What have we Learnt on Earthquakes and Volcanic Eruptions over the Last Years?

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Past Appointments

- Deputy Director of the Institute de Physique du Globe de Paris, Head of the IPGP observatories
- Head of the Seismology Department at the Institute de Physique du Globe de Paris
- …

Principal Investigator of Grants funded by:

- European Research Council
- Agence National de la Recherche, France
- National Science Foundation, USA
- …

A few words about seismic/volcanic hazard and risk

$$\text{risk} = \text{hazard} \otimes \text{vulnerability} \otimes \text{cost}$$

Hazard is the physical loading from natural phenomena, i.e., ground shaking, tsunami wave, volcanic ash fall …

Vulnerability id the degree of damage caused by various levels of loadings

Risk is expressed in terms of economic cost , loss of lives or environmental damage

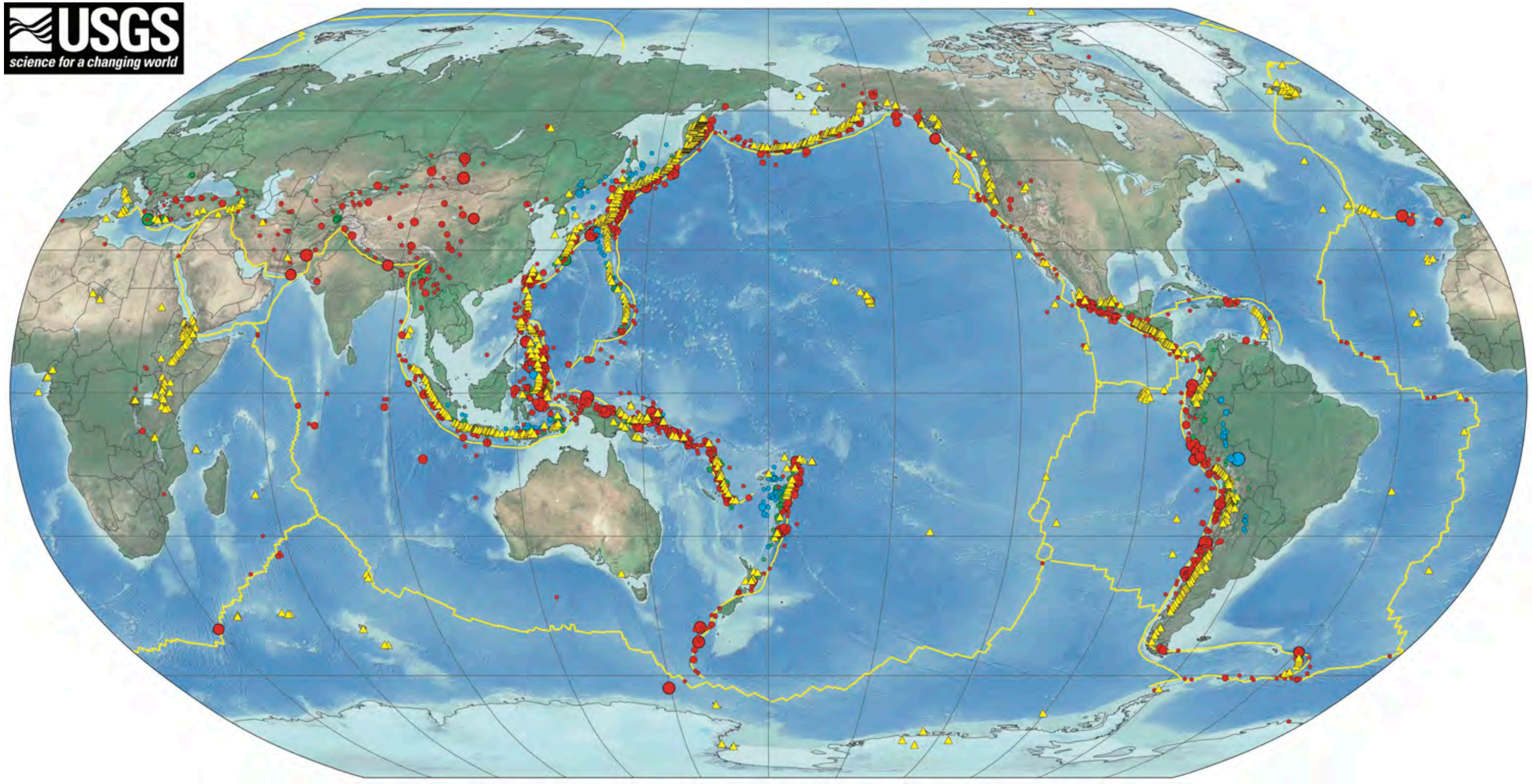
The job of **geophysicists** is not to assess risk but hazard

Assessment of seismic/volcanic hazard is based on:

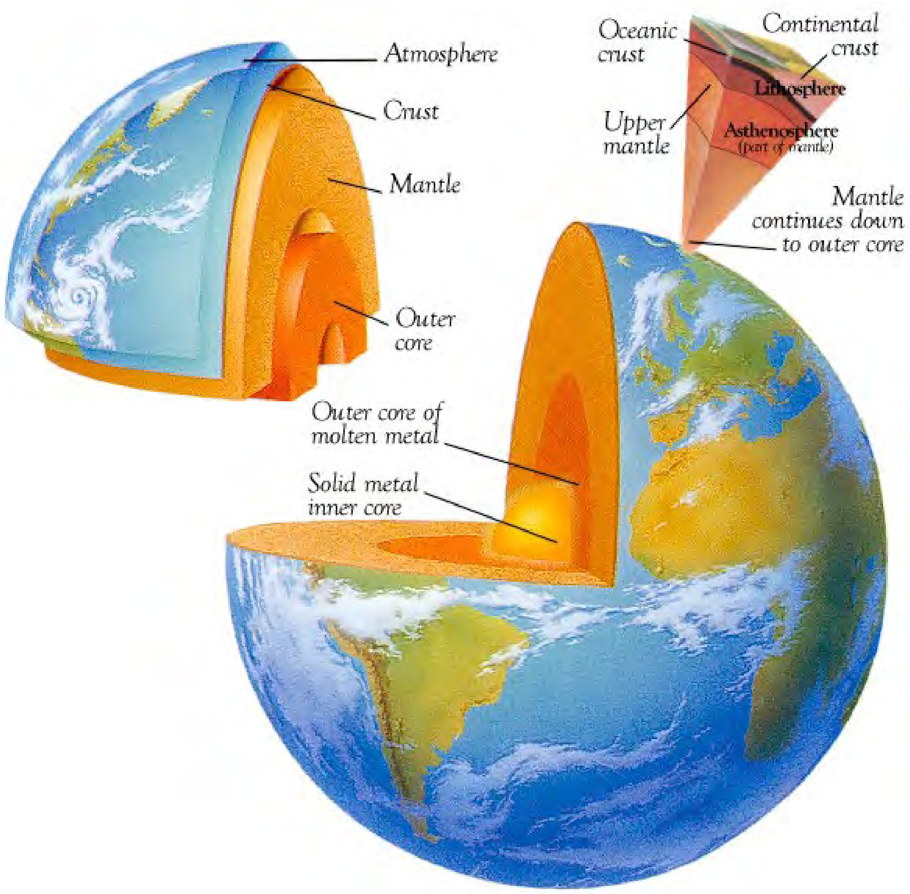
scope of today's presentation

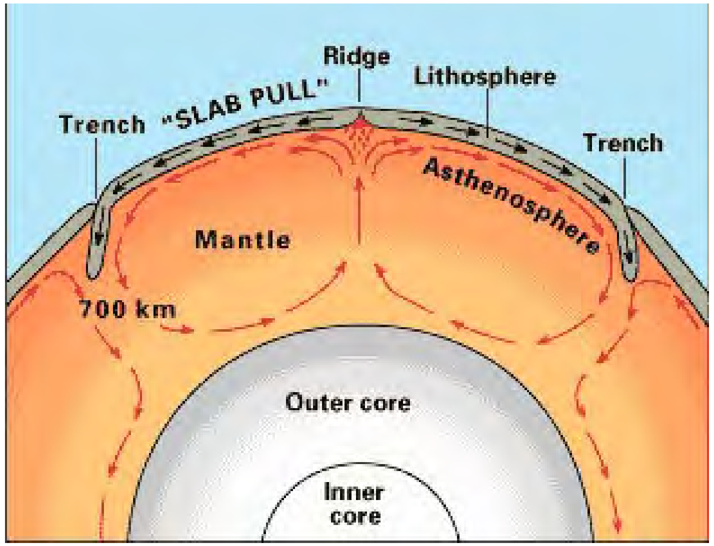
- empirical evidence (**observations**)
- physical understanding of the functioning of earthquakes/volcanoes (**models**)

Distribution of earthquakes and volcanoes



Earth’s interior structure and dynamics





Mantle convection

heat sources:

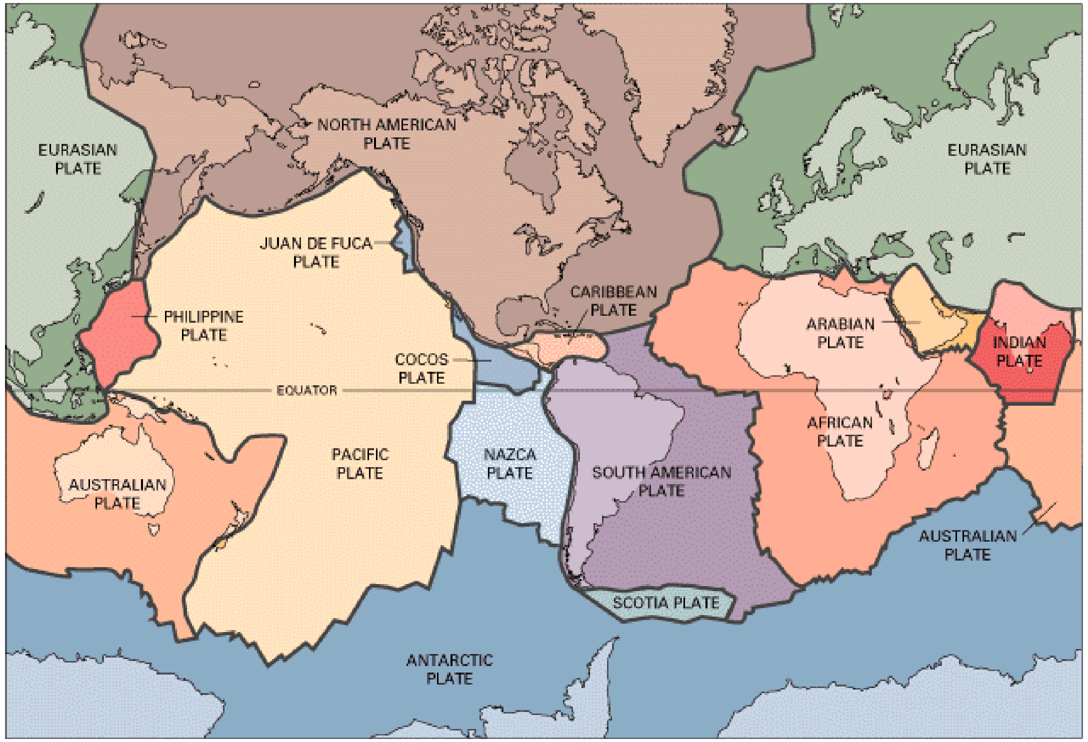
- decay of radioactive elements
- heat left over from Earth's formation

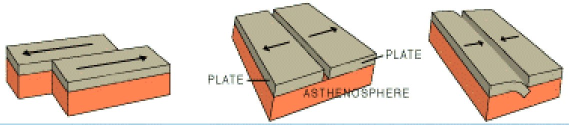
very slow process:

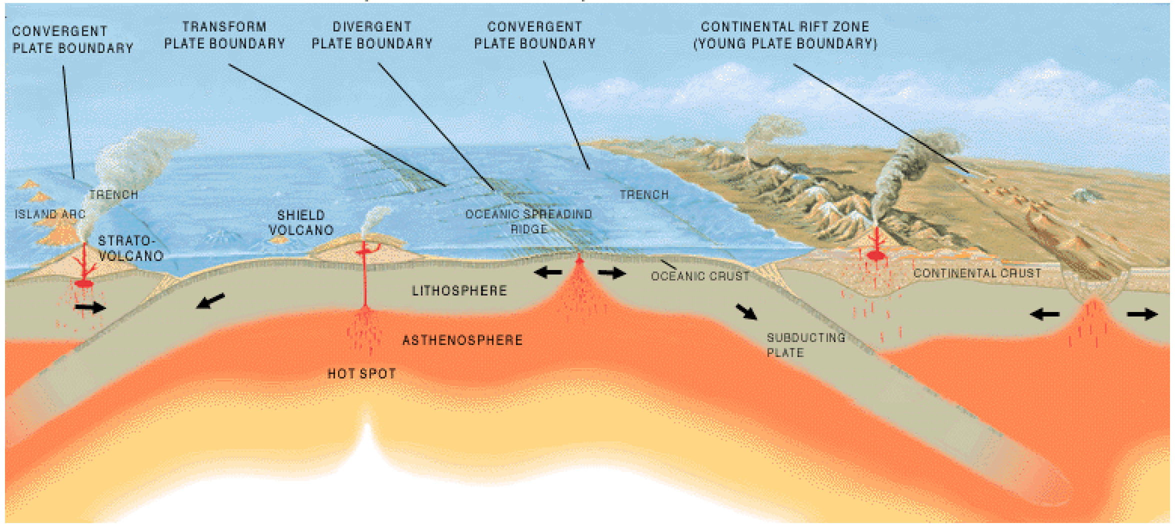
mantle flow ~ cm/year

plate tectonics

surface manifestation
of mantle convection







relative plate motion results in mechanical stresses and faulting within the outer layer of the Earth, the **lithosphere**, which is cool enough to behave as a more or less rigid shell

Challenges with understanding global seismic and volcanic cycles

Ideal "full" solution:
<u>complete physical model</u> of the whole Earth, i.e., very heterogeneous and non-stationary dynamic system with a $4.5*10^9$ years history and a $\sim5*10^8$ years convection cycle

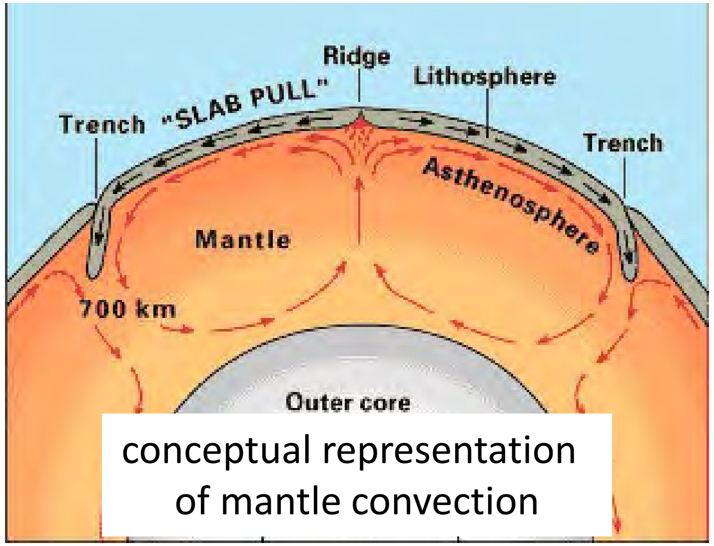
Our <u>observations</u> allowed to sample less than 0.004% of its volume during 0.00005% of it's time history

<u>Laboratory experiments</u> differ from natural systems by several orders in space and time scales

We still know very approximately what is inside and how it has been formed and is functioning

Our "physical models" often are educated guesses verified with limited sets of observations

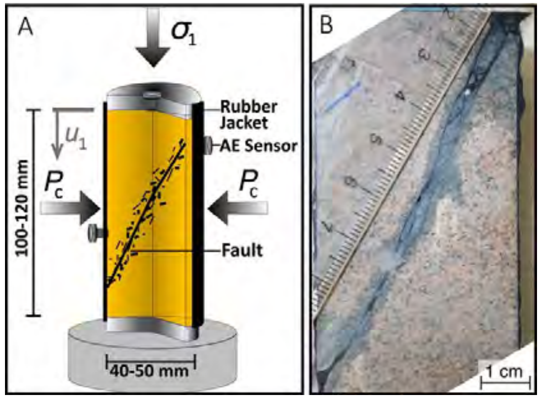
Predictive models for applications (i.e., hazard) should be as close as possible to **empirical information**

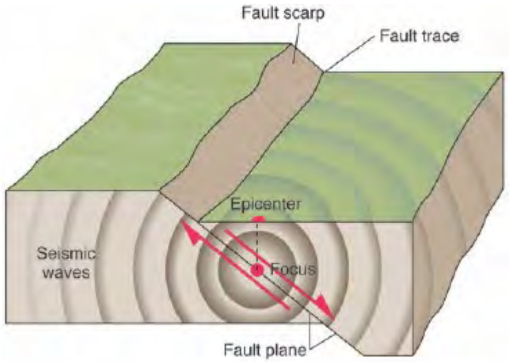


conceptual representation of mantle convection

laboratory "fault"

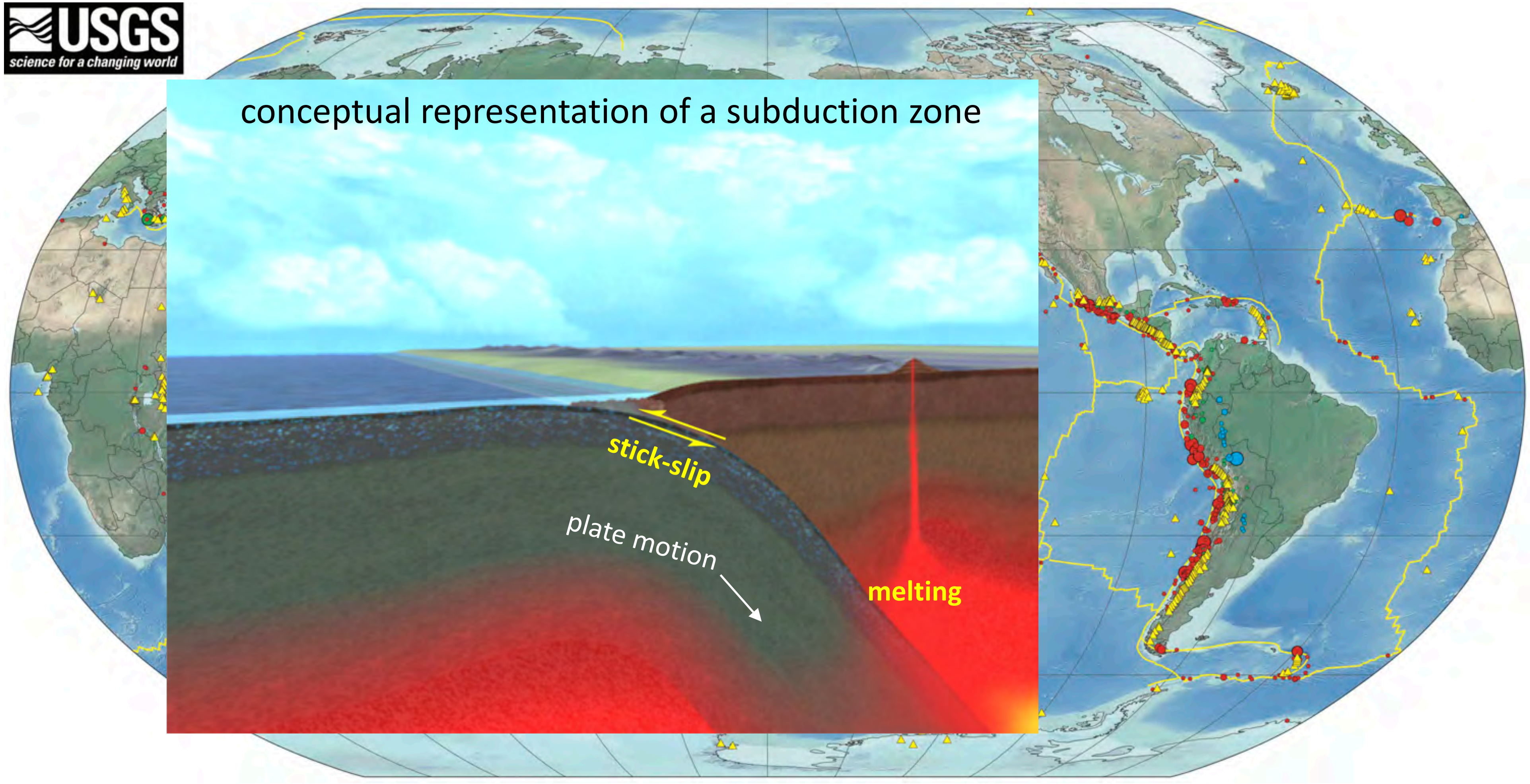
fault roots exhumed from ~40 km depth





idealized representation of a seismic fault in many models

Distribution of earthquakes and volcanoes



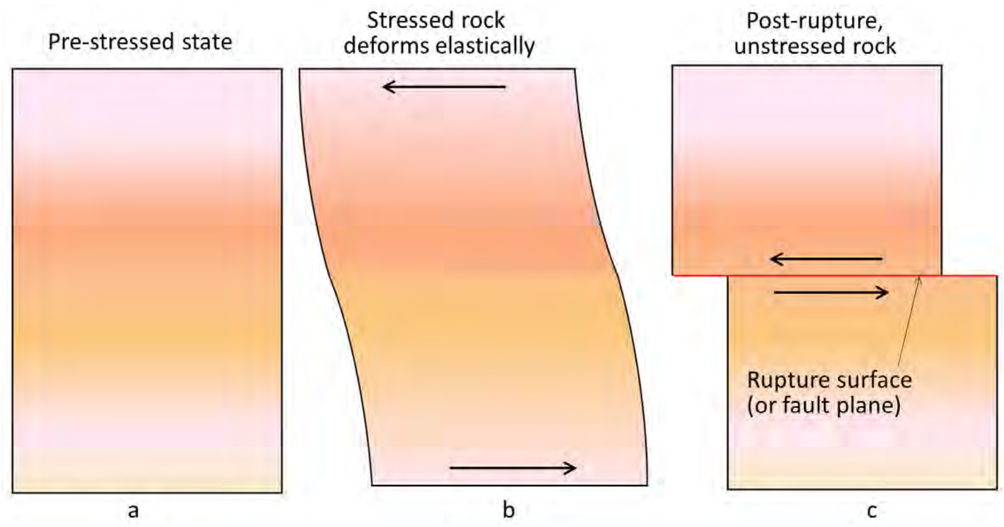
More than 90% of earthquakes and volcanoes occur in subduction zones

Physical concepts of earthquakes and volcanoes

Earthquakes

Frictional sliding and stick-slip

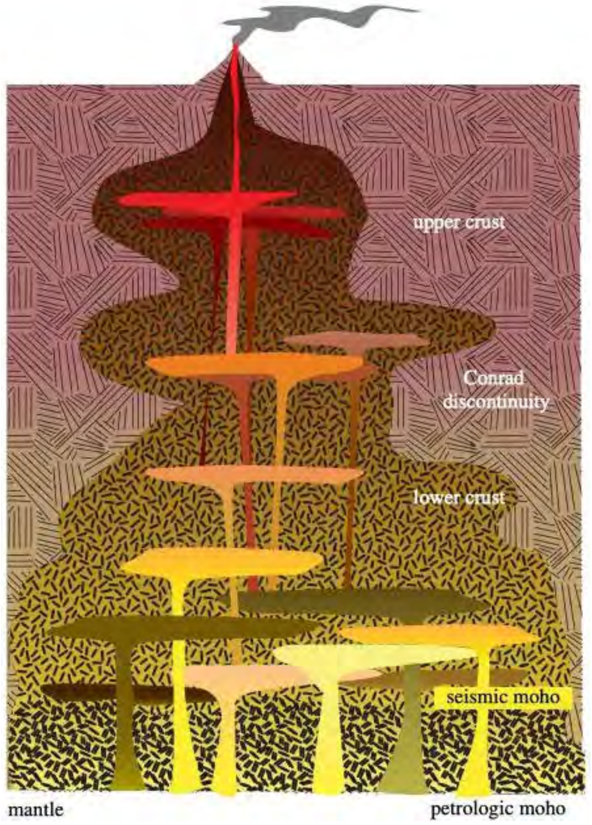
At first order – mechanical process



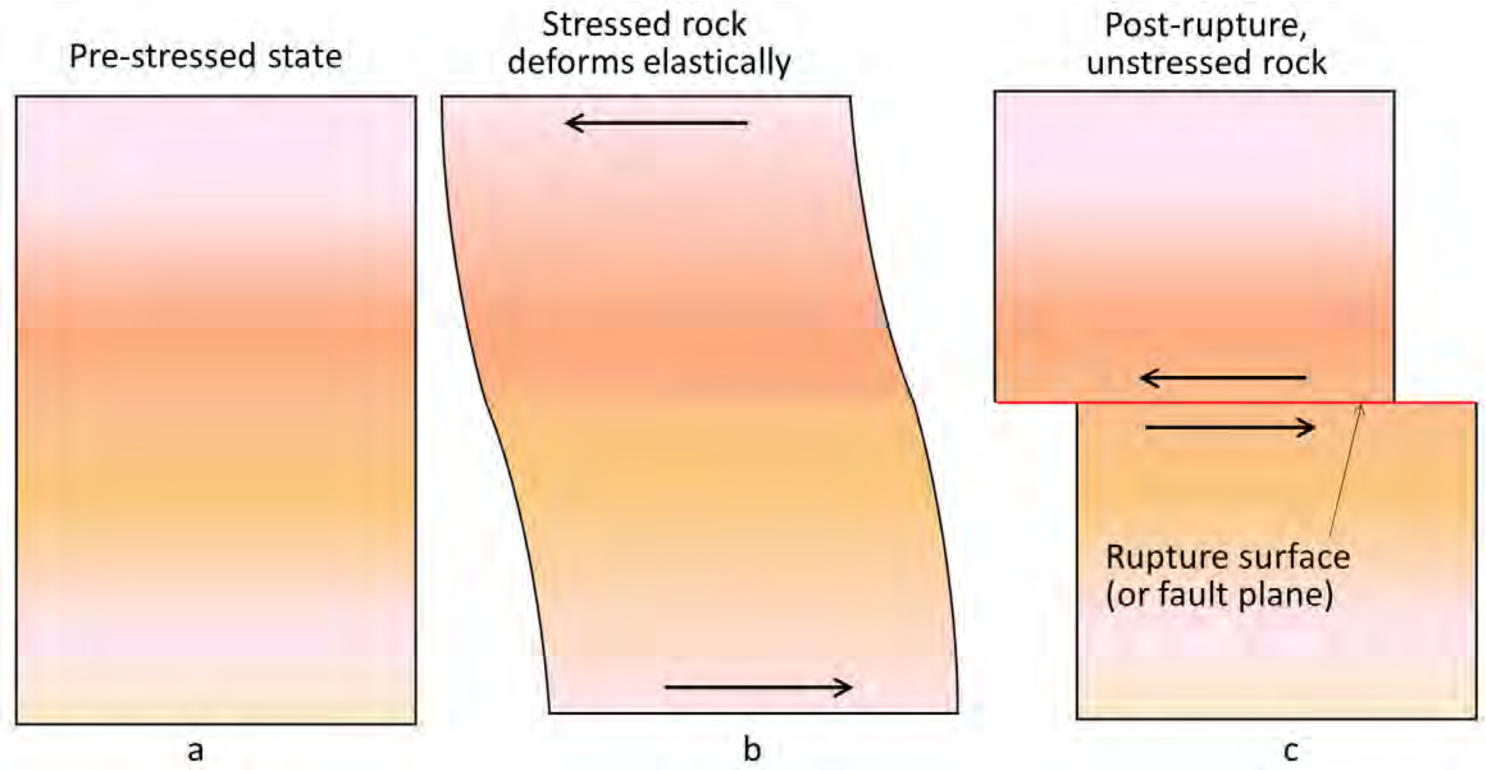
Volcanoes

Melting, magma migration and differentiation, degassing …

Complex mechanical and chemical processes

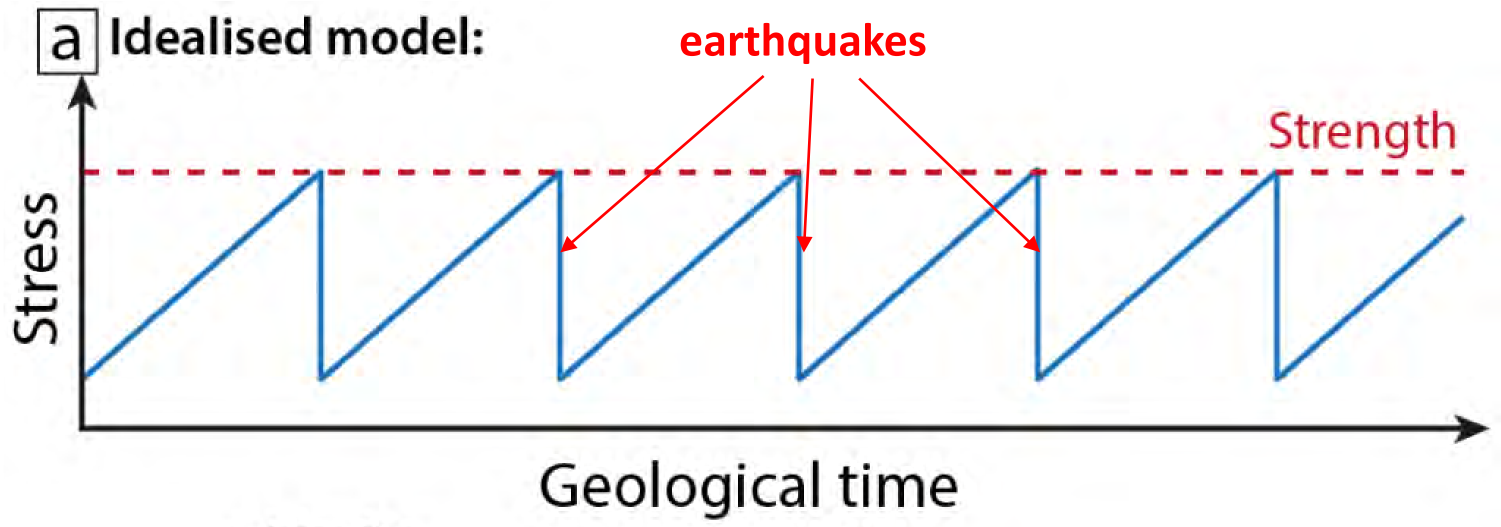


Earthquakes as a “stick-slip” phenomena



Earthquakes as a “stick-slip” phenomena

Seismic cycle



Observation of earthquakes

Fault scarps can be observed for a few strong and shallow earthquakes

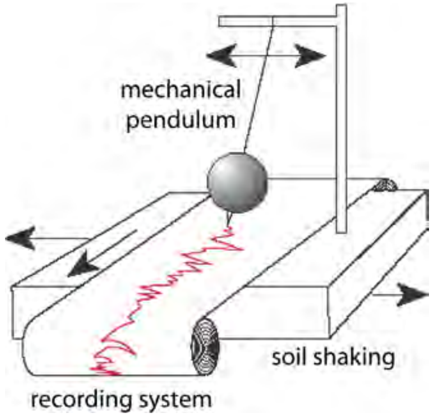
2002 Denali earthquake, Alaska

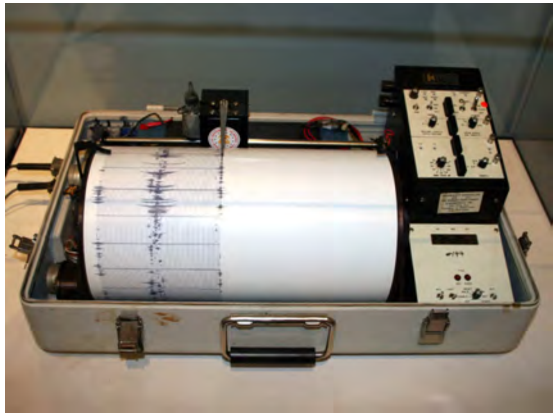
Figure 4.1-1: San Andreas fault in the Carrizo Plain.

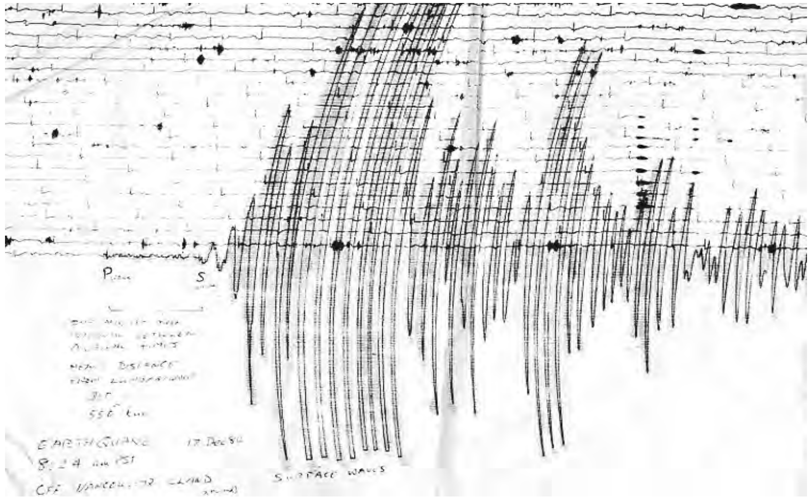
For most of earthquakes, **instrumental observations** are needed

Observation of earthquakes

Seismologicalc data: records of the motion of the Earth's surface by **seismographs**

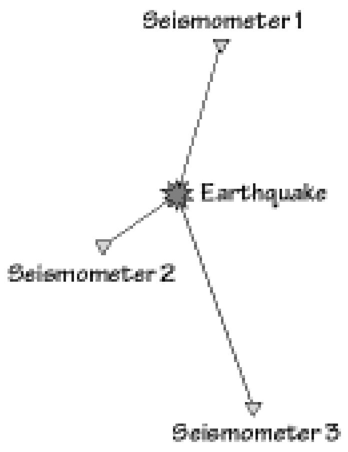


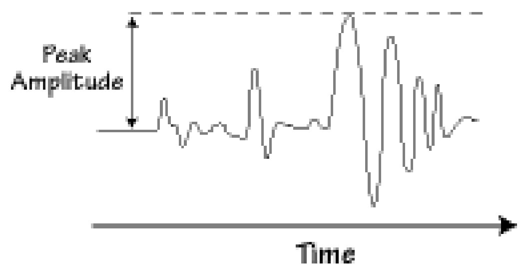


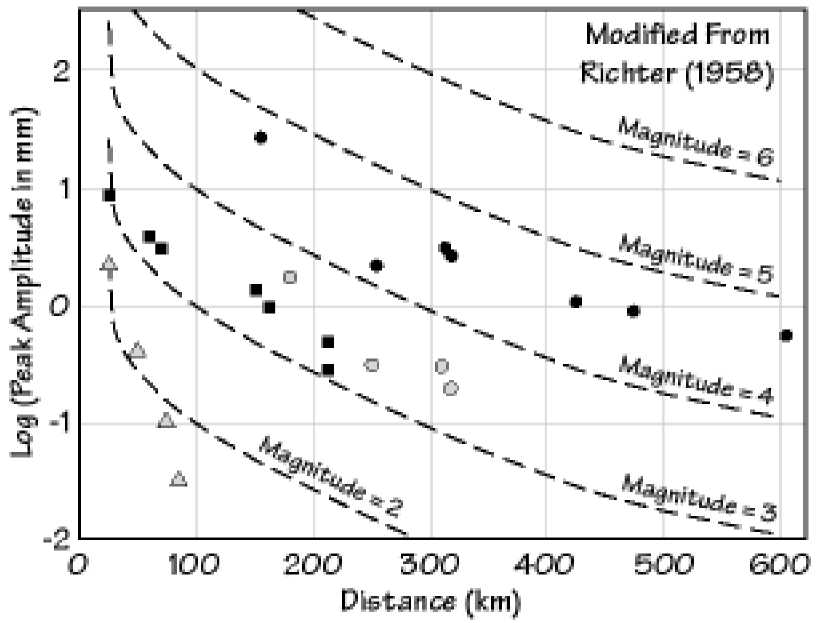


- Regular seismic records started at the end of 19-th century
- Till 1980s most of instrument had "analogous" recording system (low quality)
- In 1990s **continuous digital records** started to be systematically collected

Size of an earthquake is characterized by magnitude M

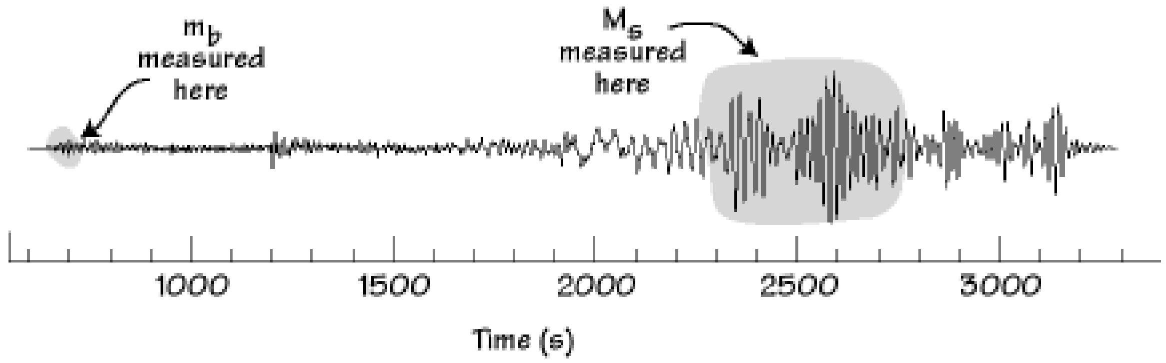






$$M_L = \log_{10}A + 2.76 \log_{10}D - 2.48$$

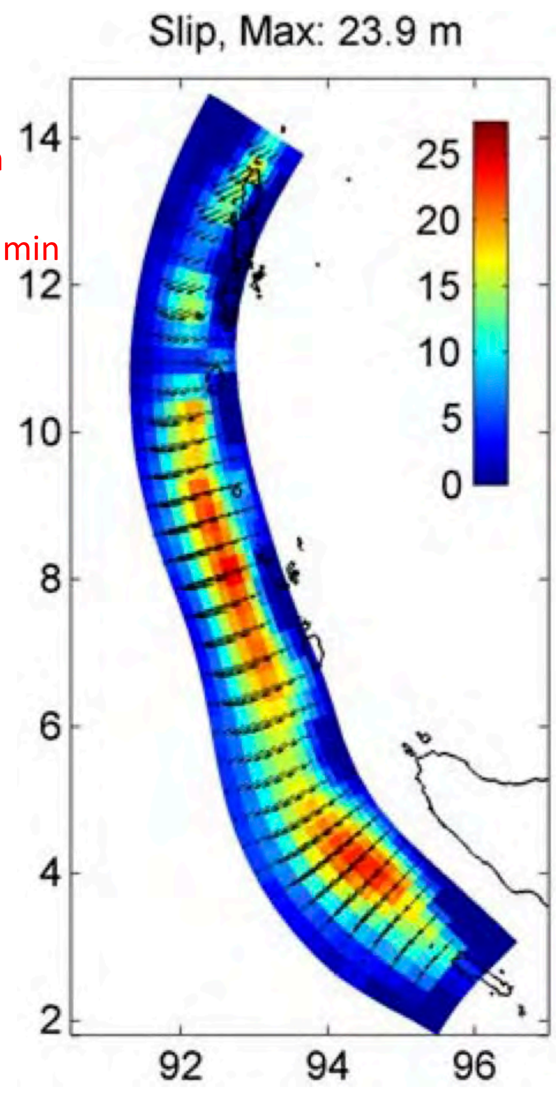
Richter, 1935



Earthquakes sizes and magnitudes

2004 Sumatra earthquake
Magnitude M = 9.1, rupture area >10^5km^2

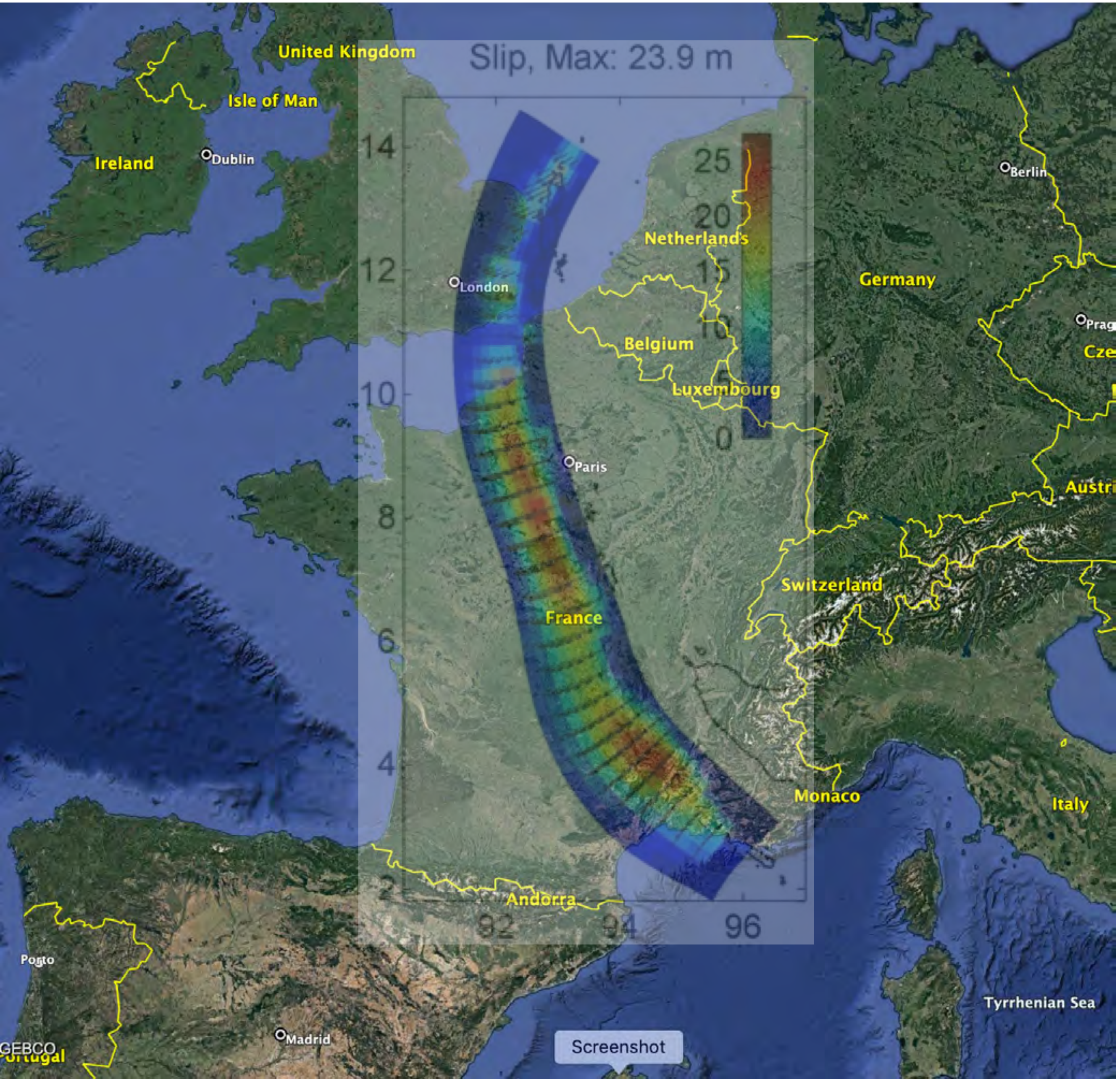
Rupture length ~ 1300 km
Rupture speed ~ 2 km/s
Earthquake duration ~ 10 min



Typical M = 5 earthquake
ruptures area of a few km^2

2004 Sumatra earthquake
Magnitude M = 9.1, rupture area >10^5km^2

Earthquakes sizes and magnitudes



Typical M = 5 earthquake
ruptures area of a few km^2

$$\mathbf{M} = \log \mathbf{S} + \text{const}$$

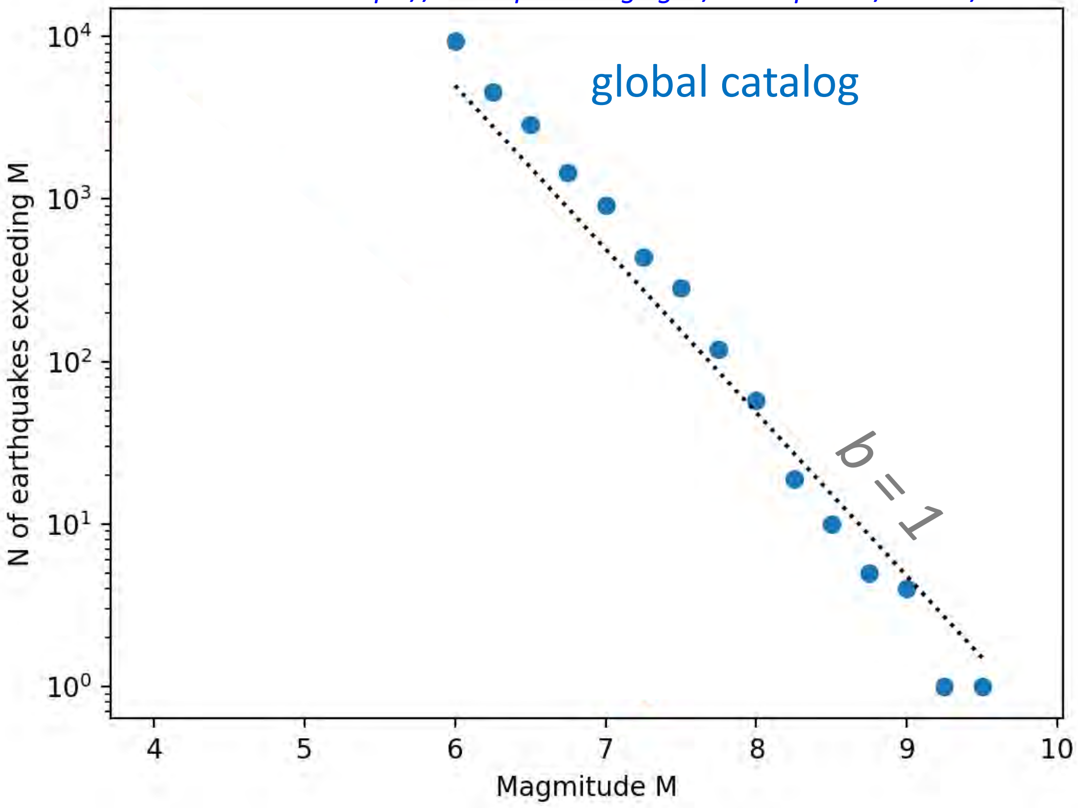
magnitude rupture area

Gutenberg-Richter law (1935)

$$\log N = a - \mathbf{b}\, M$$

earthquakes between 1955 and present

data from: *https://earthquake.usgs.gov/earthquakes/search/*



Earthquakes are **planar** objects (occur on **fault planes**)

Natural geometrical characteristics of the **size** is:

surface of ruptured fault area **S**

M>9 **S** > 10^5 km^2 (15% of mainland France)

M=5 **S** a few km^2

It is simply scaled with the magnitude:

M = log **S** + const

Gutenberg-Richter law with **b=1** implies:

N ~ 1/**S**

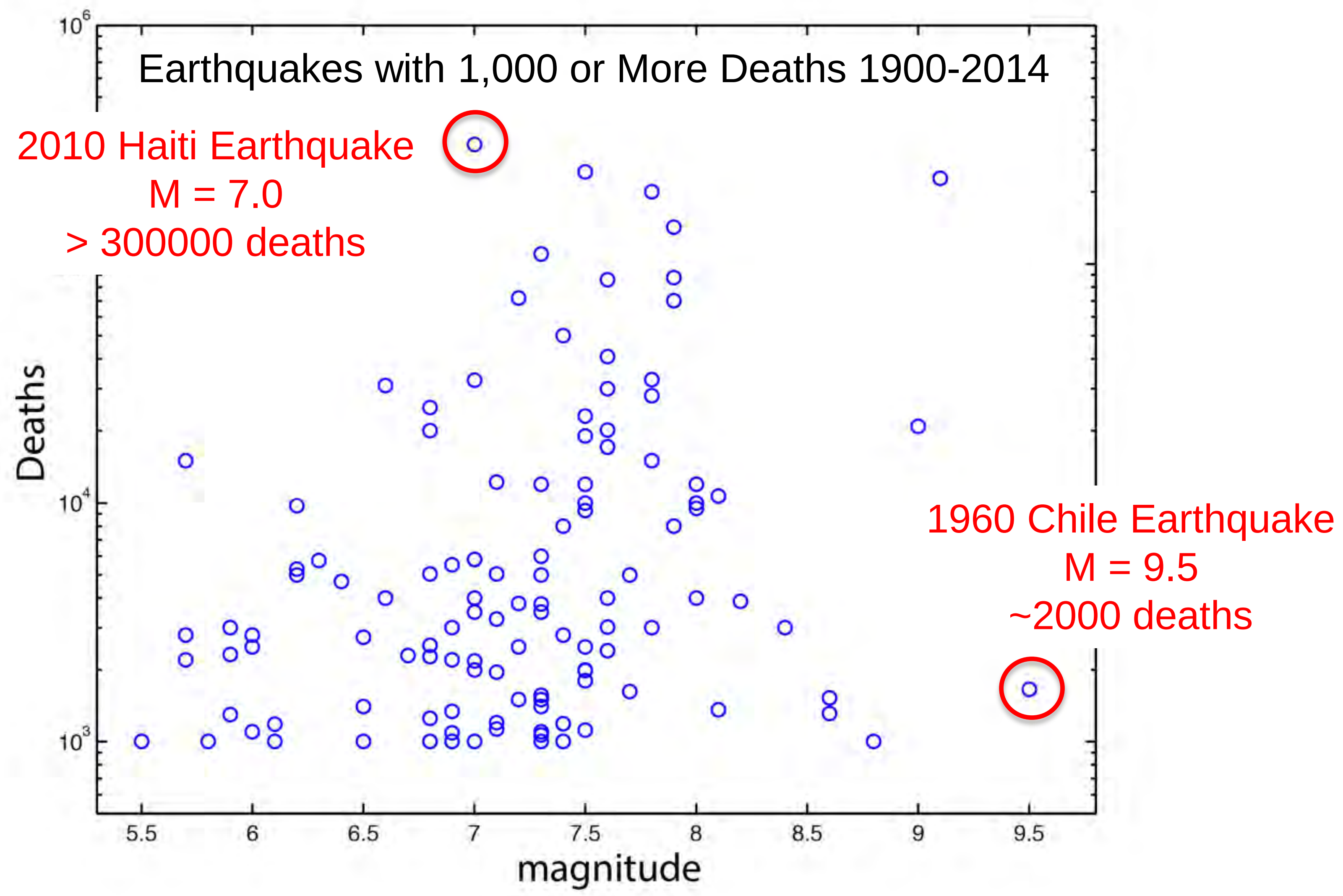
i.e., probability of an earthquake is inversely proportional to its rupture surface

For a given fault (or system of faults) the key parameters are:

- maximum magnitude $\mathbf{M_{max}}$
- its recurrence time $\mathbf{T_r}$

Magnitude and damage

Effect of an earthquake is not simply related to its size



https://earthquake.usgs.gov/earthquakes/world/world_deaths.php

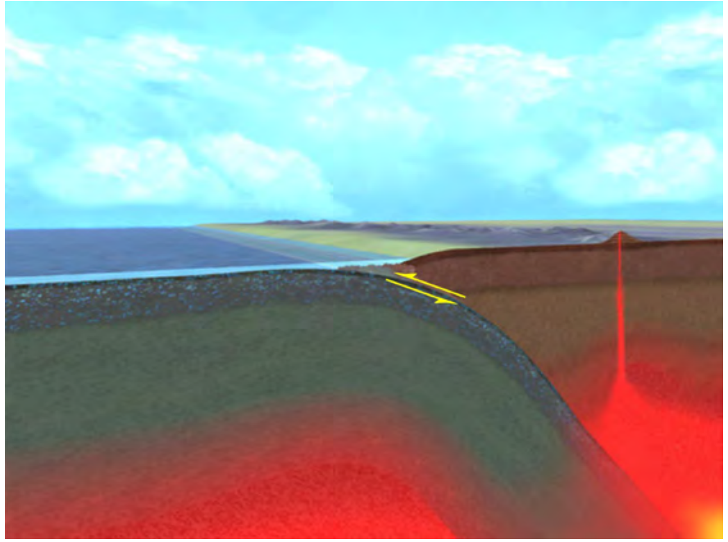
1960 Chile Earthquake

M = 9.5

(largest known earthquake)

Rupture mainly below the sea

No big cities nearby in 1960-s

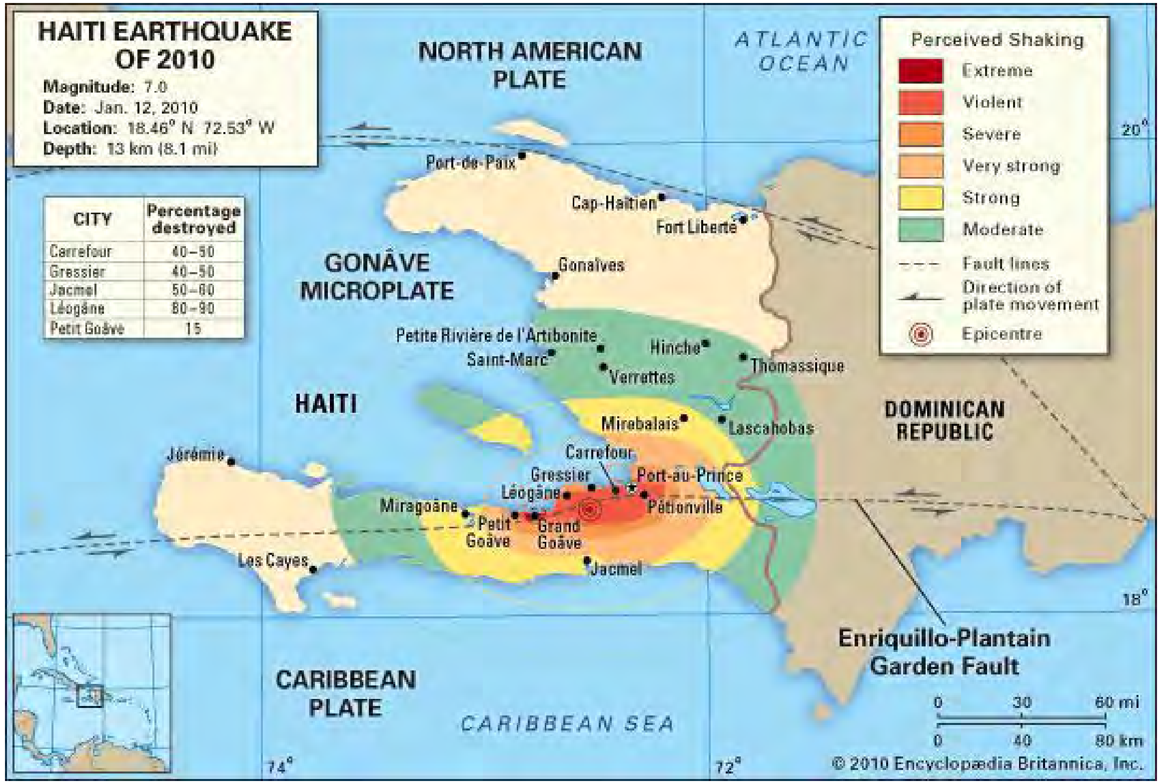


2010 Haiti Earthquake

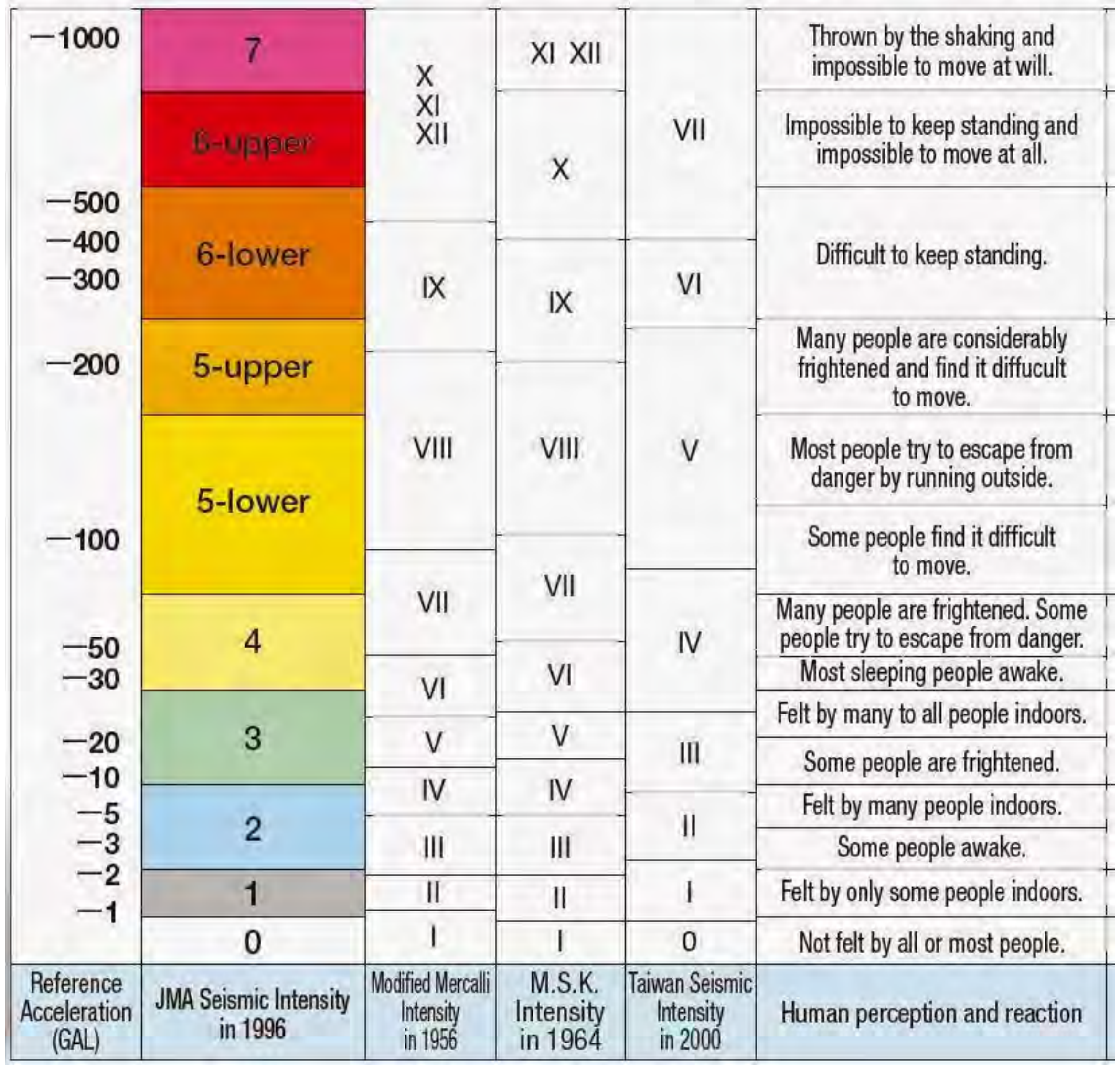
M = 7.0

Occurred on a shallow fault just below the main city

Poor constructions



Level of earthquake shaking is often characterized by macroseismic intensity



ground acceleration : physical parameter closest to **macroseismic intensity**

Seismic hazard

In general terms, the seismic hazard defines the expected seismic ground motion at a site (phenomenon that may result in destructions and losses).

Two major approaches – **deterministic** and **probabilistic** – are used for seismic hazard assessment.

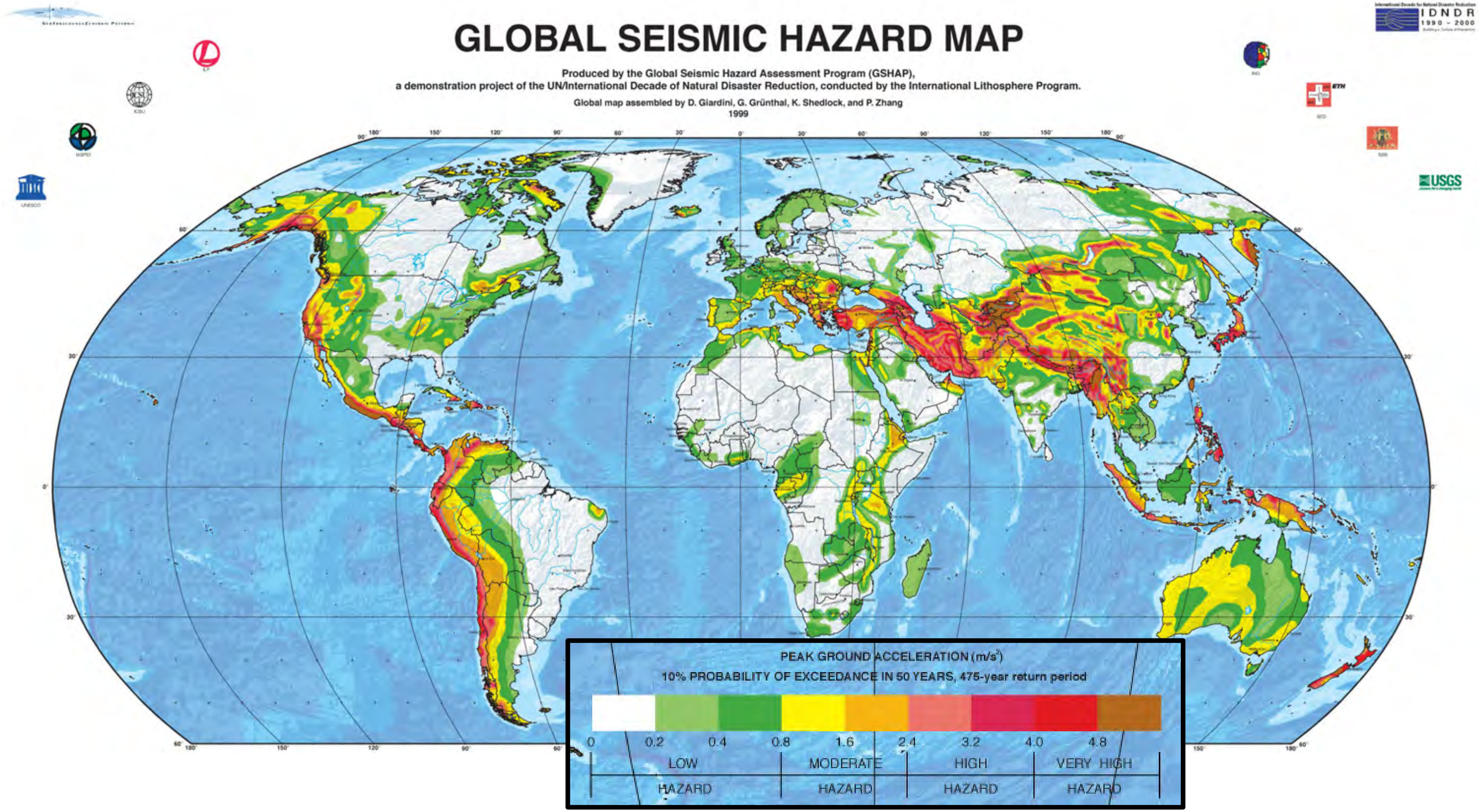
The **deterministic approach** takes into account a single, particular earthquake, the event that is expected to produce the **strongest level** of shaking at the site (macroseismic intensity, peak ground acceleration …).

In the **probabilistic approach** the seismic hazard is estimated in terms of **probability of exceedance** (or return period) of a ground motion level (macroseismic intensity, peak ground acceleration …).

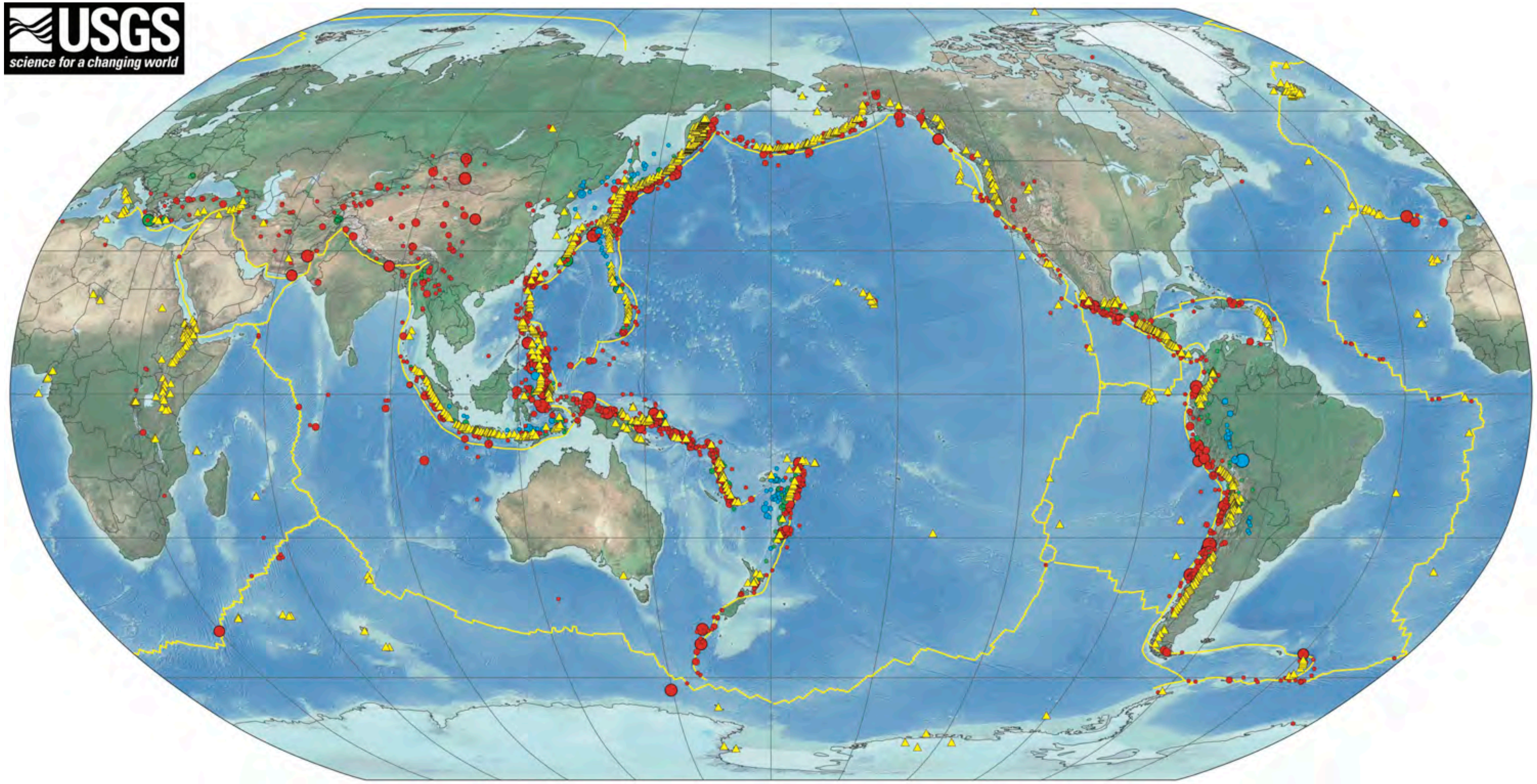
Is estimated from:

- knowledge of location of seismogenic faults and their $\mathbf{M_{max}}$ and $\mathbf{T_r}$
  seismological and geological observations
- Ground Motion Prediction Equations (**GMPE**)
  empirical information (seismological data) + physics of wave propagation

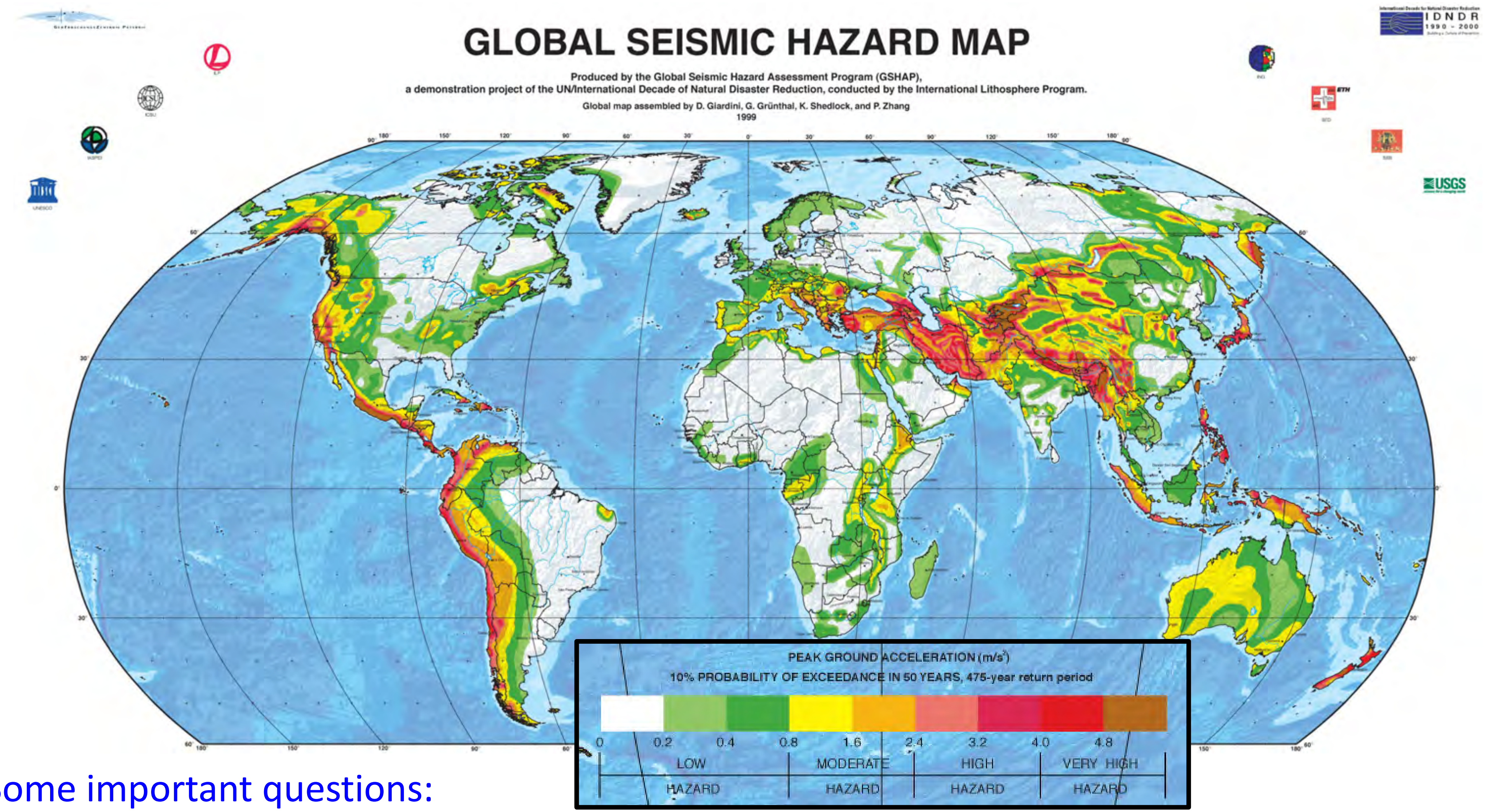
Seismic hazard



Distribution of earthquakes and volcanoes



Seismic hazard



Some important questions:

- do we miss possible seismogenic faults?
- could we underestimate maximum magnitudes?
- are earthquakes predictable (should the hazard be time-variable)?

Earthquake seismology timeline

1875 First seismographs

1894 Omori's law

1935 First Magnitude scale

1949 Gutenberg Richter law

1960s Plate tectonics

1963 Double-couple focal mechanism

1966 Seismic moment

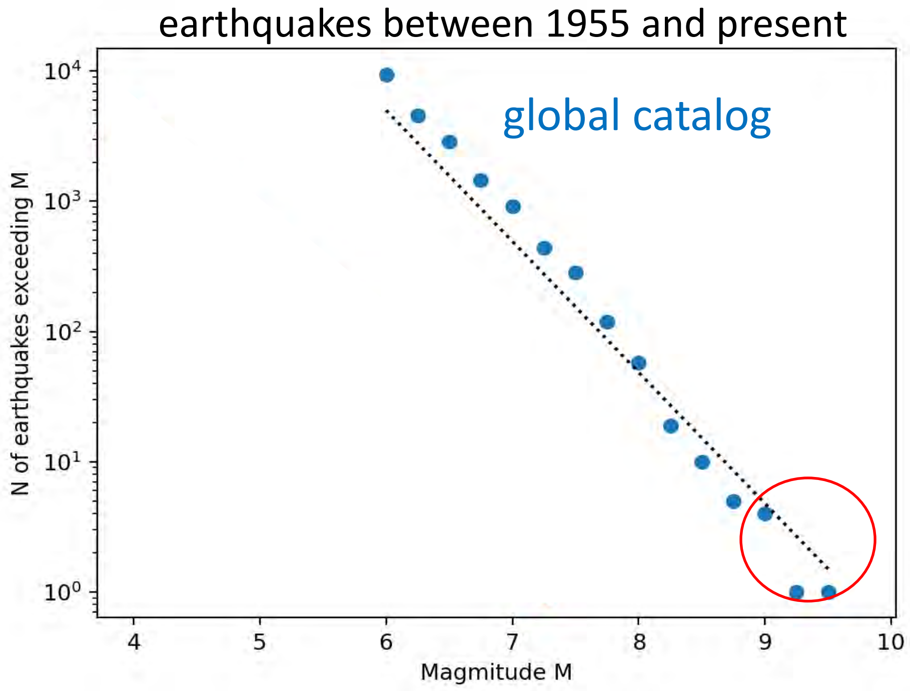
1968 Extended seismic rupture inversion

1975 Earthquake scaling laws

Main concepts of earthquake seismology were formulated and applied by the end of 1980-s.

What is changing since?

- rapidly growing vulnerability (population, infrastructure)
- growing application of paraseismic building codes
- more data (exponential growth of N of instruments)
- improved data quality (modern instruments, digital)
- new types of observations
  - Marine Geology
  - Space Geodesy
  - …
- data available in real time



Major earthquakes (M>9)

Kamchatka 1952	~2000 causalities
Chile 1960	~6000 causalities
Alaska 1964	<1000 causalities
Sumatra 2004	**~230,000 causalities**
Japan 2011	**~20,000 causalities**

21-th century M>9 earthquakes were global catastrophes in terms of human life and economic losses

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Importance of secondary hazards such as tsunami

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Japan 2011 ~20,000 causalities

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Volume 52, Issue 5, October 2012, Pages 780-792

Damage statistics (Summary of the 2011 off the Pacific Coast of Tohoku Earthquake damage)

Motoki Kazama [a], Toshihiro Noda [b]

The damage due to seismic motion alone was relatively small (<2%), in spite of the large magnitude of the earthquake.

Importance of secondary hazards such as tsunami

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  - Space Geodesy
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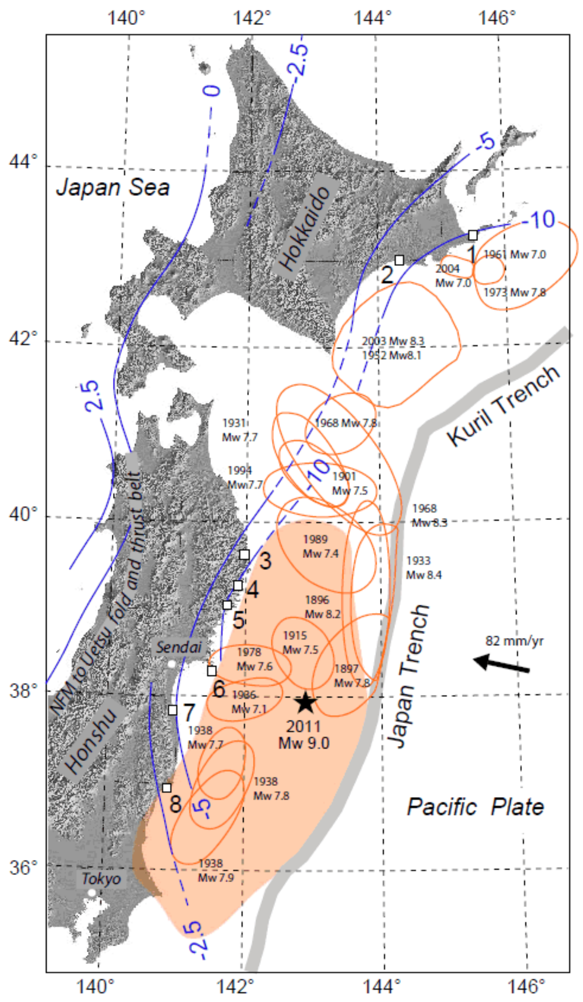
M=9 earthquake and was not expected in Japan

M~8 earthquakes were observed instrumentally

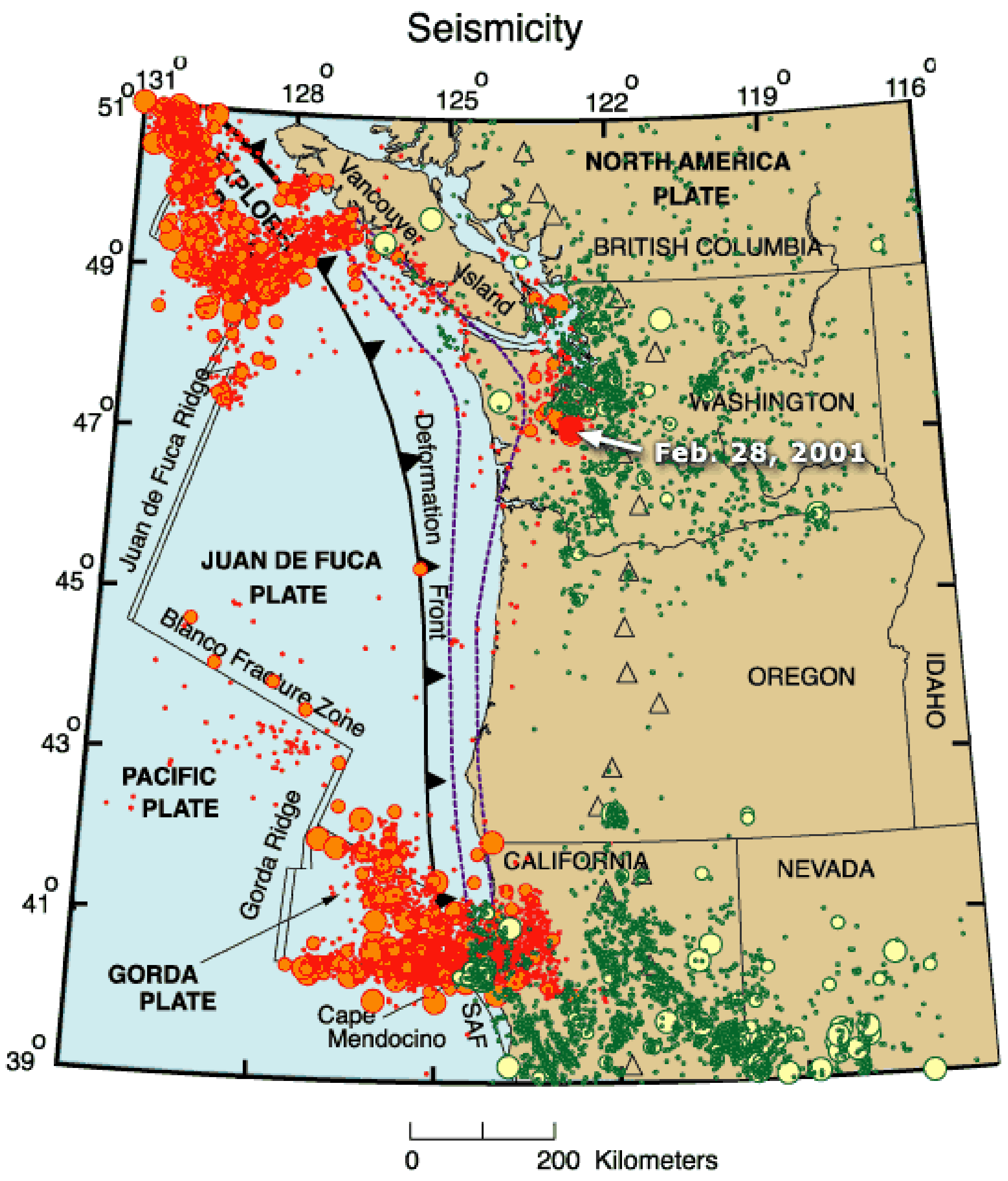
no significant difference in terms of ground shaking … dramatic underestimation of tsunami

recurrence time of a M=9 earthquake is close to 1000 years

require geological observations: **paleoseismology**

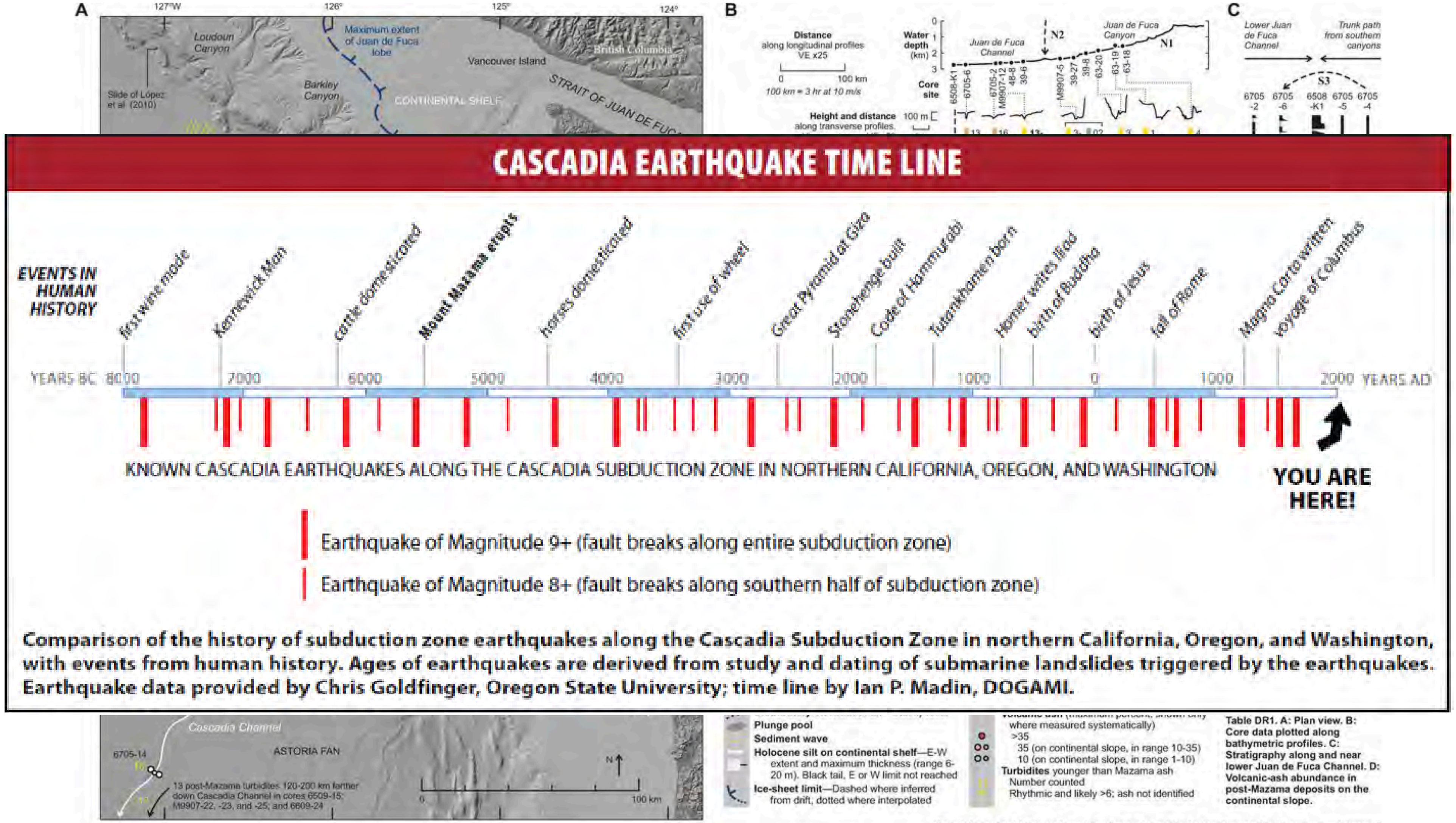


non-instrumental observations: paleoseismology



modified from Weaver and Shedlock, 1996

non-instrumental observations: paleoseismology



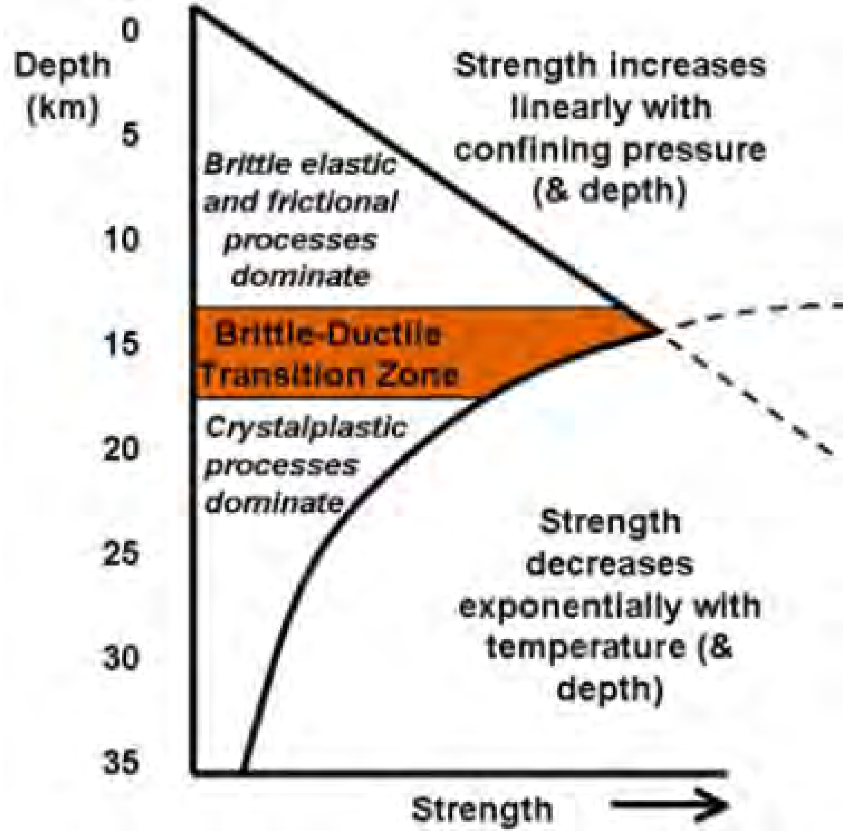
Comparison of the history of subduction zone earthquakes along the Cascadia Subduction Zone in northern California, Oregon, and Washington, with events from human history. Ages of earthquakes are derived from study and dating of submarine landslides triggered by the earthquakes. Earthquake data provided by Chris Goldfinger, Oregon State University; time line by Ian P. Madin, DOGAMI.

Rethinking turbidite paleoseismology along the Cascadia subduction zone—Figure 3
Atwater et al.
Supplement to Geology, v. 42, no. 9 (September 2014)

What is the value of absolute maximum magnitude?

Is this 9+, as already observed? probably YES

Are 10+ earthquakes possible? probably NO



thickness of the brittle seismogenic part of the Earth's lithosphere is limited

fault dimensions for a 10+ earthquake:
- fault width exceeding ~100 km
  and/or
- fault length of several thousands of km

this is highly unlikely

Some important questions:

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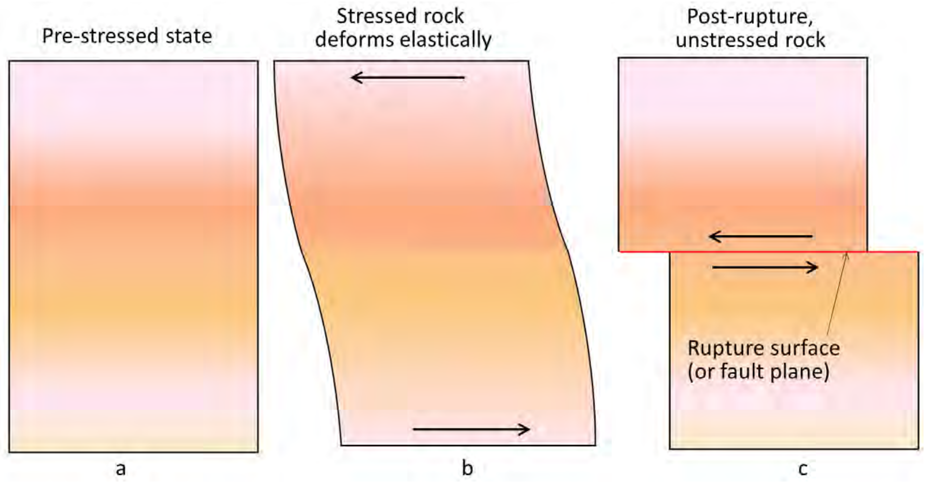
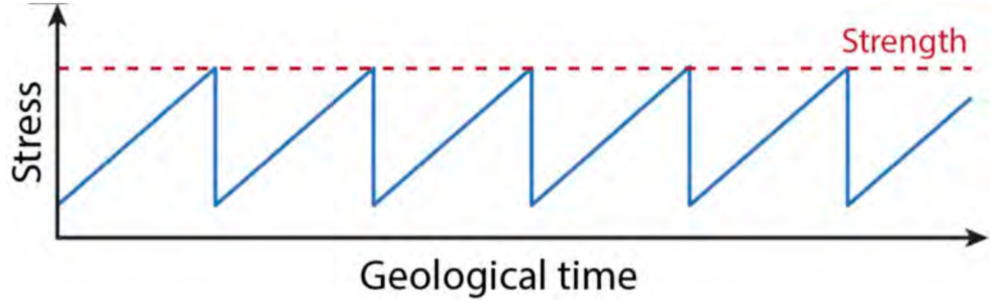
- could we underestimate maximum magnitudes?
- **are earthquakes predictable (should be the hazard time-variable)?**

Can we go beyond stick-slip description?





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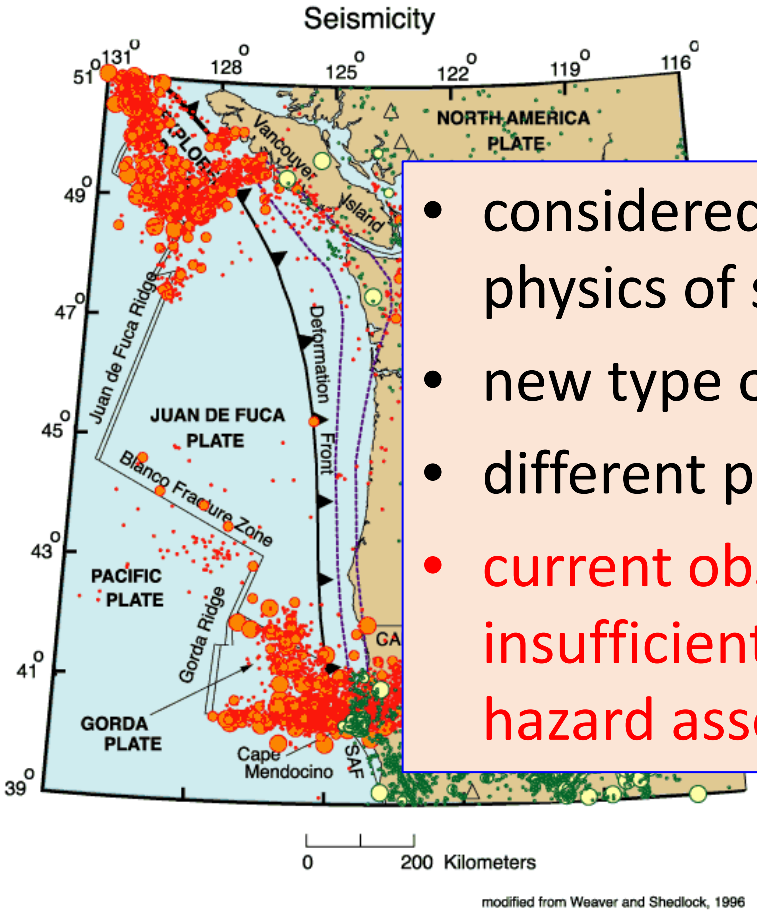
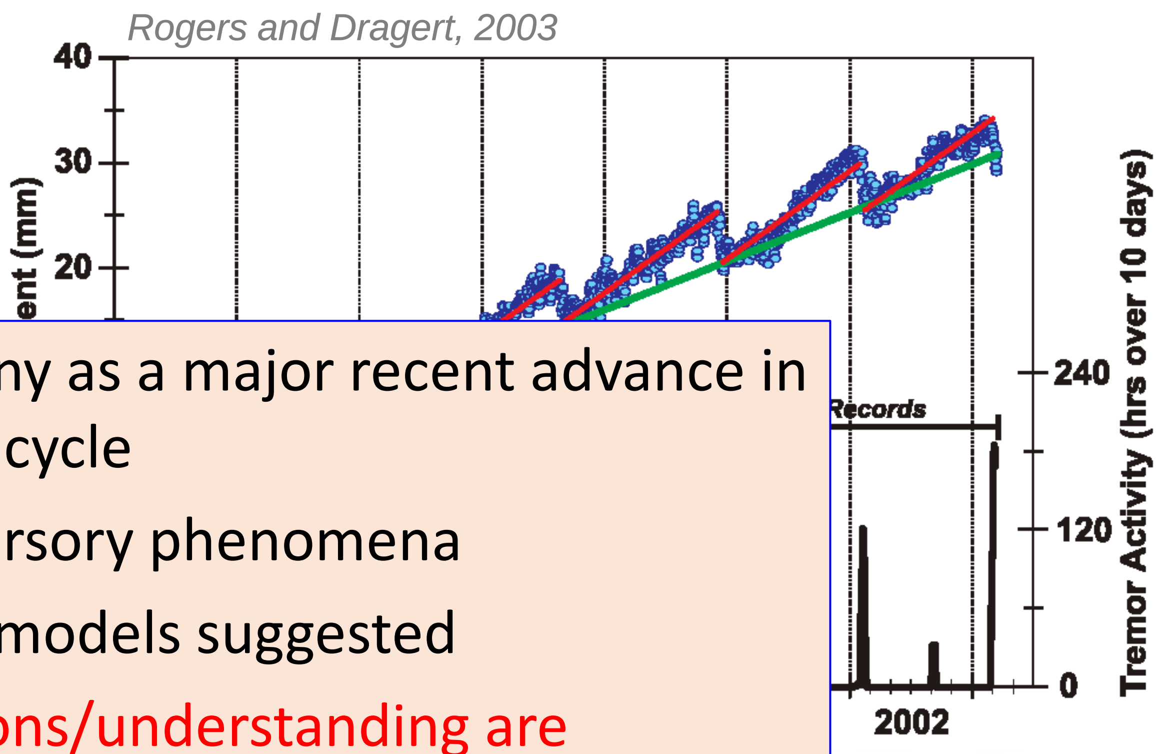
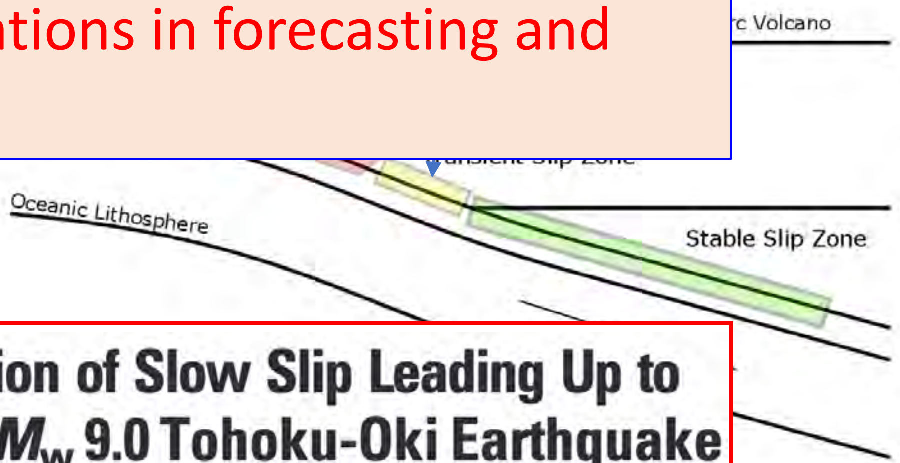
“Slow” earthquakes







- considered by many as a major recent advance in physics of seismic cycle
- new type of precursory phenomena
- different physical models suggested
- current observations/understanding are insufficient for applications in forecasting and hazard assessment

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Laboratory observations of slow earthquakes and the spectrum of tectonic fault slip modes

J. R. Leeman, D. M. Saffer, M. M. Scuderi & C. Marone

Nature Communications 7, Article number: 11104 (2016) | Cite this article

Propagation of Slow Slip Leading Up to the 2011 M_w 9.0 Tohoku-Oki Earthquake

Aitaro Kato,* Kazushige Obara, Toshihiro Igarashi, Hiroshi Tsuruoka, Shigeki Nakagawa, Naoshi Hirata

www.sciencemag.org SCIENCE VOL 335 10 FEBRUARY 2012

Space geodesy, plate motion, and earthquake recurrence

measured motion of GPS sites

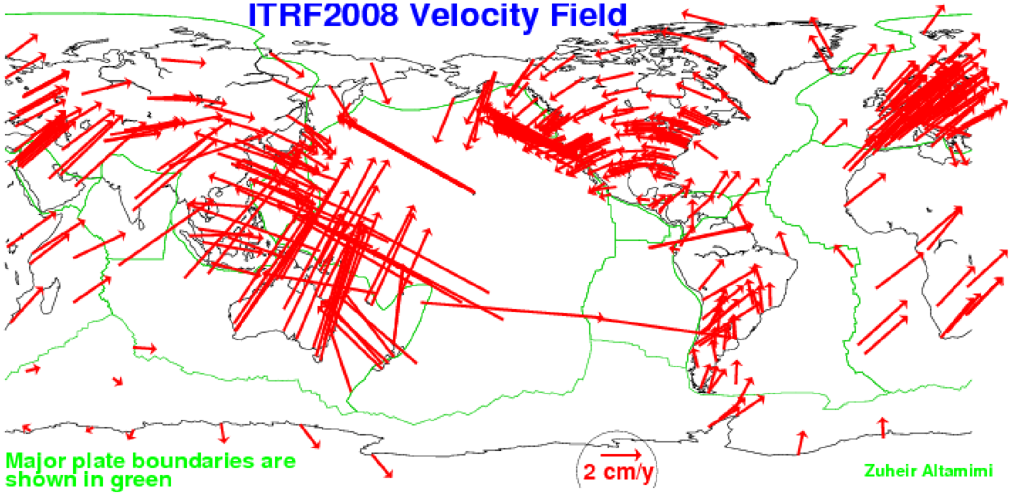
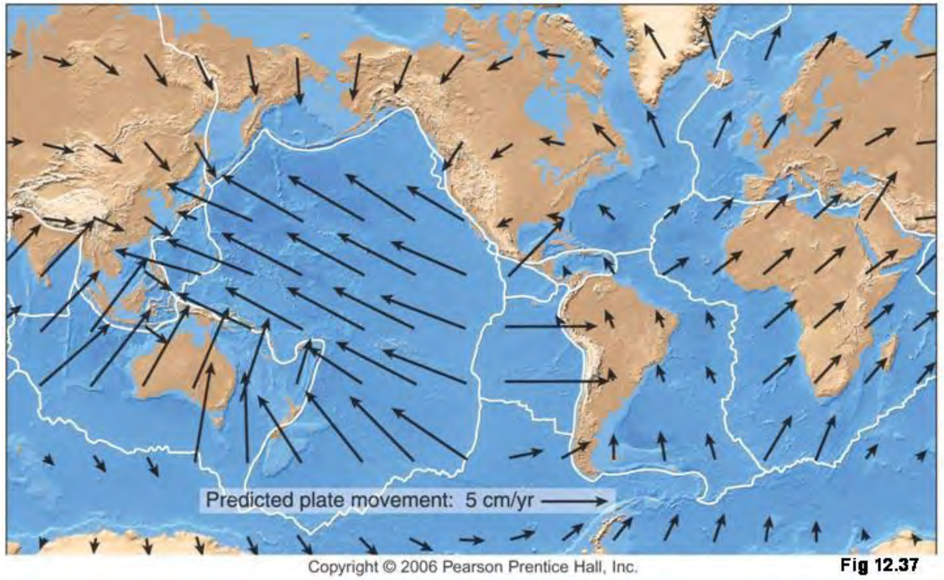
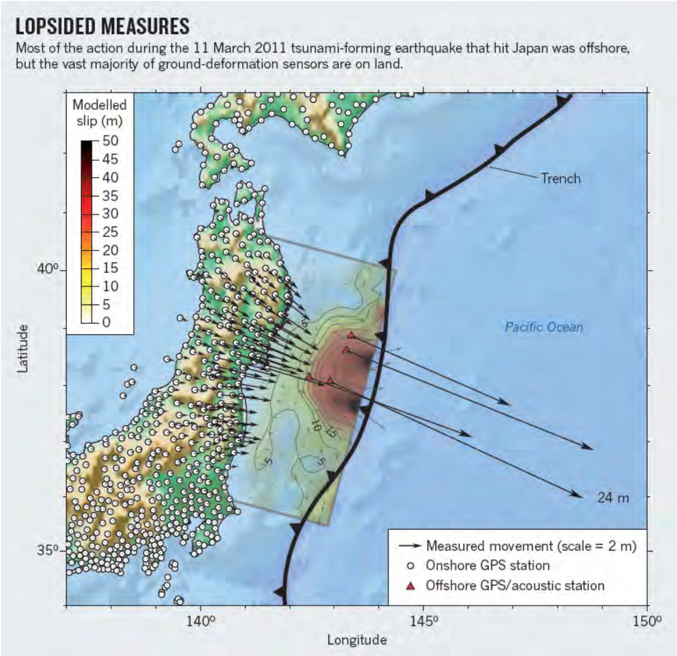


plate motion model





2011 Japan earthquake

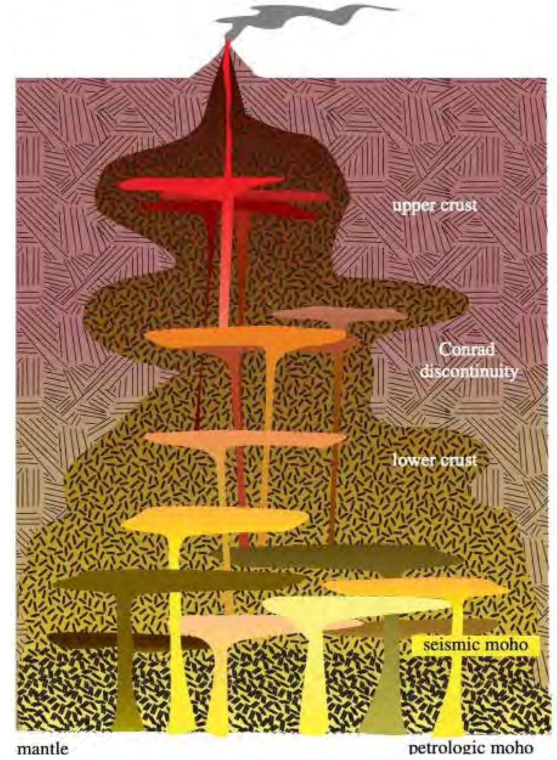
- maximum slip on the fault > 70 m
- plate convergence rate 9 cm/year
- recurrence interval > 800 years

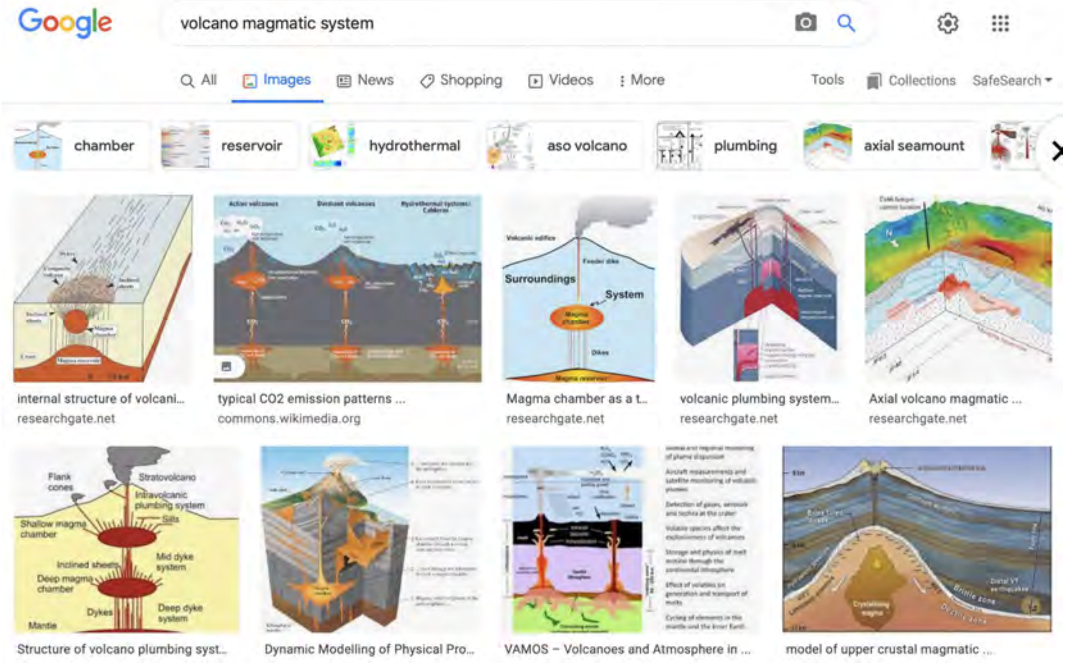
Some conclusive remarks about earthquakes and seismic cycle

- still no robust prediction algorithms despite many observed precursors
- conceptually well understood
- main loading (plate motion) is reasonably quantified
- hazard is well characterized

  with some caveat about secondary hazards (tsunami, landslides, …)

- well functioning system of instrumental observation and data sharing
- likely the whole spectrum of event sizes was observed
- good database for the hazard and risk assessment
- main issue: extending catalogs back in time to cover recurrence of major events
- physical understanding should be improved





Physical concepts of volcanoes

All representations of the volcano interior you can found are "cartoons" and we still do not really know its configuration and functioning

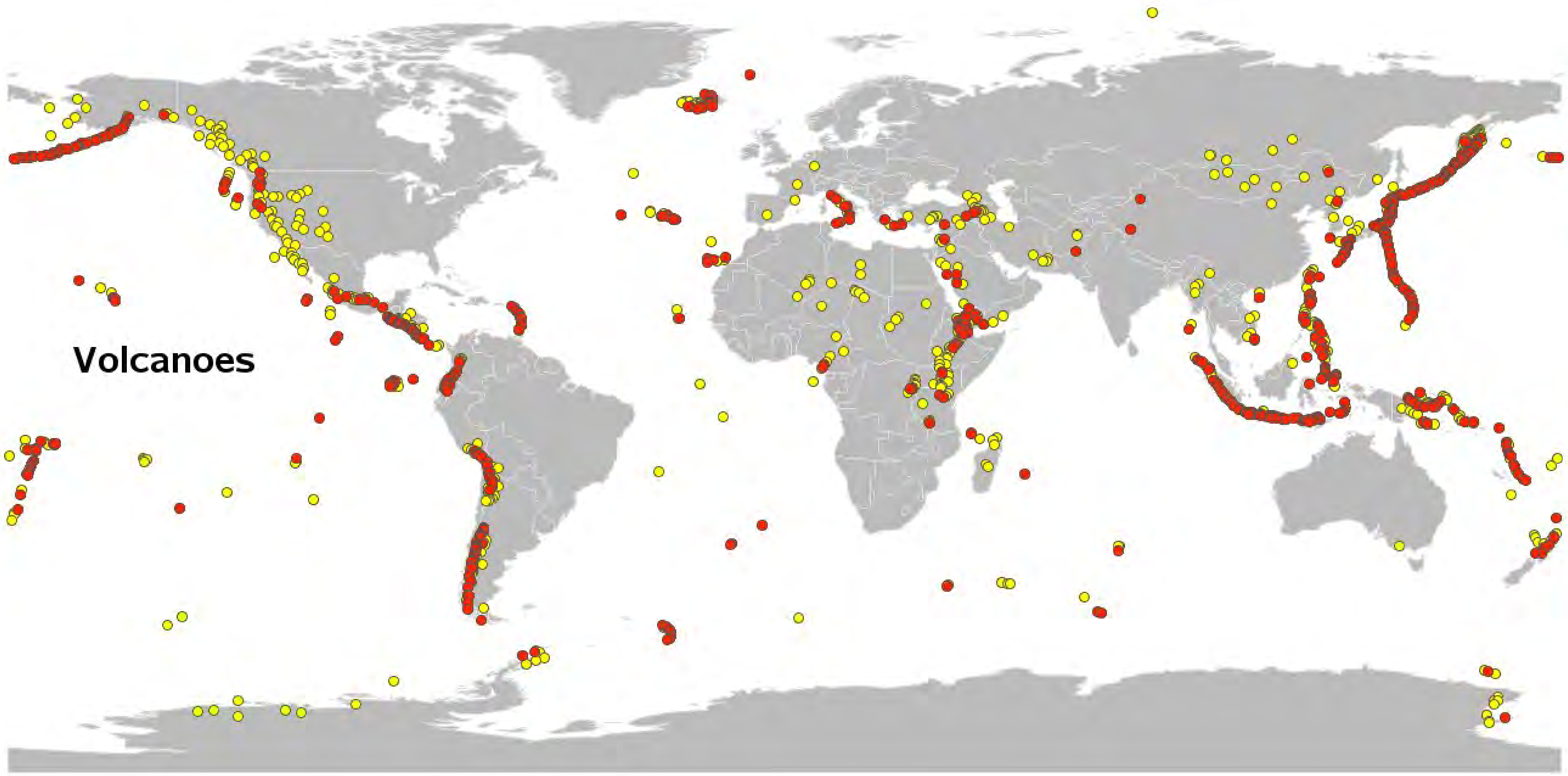
information from analysis of erupted rocks

- initial magmas are generated by melting in the mantle (~100 km depth)
- they slowly raise to the surface because of buoyancy
- storage in shallow "magma reservoirs"
- chemical transformations, degassing …

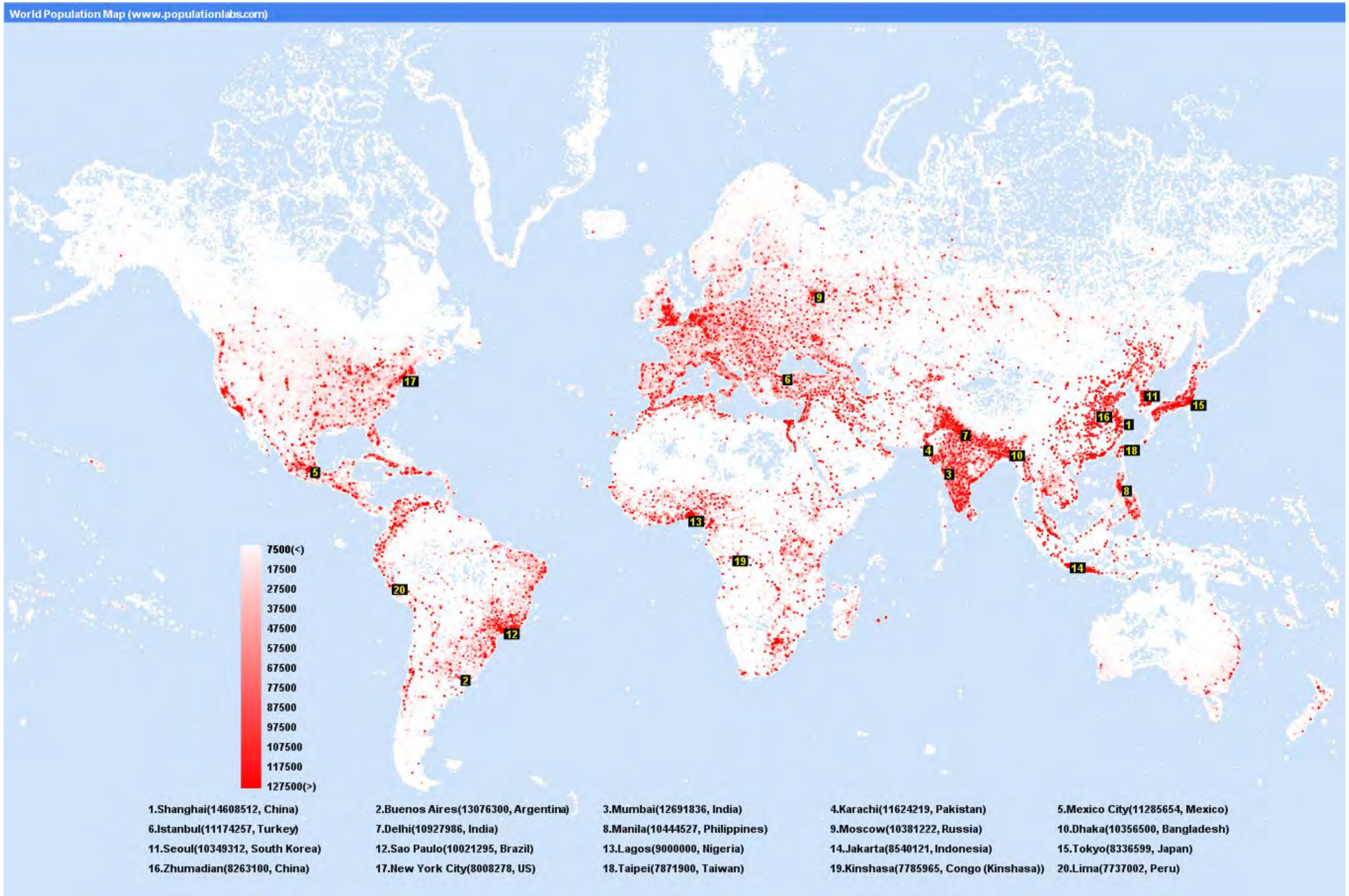
empirical observations

- strong variability of eruption styles
- predictability in time
  most of eruptions can be anticipated when volcanoes are well monitored
- no size predictability

There are more than 1500 volcanoes that has been active during last 10,000 years on the surface of the Earth



More than 500,000,000 people leave in vicinity (< 100 km) of potentially active volcanoes



Ongoing volcanic activity

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Current Eruptions

Overall, **48 volcanoes were in continuing eruption status** as of 17 March 2022. An eruption marked as "continuing" does not always mean persistent daily activity, but indicates at least intermittent eruptive events without a break of 3 months or more. Detailed statistics are not kept on daily activity, but **generally there are around 20 volcanoes actively erupting on any particular day**; this is a subset of the normal 40-50 with continuing eruptions. Additional eruption data is available for recent years.

The Smithsonian / USGS Weekly Volcanic Activity Report (WVAR) for the week ending on 26 April 2022 includes the 25 volcanoes shown below

Some well-known catastrophes caused by explosive volcanic eruptions

Vesuvius in AD79: destructed of Pompeii and Herculaneum; killed more than 10,000 people

Mount Pelée in 1915: killed 30,000 people

A recent effusive eruption: La Palma 2021

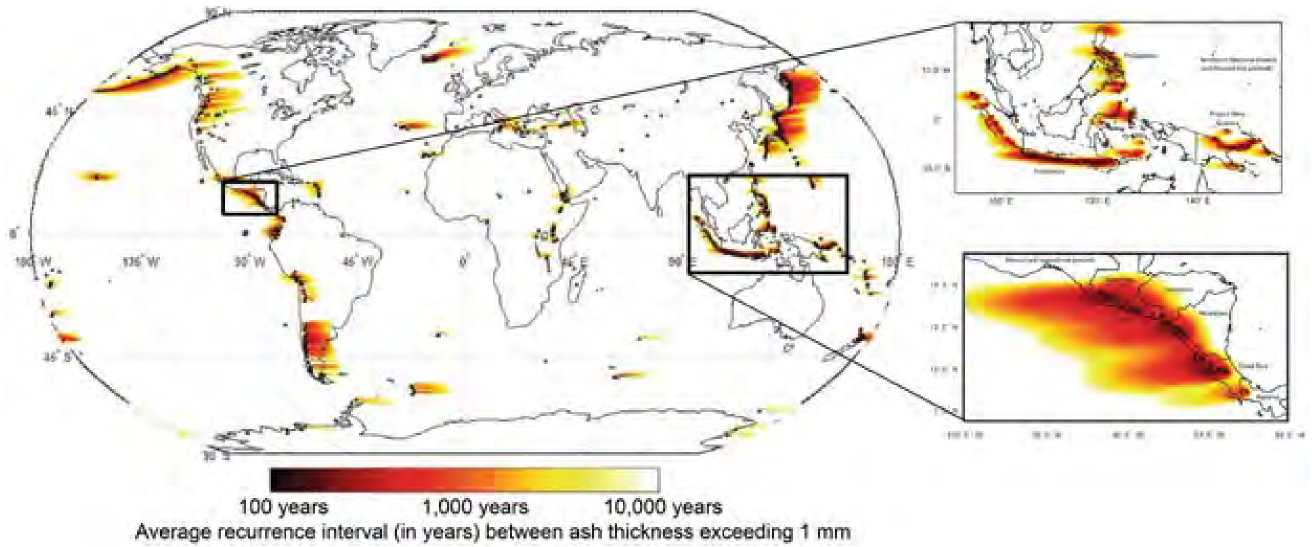
Volcanic hazards are difficult to assess

Multiple dangerous phenomena

- lava flows
- pyroclastic flows
- lahars
- landslides
- debris avalanches
- tephra or ash falls
- releases of gas
- tsunamis
- shock waves
- climat change
- …

Volcanic hazard are mostly estimated locally for relatively well studied volcanoes

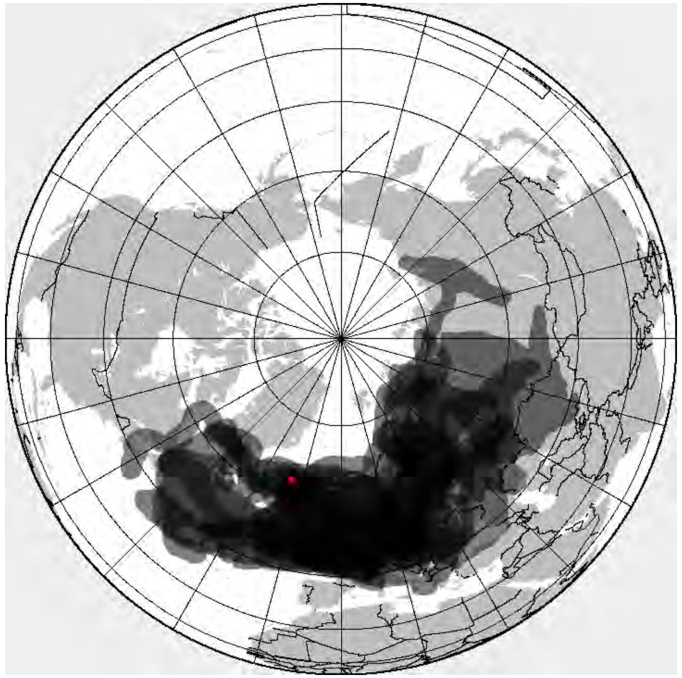
Global hazard models are difficult to compile and validate



Probabilistic volcanic hazard map showing global volcanic ash fall hazard.

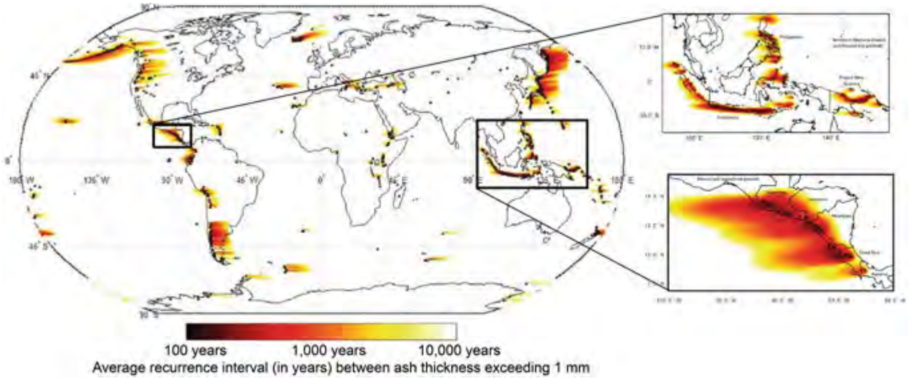
Modified from Jenkins et al. (2015)

Air travel disruption after the 2010 Eyjafjallajökull eruption

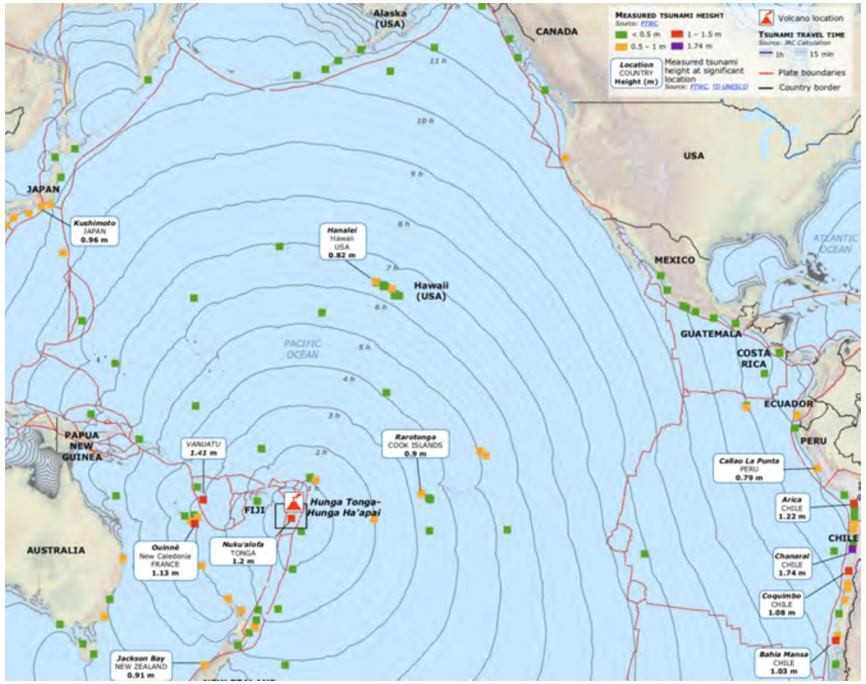


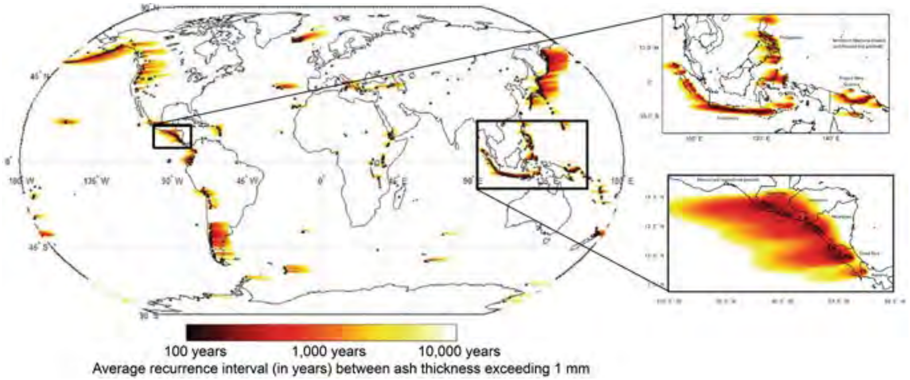
Composite map of the volcanic ash cloud spanning 14–25 April 2010

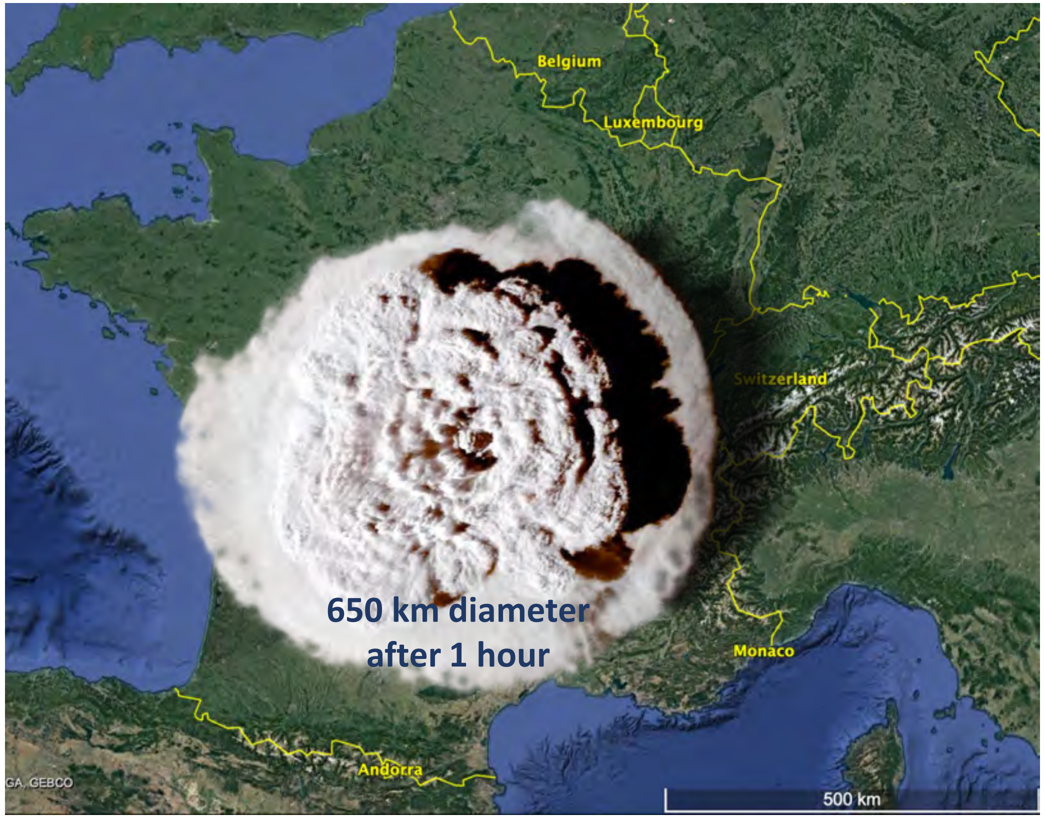
- **107,000 flights cancelled during April 15-23 2010**
- **48% of total air traffic and roughly 10 million passengers**
- **total loss for the airline industry ~ US $1.7 billion**



2022 Hunga Tonga eruption







Volcanoes and magmatic reservoirs are **volumetric** objects

This is natural to characterize eruptions with erupted volume **V**

Tephra Falls of the 1991 Eruptions of Mount Pinatubo

By Ma. Lynn O. Paladio-Melosantos,[1] Renato U. Solidum,[1] William E. Scott,[2] Rowena B. Quiambao,[1] Jesse V. Umbal,[3] Kelvin S. Rodolfo,[3] Bella S. Tubianosa,[1] Perla J. Delos Reyes,[1] Rosalito A. Alonso,[4] and Hernulfo B. Ruelo[5]

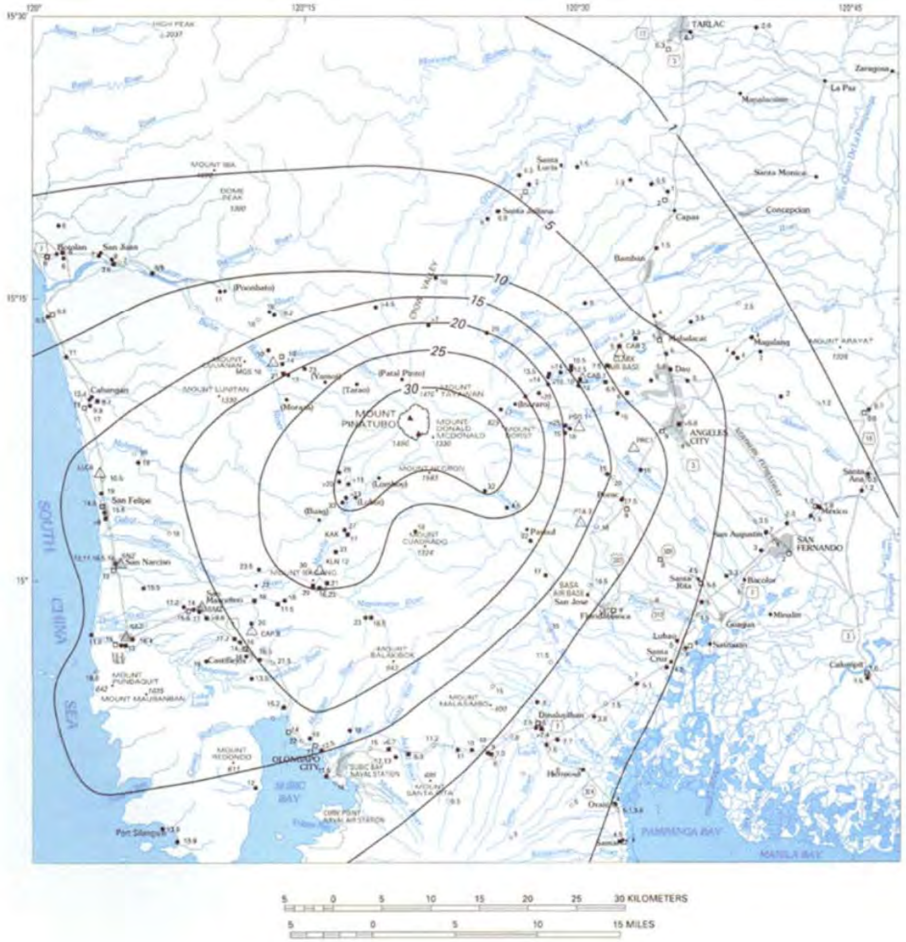


Figure 7. Distribution of tephra-fall deposits of the climatic eruption of June 15 (phase VI of Wolfe and Hoblitt, this volume), layer C, and locations of sections (triangles) sampled for grain-size and component data. KAK is location of section sketched in figure 1. Isopachs are in centimeters; sources of data as in figure 3, but open circles show total thickness of section (in centimeters), which may also include layers A and (or) B.

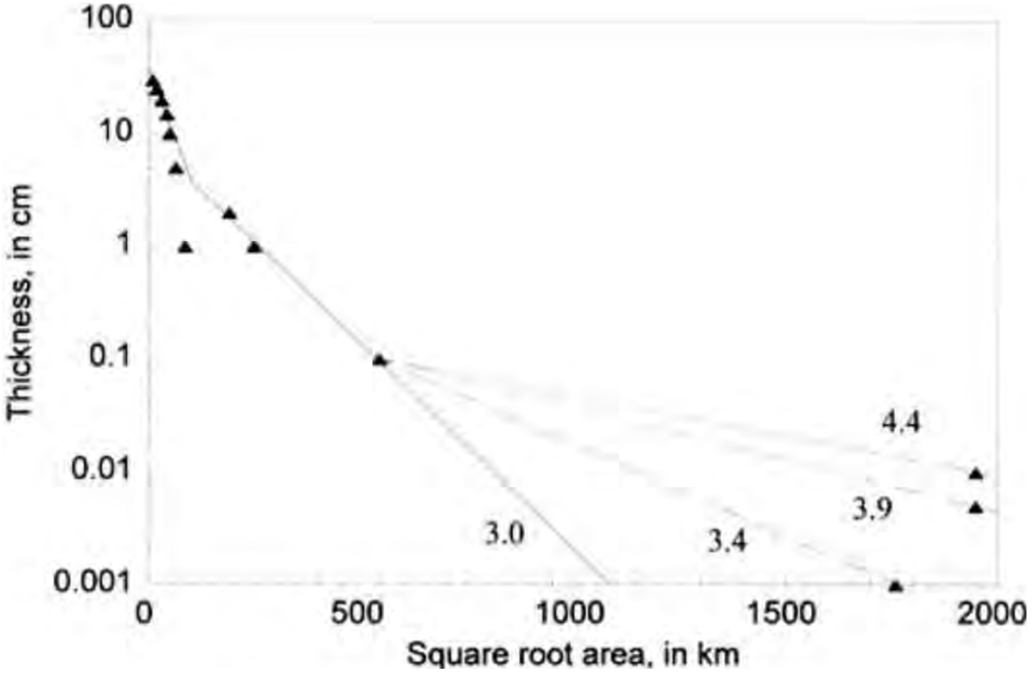


Figure 8. Log of thickness versus square root of area for layer C that includes proximal on-land data from Luzon (fig. 5), marine data from Weisner and Wang (this volume), and three possible distributions for distal tephra-fall deposits (dashed lines) based on two values for area of distal isopach (3.1 and 3.8 million km^2; fig. 9), and three values for thickness of distal isopach (0.01, 0.05, and 0.1 mm). Numerals in boxes are calculated bulk volumes in cubic kilometers.

Volcanoes and magmatic reservoirs are **volumetric** objects

This is natural to characterize eruptions with erupted volume **V**

Logarithmic scale of eruption sizes
Volcanic Explosivity Index (**VEI**)

$$\mathbf{VEI} = \log \mathbf{V} + 5 \qquad \text{(for volume in km}^3\text{)}$$

Probability of an eruption can be expected to be inversely proportional to its volume

In this case we should observe a Gutenberg-Richter like eruption size distribution:

$$\log N = a - b\mathbf{VEI}$$

with $\mathbf{b = 1}$

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Volcanic Explosivity Index

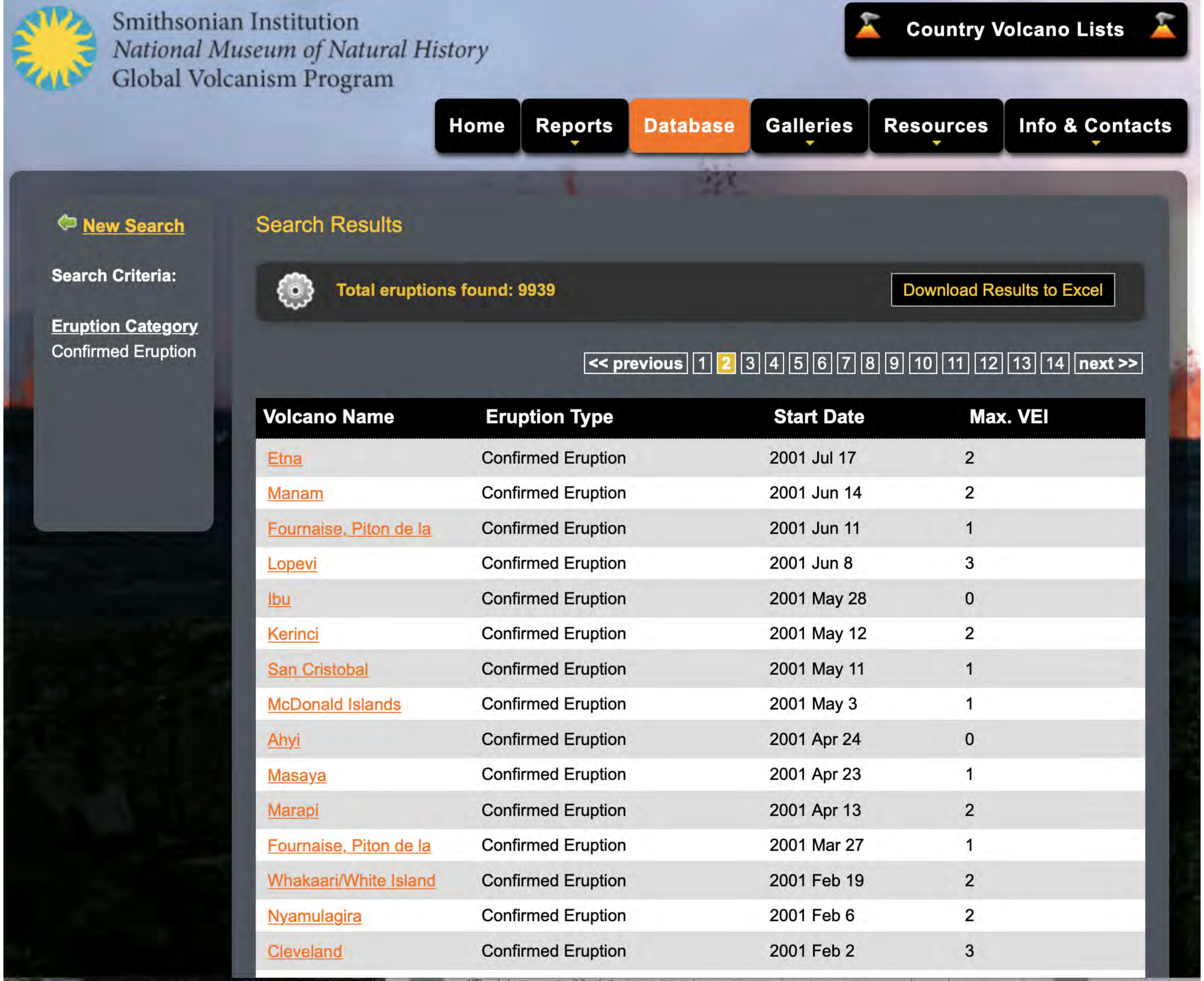
From Wikipedia, the free encyclopedia

"VEI" redirects here. For the company, see Visual Entertainment Inc.

The **Volcanic Explosivity Index** (**VEI**) is a relative measure of the explosiveness of volcanic eruptions. It was devised by Chris Newhall of the United States Geological Survey and Stephen Self at the University of Hawaii in 1982.

Volume of products, eruption cloud height, and qualitative observations (using terms ranging from "gentle" to "mega-colossal") are used to determine the explosivity value. The scale is open-ended with the largest eruptions in history given a magnitude of 8. A value of 0 is given for non-explosive eruptions, defined as less than 10,000 m^3 (350,000 cu ft) of tephra ejected; and 8 representing a mega-colossal explosive eruption that can eject 1.0×10^{12} m^3 (240 cubic miles) of tephra and have a cloud column height of over 20 km (66,000 ft). The scale is logarithmic, with each interval on the scale representing a tenfold increase in observed ejecta criteria, with the exception of between VEI-0, VEI-1 and VEI-2.[1]

VEI and ejecta volume correlation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New Search

Search Criteria:

Eruption Category
Confirmed Eruption

Search Results

Total eruptions found: 9939

Download Results to Excel

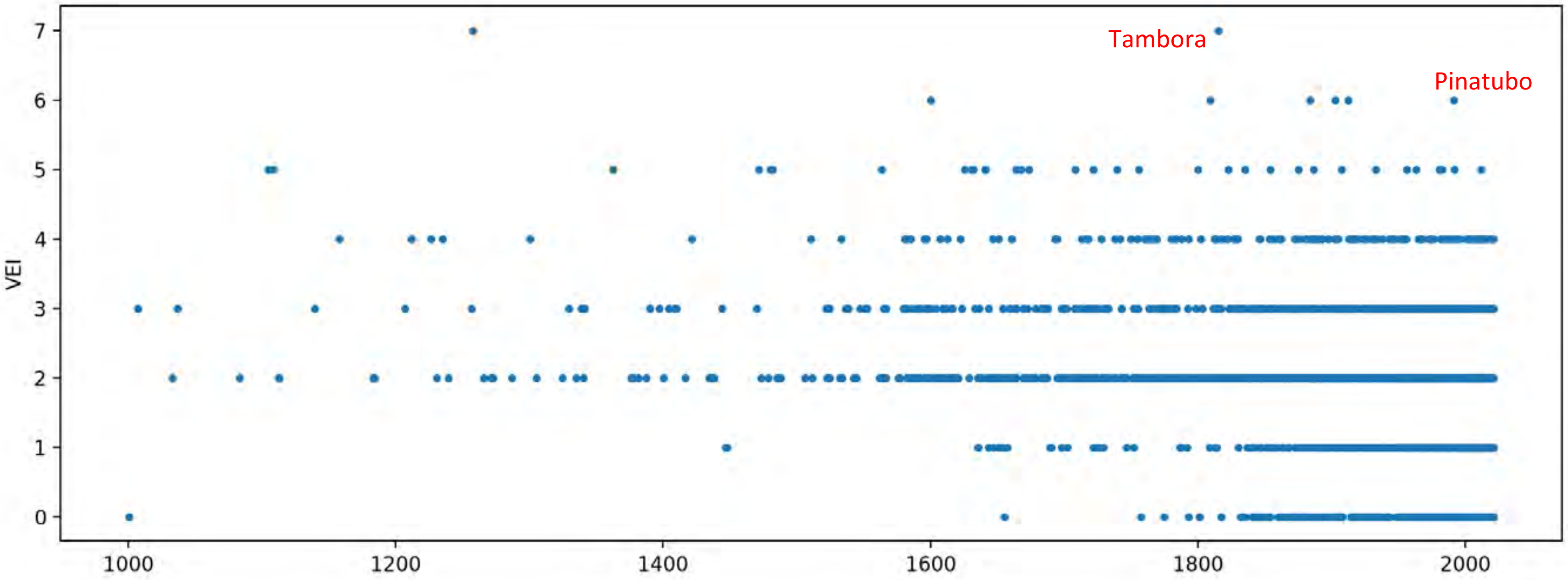
<< previous 1 2 3 4 5 6 7 8 9 10 11 12 13 14 next >>

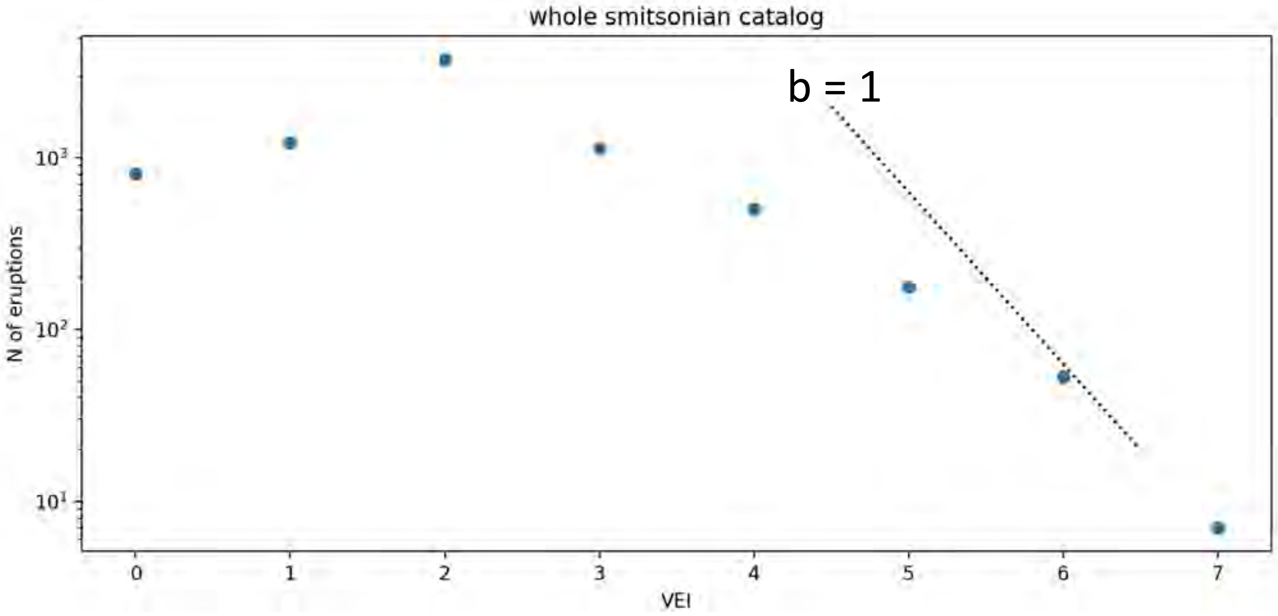
Volcano Name	Eruption Type	Start Date	Max. VEI
Etna	Confirmed Eruption	2001 Jul 17	2
Manam	Confirmed Eruption	2001 Jun 14	2
Fournaise, Piton de la	Confirmed Eruption	2001 Jun 11	1
Lopevi	Confirmed Eruption	2001 Jun 8	3
Ibu	Confirmed Eruption	2001 May 28	0
Kerinci	Confirmed Eruption	2001 May 12	2
San Cristobal	Confirmed Eruption	2001 May 11	1
McDonald Islands	Confirmed Eruption	2001 May 3	1
Ahyi	Confirmed Eruption	2001 Apr 24	0
Masaya	Confirmed Eruption	2001 Apr 23	1
Marapi	Confirmed Eruption	2001 Apr 13	2
Fournaise, Piton de la	Confirmed Eruption	2001 Mar 27	1
Whakaari/White Island	Confirmed Eruption	2001 Feb 19	2
Nyamulagira	Confirmed Eruption	2001 Feb 6	2
Cleveland	Confirmed Eruption	2001 Feb 2	3

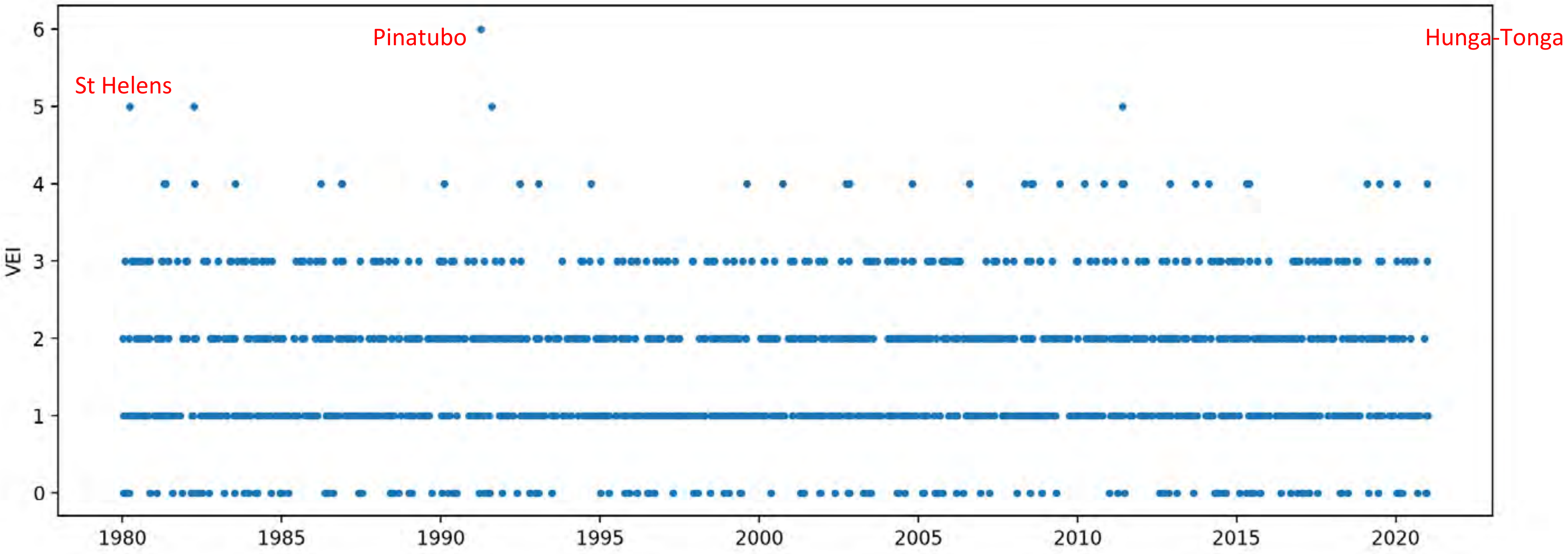
Catalog of volcanic eruptions available online

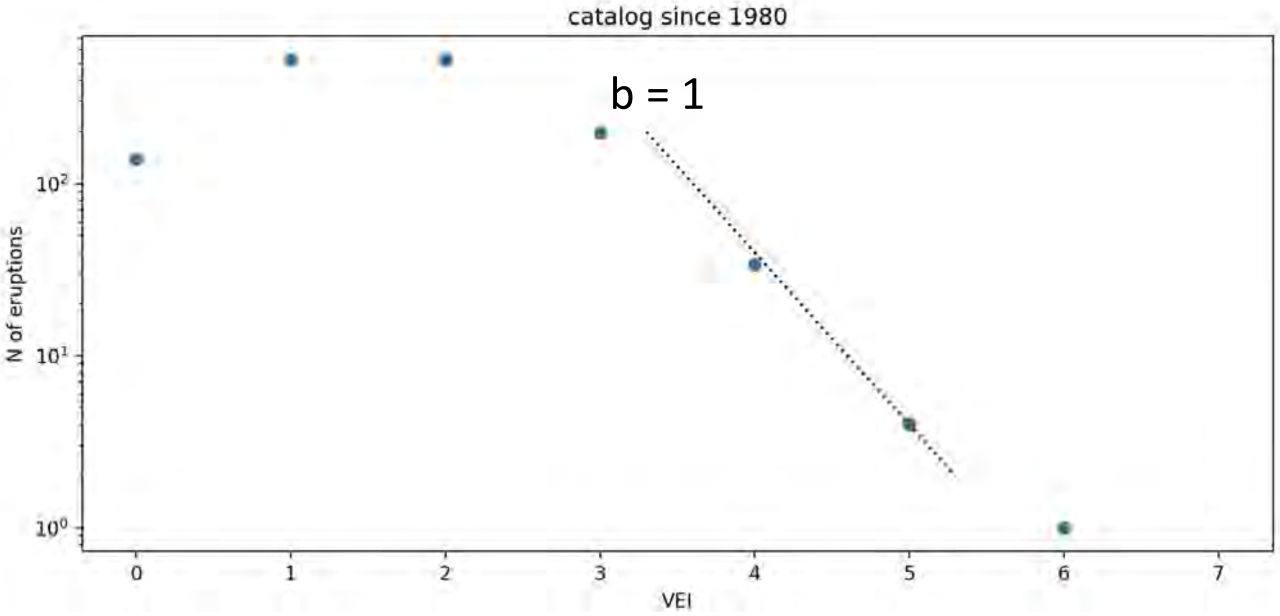
- Huge effort of the volcanology community
- Extends to pre-historic times
- Provides a base for statistical analysis

- VEI values are highly uncertain
- Timing of eruptions is very approximate
- No detailed time histories available for catalogued eruptions


Tambora
Pinatubo
VEI
7
6
5
4
3
2
1
0
1000
1200
1400
1600
1800
2000


whole smitsonian catalog
b = 1
N of eruptions
10^3
10^2
10^1
0
1
2
3
4
5
6
7
VEI


Pinatubo
St Helens
Hunga-Tonga
VEI
6
5
4
3
2
1
0
1980
1985
1990
1995
2000
2005
2010
2015
2020


catalog since 1980
b = 1
N of eruptions
10^2
10^1
10^0
0
1
2
3
4
5
6
7
VEI

Some critical questions

- Do we have reliable observations of the impact of major (VEI 6+) eruptions on modern infrastructure?

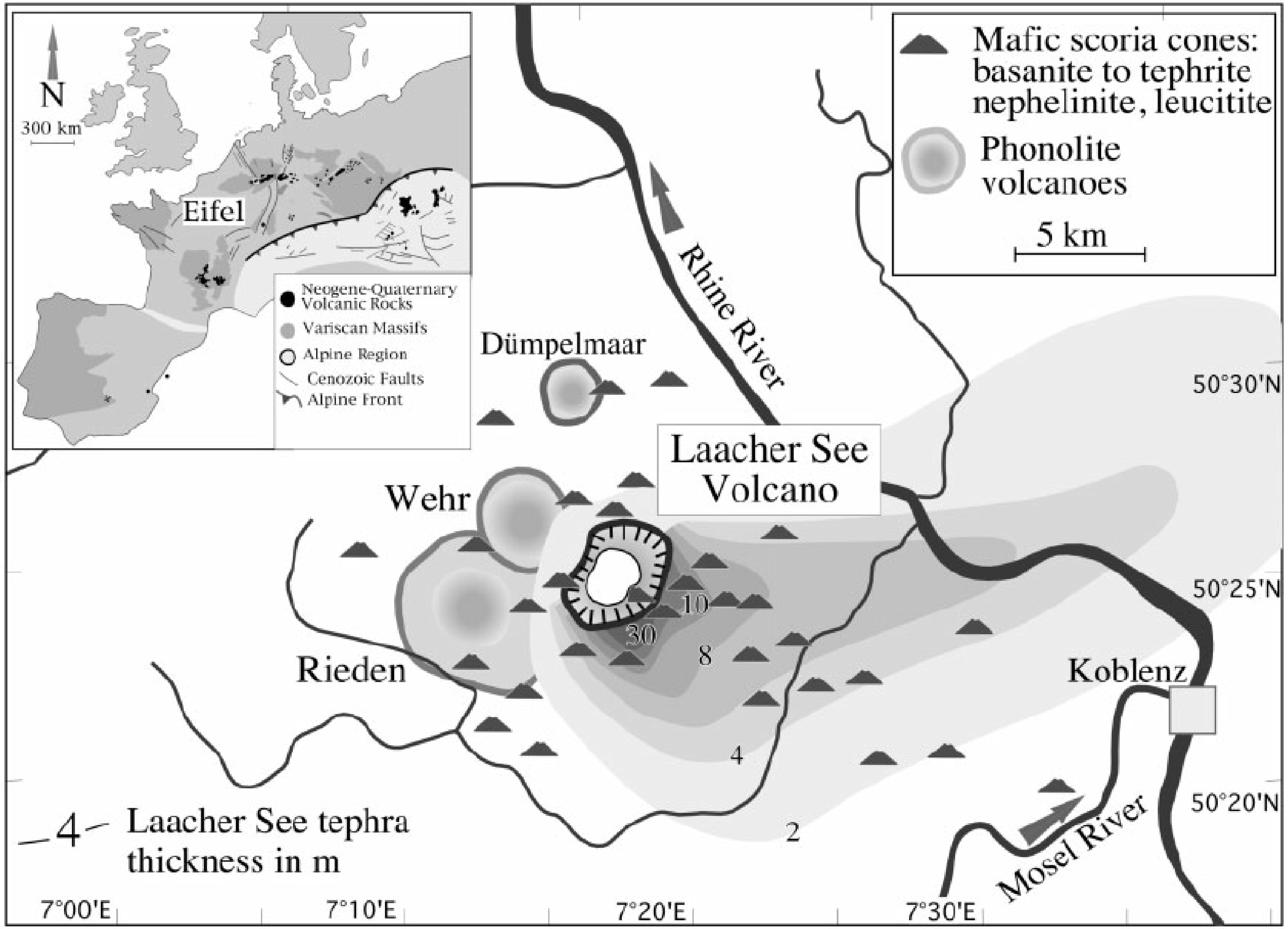
NO

- Are major (VEI 6+) eruptions possible in populated/developed regions?

YES

- **What are maximum possible eruptions (Dragon Kings)?**

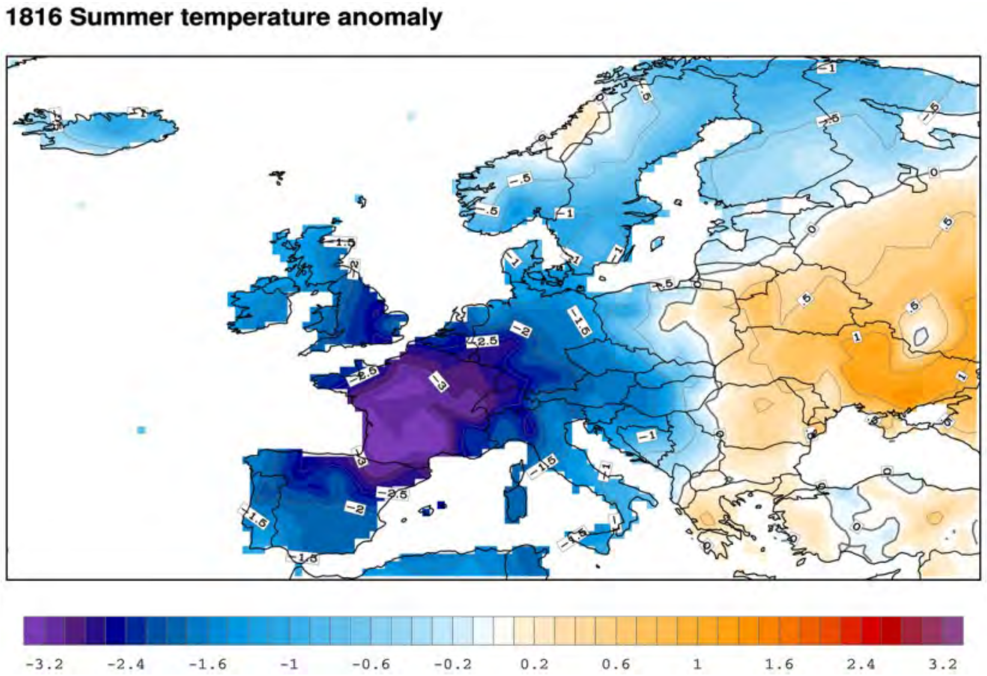
Laacher Sea volcano VEI=6 eruption 13,000 years ago



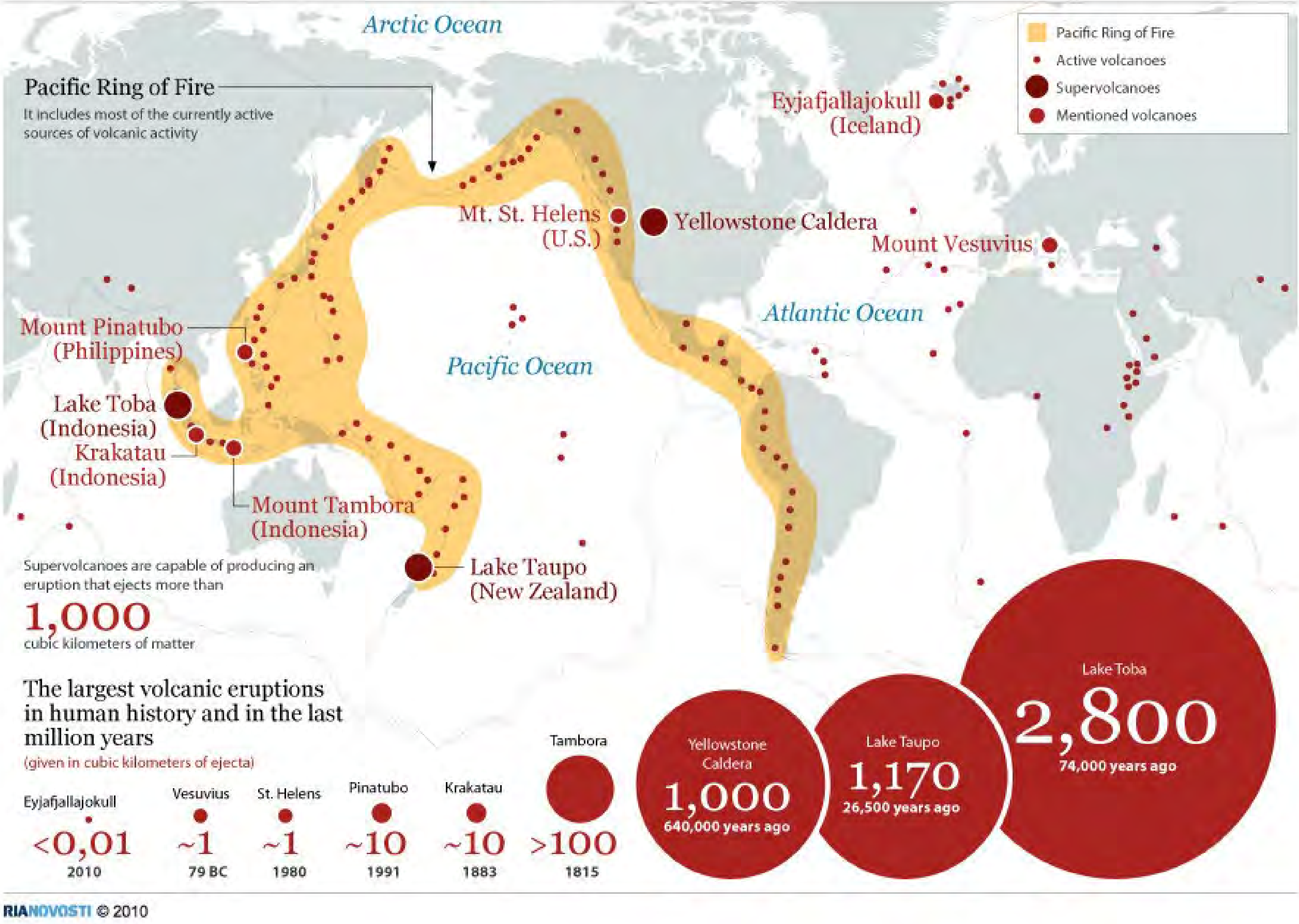
1815 eruption of Mount Tambora, Indonesia

- volcano height decreased from 4300 m to 2850 m
- ejected up to 150 km^3 of ashes
- ~10,000 people were killed directly by the eruption
- ~80,000 people died in Indonesia from deceases and starvation
- ~200,000 people died in Europe because of the famine caused by the "volcanic winter" in 1916

150 km^3 ≈ 2800 km^2 covered by 50 m of volcanic ash



Supervolcanic eruptions



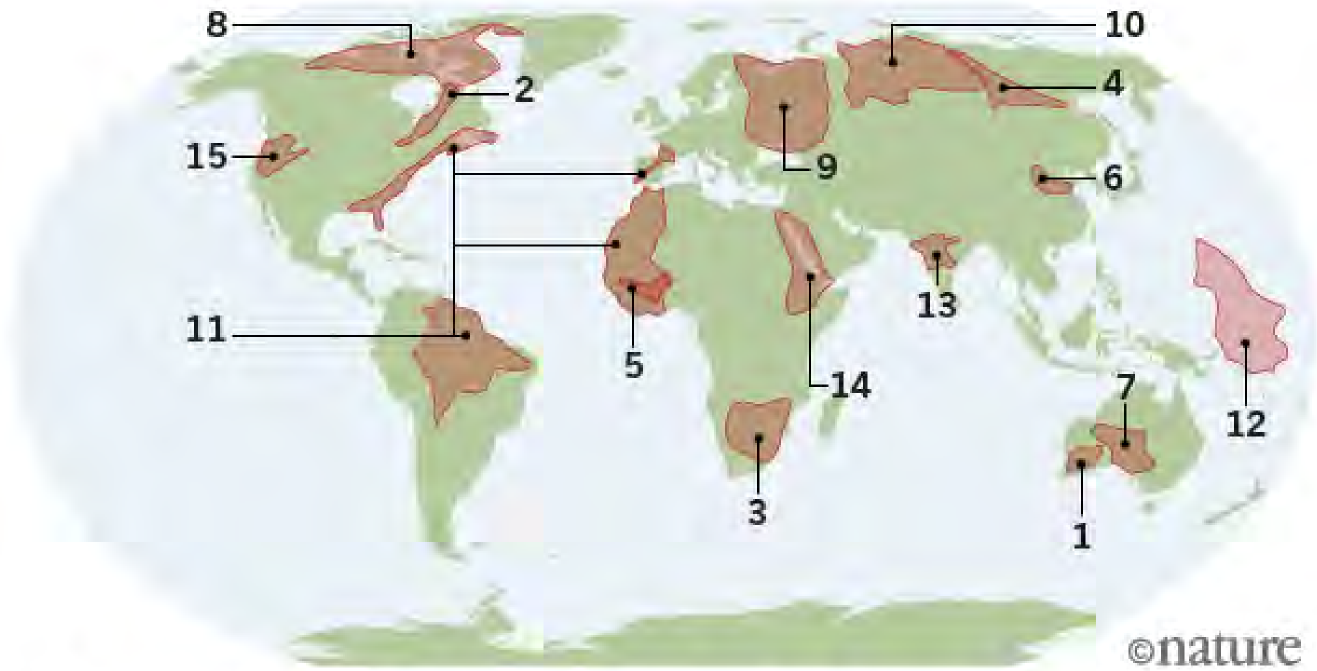
Toba super-eruption 74,000 years ago

2800 km^3 ≈ 2800 km^2 covered by 1 km of volcanic ash

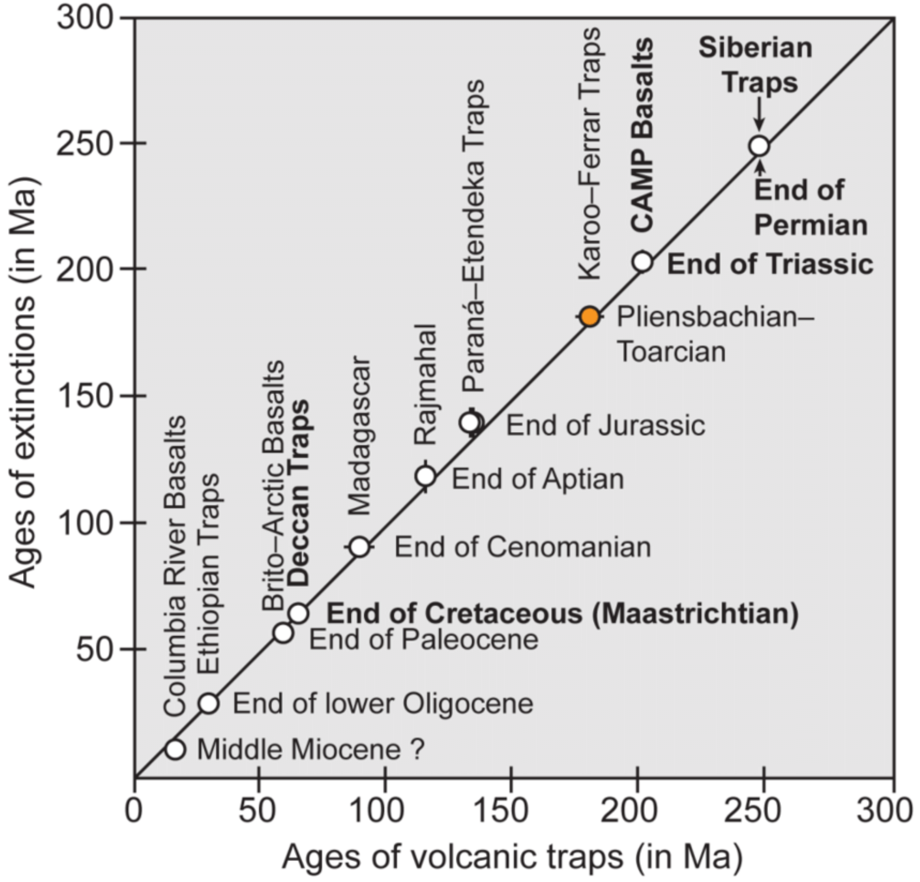
- one of the Earth's largest known explosive eruptions
- ejected ~2800 km3 of erupted material
- possibly caused a global volcanic winter of six to ten years
- possibly caused a 1,000-year-long cooling episode
- possibly caused a bottleneck in human evolution

World changing eruptions

erupted volumes > 10^6 km^3



1. **Widgiemooltha** 2.42 billion years
2. **Ungava** 2.22 billion years
3. **Bushveld** 2.05 billion years
4. **Timpton** 1.75 billion years
5. **Essakane** 1.52 billion years
6. **Dashigou** 920 million years
7. **Gairdner** 820 million years
8. **Franklin** 725 million years
9. **Kola–Dneiper** 370 million years
10. **Siberian Traps** 252 million years
11. **Central Atlantic Magmatic Province** 200 million years
12. **Ontong Java** 120 million years
13. **Deccan Traps** 66 million years
14. **Afro–Arabian** 30 million years
15. **Columbia River** 17 million years



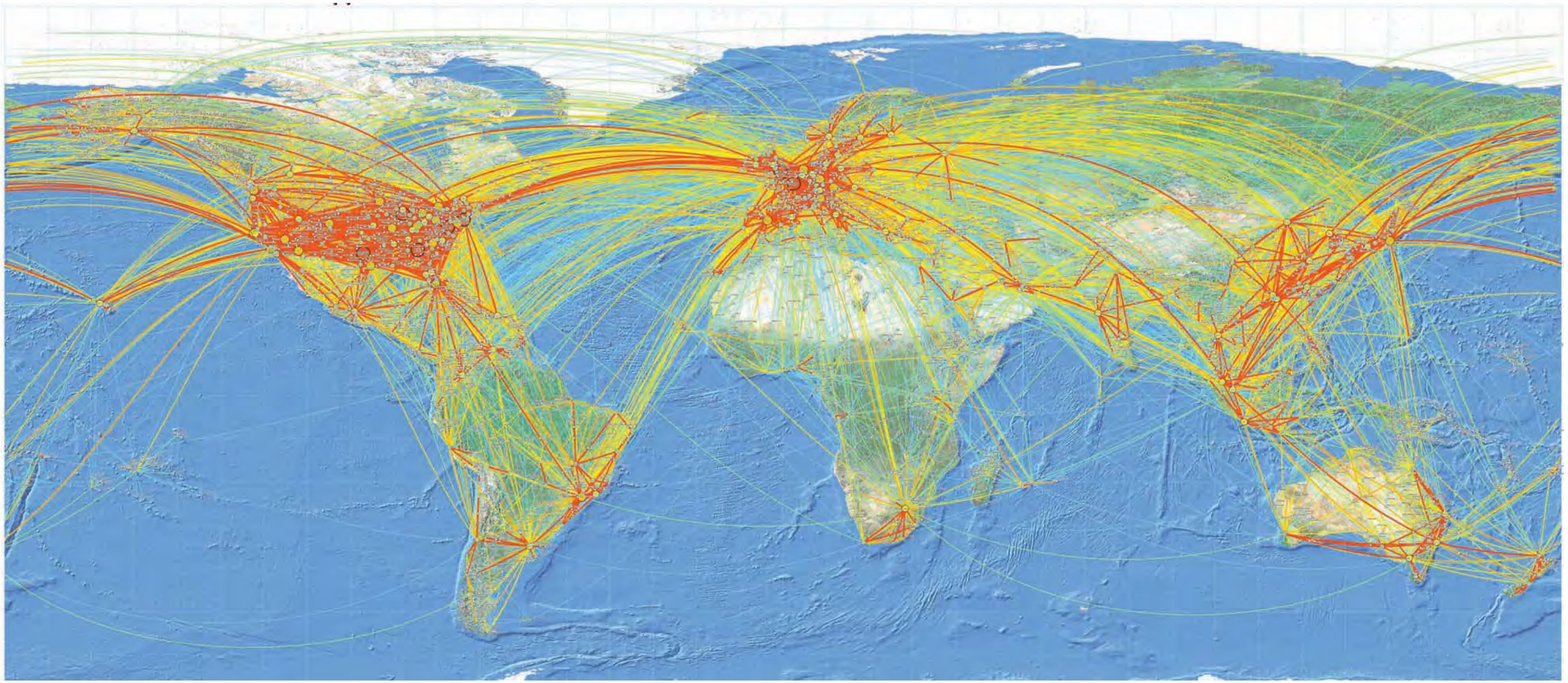
Some conclusive remarks about volcanic eruptions

- time predictable but not size predictable
- physics still not sufficiently understood
- main loading (magma production rate) is very poorly quantified
- hazards are multiple and difficult to quantify
- volcanic hazard should be considered as a **global phenomena**
- most of information is from geological observations that are difficult to collect
- major events were not observed in real industrialized environment
- **no empirical data for the major hazard and risk assessment**
- **Dragon-King events should be expected (when?)**

Thank you!

Questions?

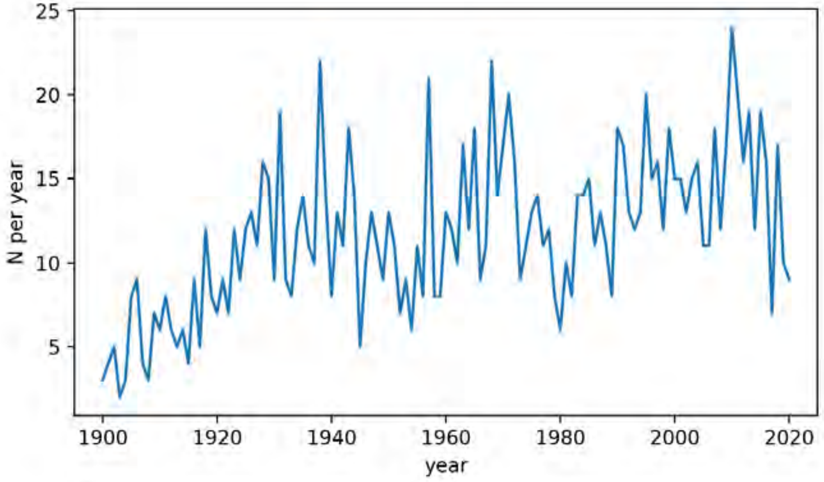
Many aviation flight corridors pass in the vicinity of active volcanoes

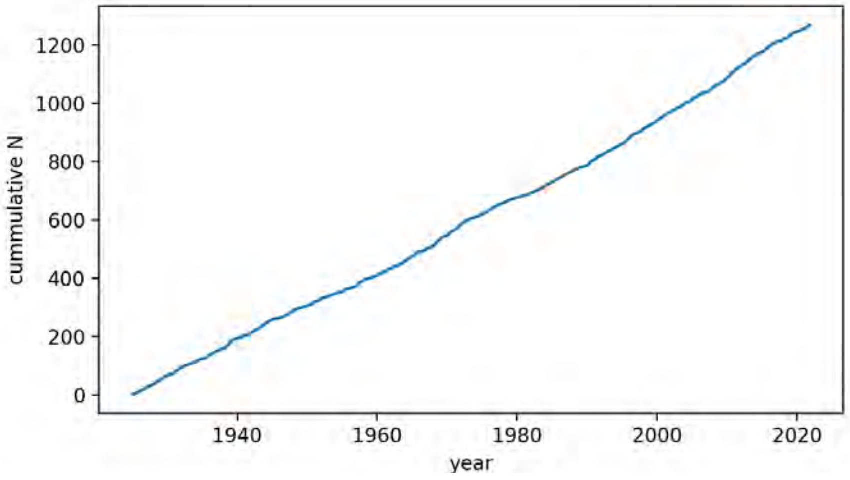


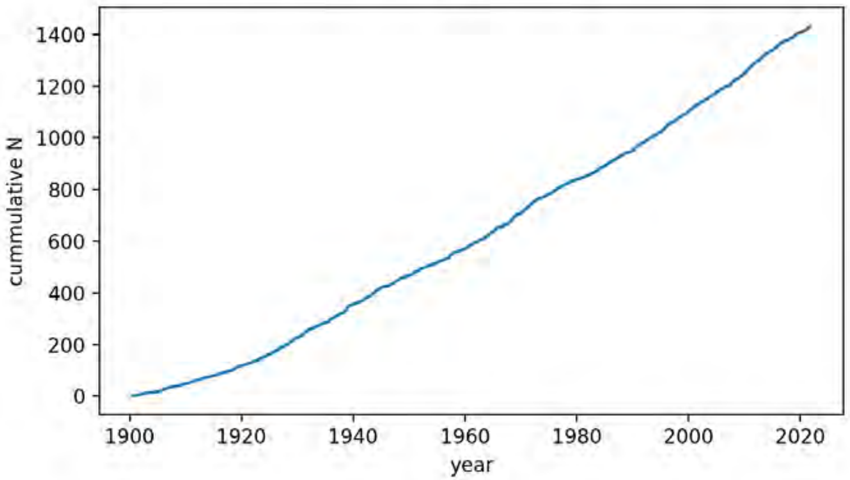
Some important questions:

- do we miss possible seismogenic faults?
- could we underestimate maximum magnitudes?
- **are earthquakes predictable (should be the hazard time-variable)?**

global M = 7+ earthquakes







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Latest Earthquakes

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Random variability explains apparent global clustering of large earthquakes

January 1, 2011

The occurrence of 5 Mw ≥ 8.5 earthquakes since 2004 has created a debate over whether or not we are in a global cluster of large earthquakes, temporarily raising risks above long-term levels. I use three classes of statistical tests to determine if the record of M ≥ 7 earthquakes since 1900 can reject a null hypothesis of independent random events with a constant rate plus localized aftershock sequences. The data cannot reject this null hypothesis. Thus, the temporal distribution of large global earthquakes is well-described by a random process, plus localized aftershocks, and apparent clustering is due to random variability. Therefore the risk of future events has not increased, except within ongoing aftershock sequences, and should be estimated from the longest possible record of events.

- Digital Object Identifier: 10.1029/2011GL049443
- Source: USGS Publications Warehouse (indexId: 70036164)

Contacts

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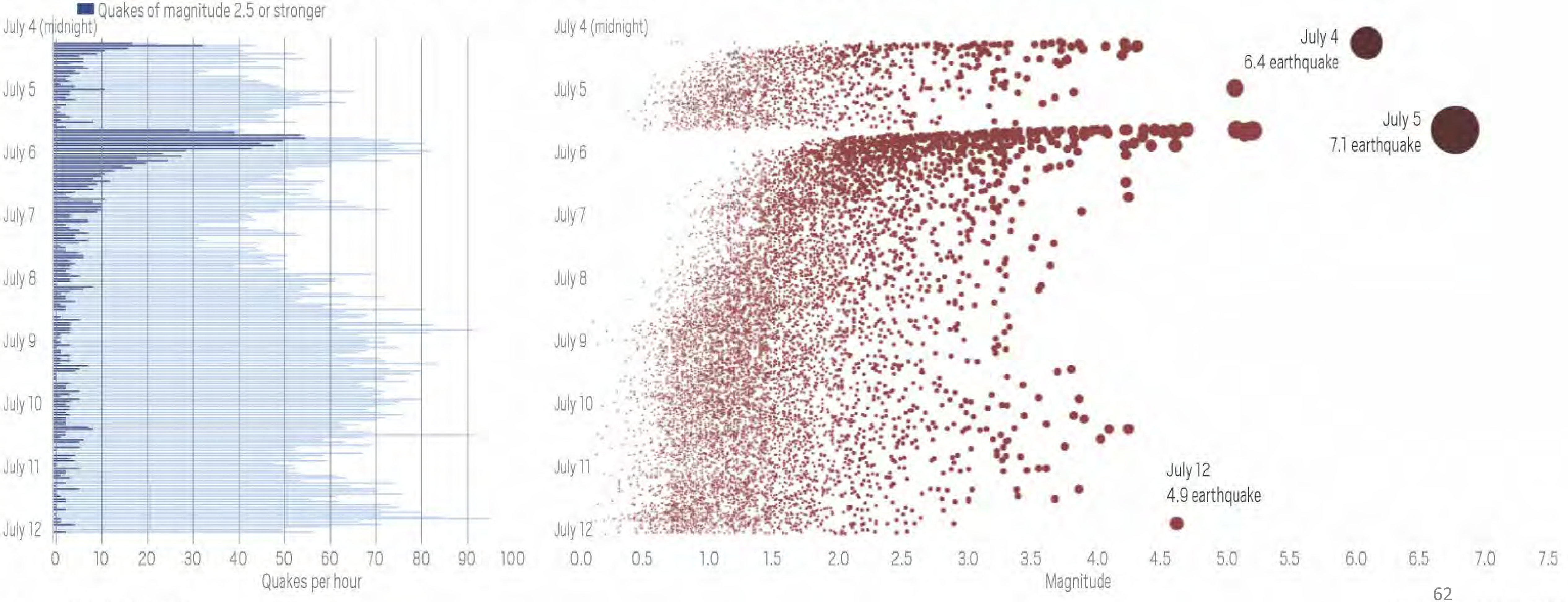
Email: ajmichael@usgs.gov
Phone: 650-439-2777

data from: *https://earthquake.usgs.gov/earthquakes/search/*

Aftershocks and foreshocks

Ridgecrest-area quakes

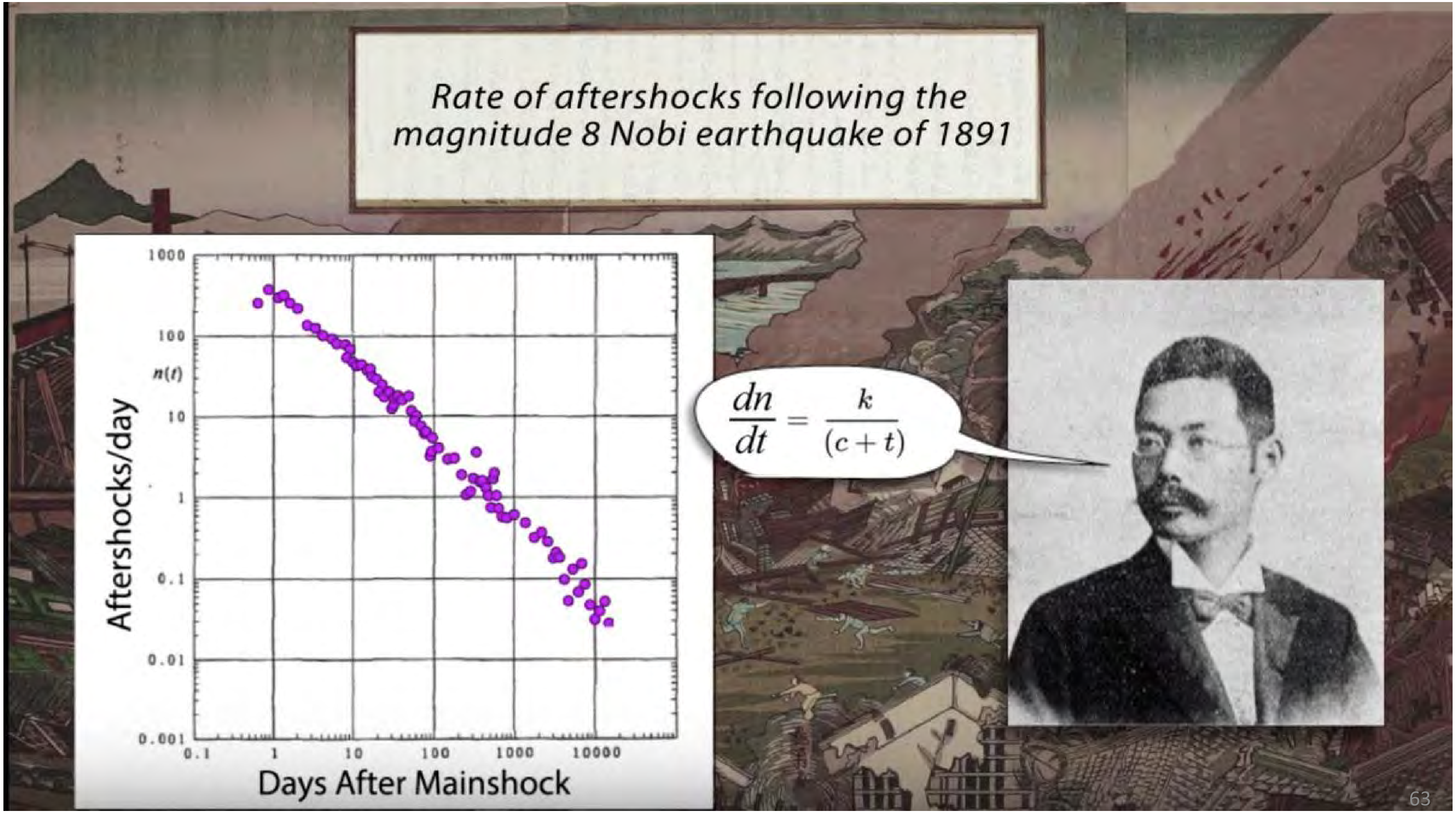
Here is a representation of all 11,887 earthquakes recorded by the U.S. Geological Survey between 10 a.m. July 4 and 10 a.m. July 12 in a 50-mile radius of the largest quake in the Ridgecrest series. The lack of small earthquakes right after the largest ones isn't because they weren't happening, seismologists say, but because equipment couldn't pick them out of the larger movements.



Source: U.S. Geological Survey

NIKIE JOHNSON, SNCG

Aftershocks (release of the mainshock induced stress) Omori's law (1894)



Aftershocks and foreshocks

Aftershocks

- systematically observed
- well described by statistical models (Omori’s, ETAS, …)
- can be used for short-term hazard assessment?

Foreshocks

- precursory phenomena
- intermittent (are not systematically observed)
- cannot be robustly used for forecasting