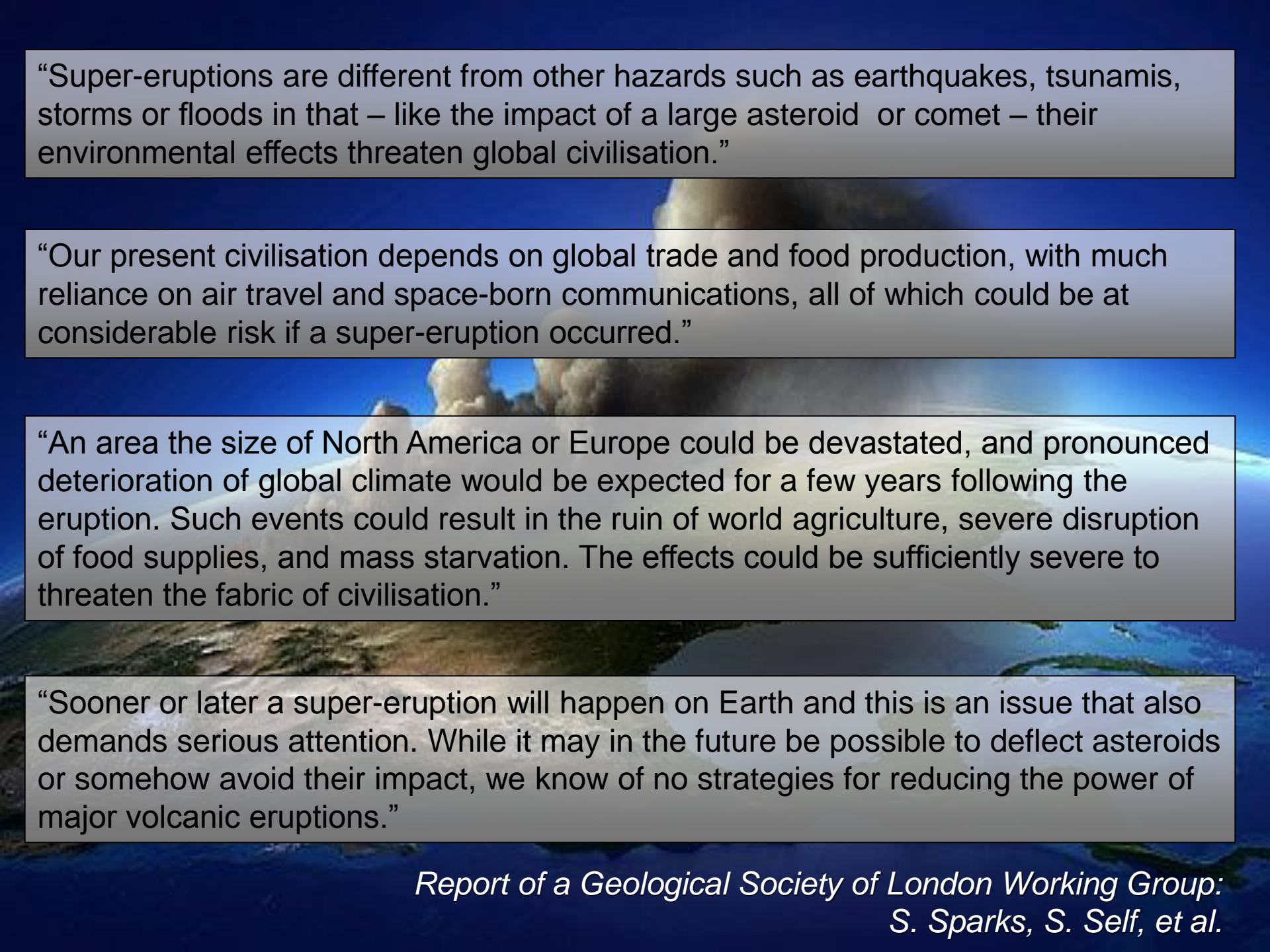
Mount St. Helens
1980: 2.8 km³

Piñatubo 1991: ~12
km³



The energy release can be estimated as 1,000 Hiroshima atomic bombs exploding every second (!!!)

The Toba eruption is associated to the Toba catastrophe theory: the eruption caused a 6 – 10 years global winter and possibly triggered a ~1000 years cooling period, nearly leading to extinction of several species; studies on human mitochondrium suggest that about 75,000 years ago humans were decreased to a few thousands units, providing an explanation to the poor genetic variability of our species



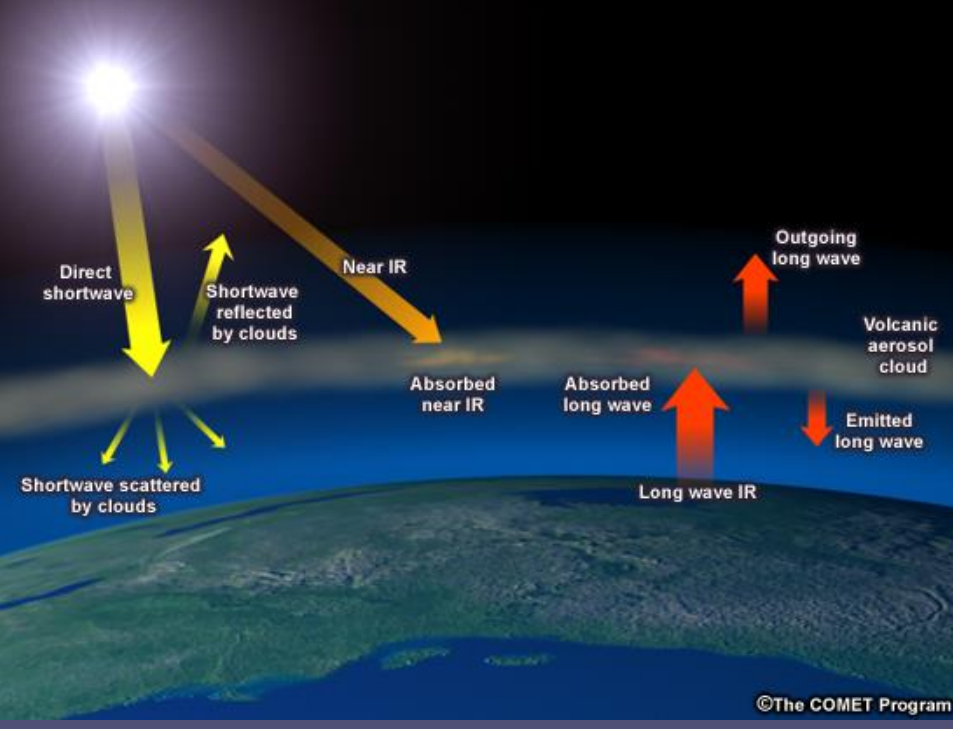
“Super-eruptions are different from other hazards such as earthquakes, tsunamis, storms or floods in that – like the impact of a large asteroid or comet – their environmental effects threaten global civilisation.”

“Our present civilisation depends on global trade and food production, with much reliance on air travel and space-borne communications, all of which could be at considerable risk if a super-eruption occurred.”

“An area the size of North America or Europe could be devastated, and pronounced deterioration of global climate would be expected for a few years following the eruption. Such events could result in the ruin of world agriculture, severe disruption of food supplies, and mass starvation. The effects could be sufficiently severe to threaten the fabric of civilisation.”

“Sooner or later a super-eruption will happen on Earth and this is an issue that also demands serious attention. While it may in the future be possible to deflect asteroids or somehow avoid their impact, we know of no strategies for reducing the power of major volcanic eruptions.”

*Report of a Geological Society of London Working Group:
S. Sparks, S. Self, et al.*



Volcanic ash

Fine volcanic ash can remain suspended in the atmosphere for months to years and be dispersed worldwide. Ash shades sunlight and cause **cooling** over large areas of the Earth.

Sulphur

Sulfur dioxide discharged into the atmosphere is **much more effective** than ash particles at cooling the climate. Sulfur dioxide combines with water to form sulfuric acid aerosols. The sulfuric acid makes a haze of tiny droplets in the stratosphere that reflects incoming solar radiation, causing **cooling** of the Earth's surface. The aerosols can stay in the stratosphere for up to three years, moved around by winds and causing significant cooling worldwide.

Greenhouse gases

Volcanoes also release large amounts of greenhouse gases such as water vapor and carbon dioxide. The amounts put into the atmosphere from a large eruption don't change the global amounts of these gases very much. However, there have been times during Earth history when intense volcanism has significantly increased the amount of carbon dioxide in the atmosphere and caused **global warming**.

Piñatubo, Philippines, 1991



Height: 40 km

SO₂ injection: 17 Mtons

- Largest perturbation to the stratospheric aerosol since Krakatau 1883
- The aerosol rounded the globe in 3 weeks, and attained global coverage in 1 year, causing a dramatic decrease in the amount of net radiation reaching the Earth surface
- Cooling of Northern Hemisphere of up to 0.5 – 0.6 °C

The Piñatubo climate forcing was stronger than the opposite, warming effects of either the El Niño event or anthropogenic greenhouse gases in the period 1991-93.

As a result of the presence of the aerosol particles, midlatitude ozone concentrations reached their lowest levels on record during 1992-93, the Southern Hemisphere "ozone hole" increased in 1992 to an unprecedented size, and ozone depletion rates were observed to be faster than ever before recorded.

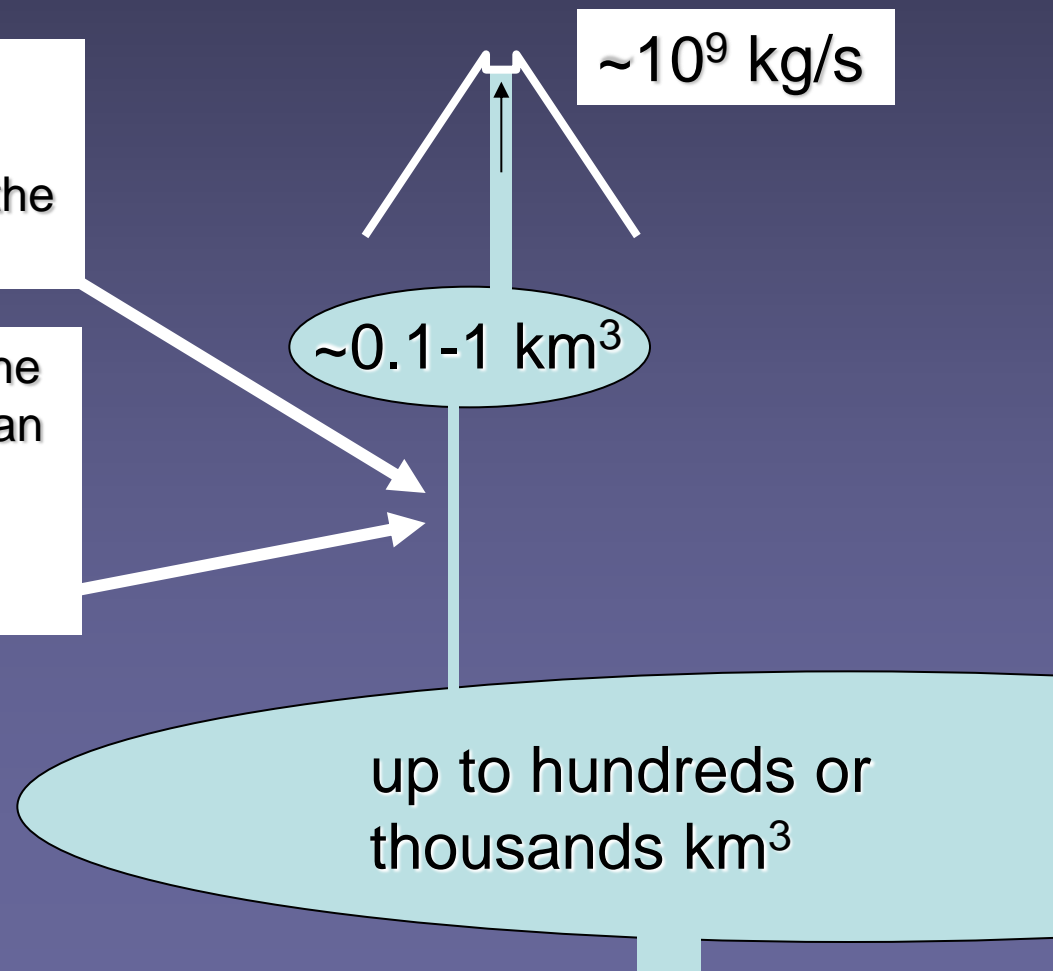
One of the most critical problems in volcanology:

There is not yet a confident method to estimate the scale of a likely or imminent eruption from the pre-eruptive observations

If the flux is not sustained here, the pressure in the shallow system is destined to rapidly decrease closing the eruption

If instead the flux is sustained here, the magma in the deep, large reservoir can be discharged abundantly before pressure decrease leads to caldera formation

The efficiency of deep interconnections is critical in determining the size and impact of an eruption



A second critical problem in volcanology

Anticipating the occurrence of an eruption at calderas is far more difficult than for typical stratovolcanoes



Campi Flegrei caldera, in Italy,
and the city of Naples, 3
million people

CALDERAS: why are they different?

- The structure of calderas is profoundly different from that of stratovolcanoes

- “negative” as opposed to “positive” edifice
- boarder faults
- chaotic rock assemblage
- development of large geothermal circulation
- resurgency
- compressional/extensional portions
- several distinct post-collapse vents
- ...

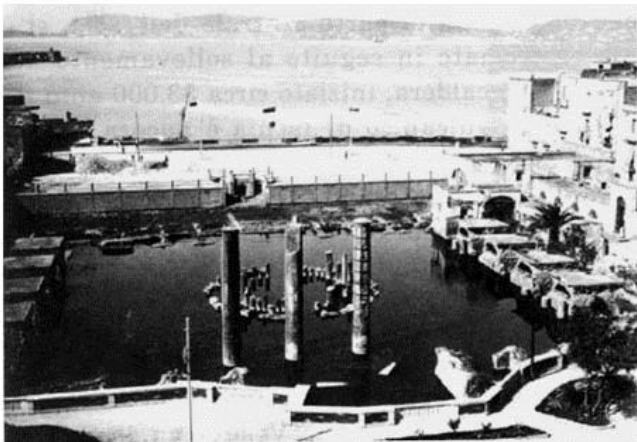
CALDERAS: why are they different?

They often display unrest dynamics that if observed at central volcanoes, they would almost certainly culminate into an eruption

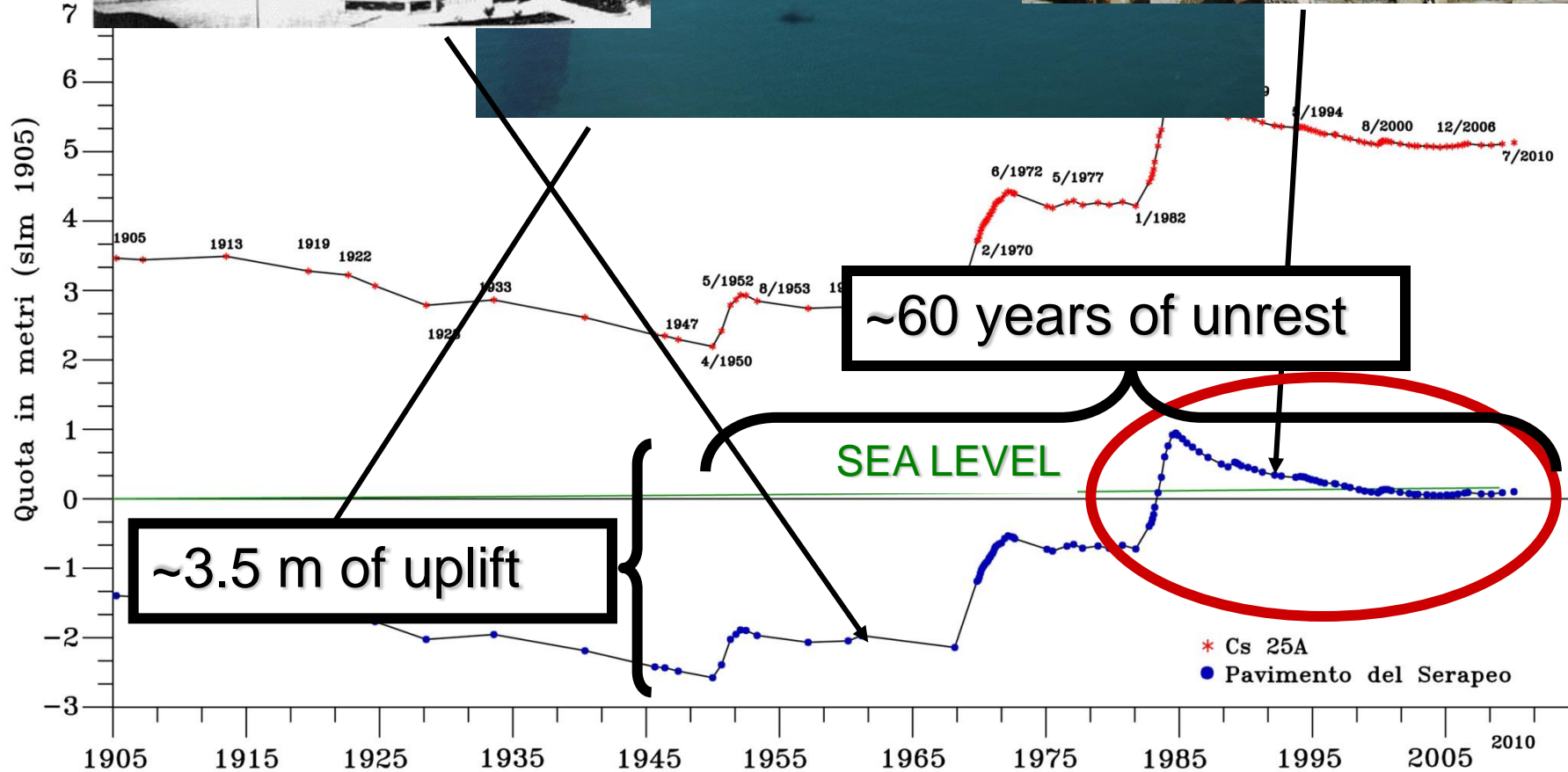
Observations that are often reported as “critical” for near-term eruption forecast:

- acceleration in seismicity
- acceleration in deformation
- increase of gas fluxes, especially CO₂ flux (and concentration)

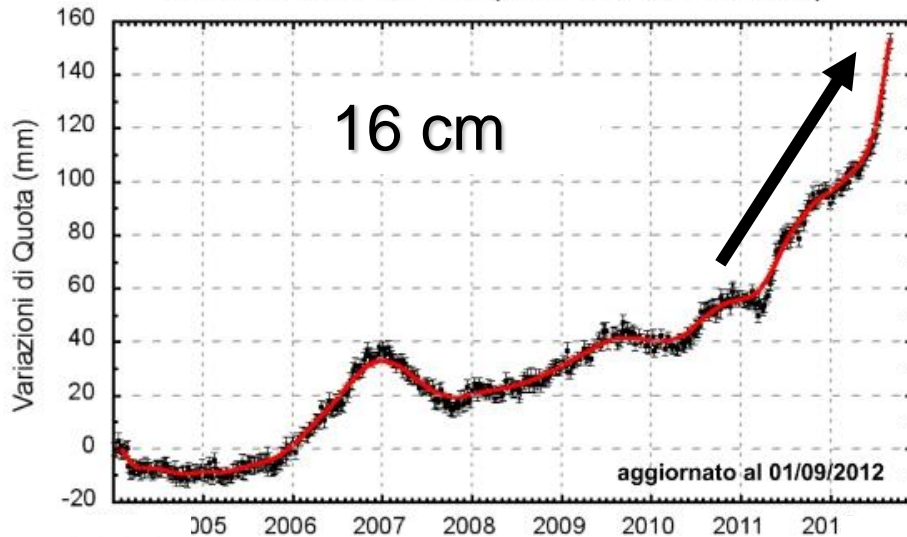
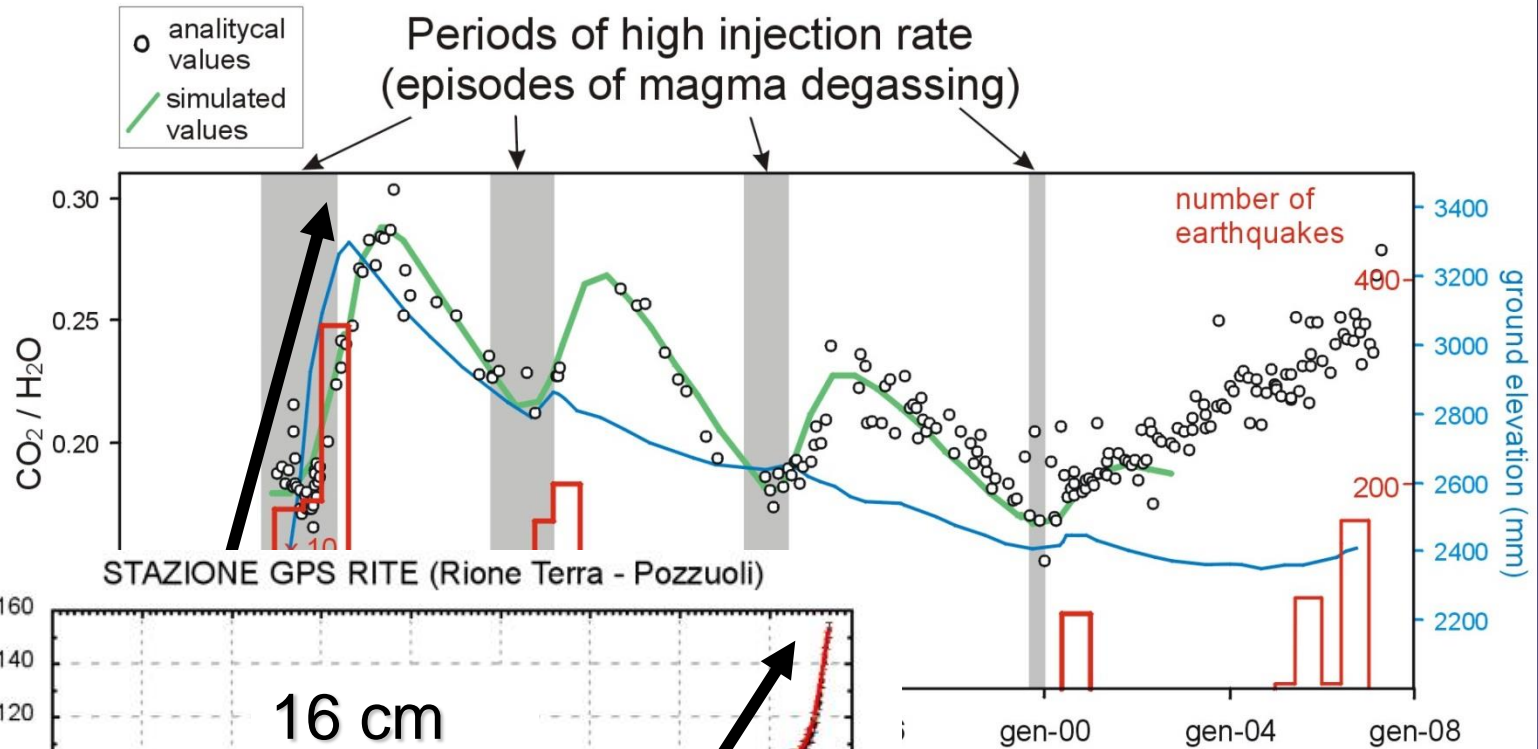
Are they equally diagnostic / critical at calderas?



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Campi Flegrei caldera, Italy



2004

2013

From *Chiodini et al., 2008.*

RABAUL caldera, Papua New Guinea



“The eruption began on September 18, **after less than a day of intense seismicity...**”

“The people who lived there were reminded of the inevitability of an eruption by intense earthquake activity and uplift of the ground within the caldera in the mid-1980's.”

“However, despite warnings and a declared stage-2 emergency in 1983 and 1984, Rabaul did not erupt and, in fact, **activity waned and remained at low levels until hours before the latest eruption broke out...**”

Source: http://hvo.wr.usgs.gov/volcanowatch/1994/94_09_23.html

CALDERAS: the “hot” questions

- what's the relative roles of magma and hydrothermal circulation in determining unrest dynamics at calderas?
- why so often large unrest dynamics do not culminate in an eruption, whereas instead variations much smaller in duration and amplitude may do?
- how to anticipate the occurrence of eruptions at calderas?

THE FACTS

Large to monster-size caldera-forming eruptions happen!

We do not have (or only have very limited) direct experience of them

Their impacts are global, and can be devastating. There's no large-scale, regional or global resilience plan in place, anywhere

Our capability to anticipate them is limited (no previous instrumental observations; on a lower scale, no confident methods to anticipate the scale of the eruption; large uncertainties in eruption forecasts at calderas)

WE ARE NOT PREPARED!

WHAT TO DO?

*Report of a Geological Society of London
Working Group: S. Sparks, S. Self, et al.*

“Although at present there is no technical fix for averting super-eruptions, improved monitoring, awareness-raising and research-based planning would reduce the suffering of many millions of people.”

“**Preparedness** is the key to mitigation of the disastrous effects of a super-eruption.”

Investment in research to improve our understanding of regional and global impacts of major volcanic eruptions” [and] “to determine more accurately the composition and amount of volcanic gases and dust released in super-eruptions;”

“An expanded programme to produce comprehensive **inventory of large magnitude explosive eruptions** in recent geological times”

“Initiatives to improve **public understanding** of the nature of volcanic hazards.”

“Establishment of a **multidisciplinary Task Force** to consider the environmental, economic, social, and political consequences of large magnitude volcanic eruptions.”

My addition:

Promotion of regional-scale and global-scale **resilience plans**, to be managed by regional governments (e.g., the U.S. Federal Government; the European Community; etc.) and international organizations (e.g. the United Nations)

Forecasts at calderas are generally characterized by **uncertainties** much larger than for central volcanoes!

Campi Flegrei – Pre-eruptive Event Tree

ELICITATION V		BACKGROUND	Gray area	UNREST	Gray area	MAGM. UNREST	Gray area	ERUPTION
VT (M > 0.8)	[ev/day]	5	15					
LP/VLP/ULP	[ev/month]	2	10					
Rate uplift	[cm/month]	0.7	1.3					
Uplift	[cm]	2	6	6	15			
T Pisciarelli		100	110					
VLP/ULP				1	5			
Deep VT (M > 0.8)	[ev/day]			2	20			
Deep LP (> 2 Km)	[ev/day]			3	20			
Disp. Hypocenters	[km]						1	3
Tremor								YES
Deep Tremor (>3.5 Km)						YES		
Acc. seismic events								YES
Acc. RSAM								YES
New fractures								YES
Macr. (dm)								YES
variation in def.								YES
Migr. max uplift								YES
Ext degassing				YES				
Magm. comp. gases						YES		
HF - HCl - SO2						YES		YES
Phreatic activity								YES

DELPHI METHOD

Red parameters: Seismicity

Green parameters: Deformation

Blue parameters: Geochemistry

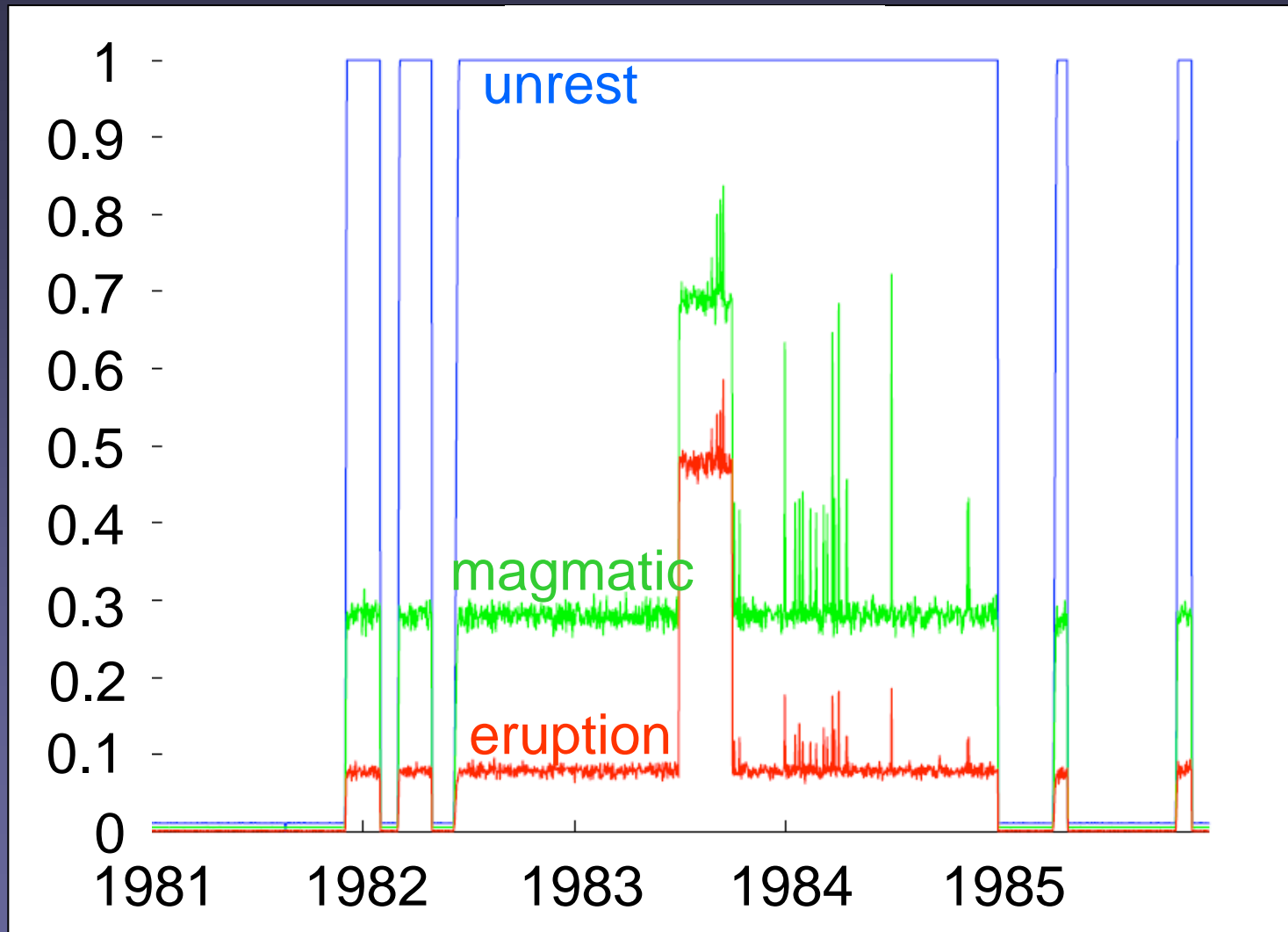
Boolean parameters are represented by "YES"

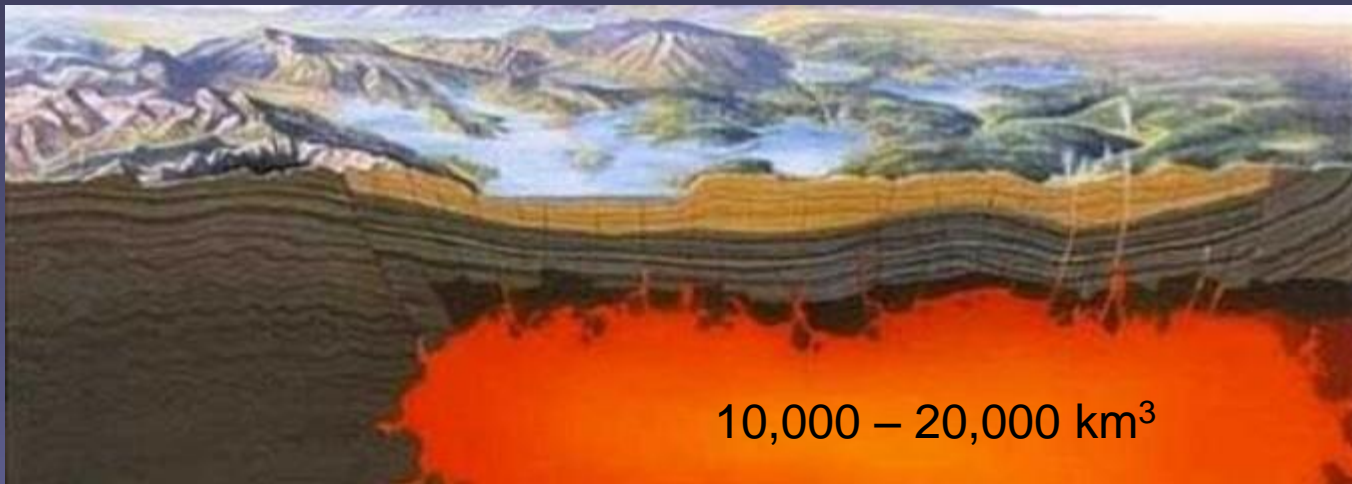
"Gray areas" correspond to variable probability of being in the adjacent states, depending on the measured values

after Selva et al., 2011

Probabilistic approach to eruption forecast

Application to Campi Flegrei crisis 1982-1984





Yellowstone National Park



Image: Sean Callinan Source: News Limited



Iceland at noon, during the Eyjafjallajökull eruption, Iceland, in 2010

Creative Commons Gunnlaugur P. Briar



Ash-covered, devastated landscape after the 1991 Piñatubo eruption, Philippines