# Introduction to Seismic Hazard Analysis

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# Earthquake Hazard – A widespread danger

Earthquakes are one of the most costly natural hazards worldwide

Munich RE

## Loss events worldwide 1980 – 2014
10 costliest events ordered by overall losses

| Date | Event | Affected area | Overall losses in US$ m original values | Insured losses in US$ m original values | Fatalities |
|---|---|---|---|---|---|
| 11.3.2011 | Earthquake, tsunami | Japan: Aomori, Chiba, Fukushima, Ibaraki, Iwate, Miyagi, Tochigi, Tokyo, Yamagata | 210,000 | 40,000 | 15,880 |
| 25-30.8.2005 | Hurricane Katrina, storm surge | USA: LA, MS, AL, FL | 125,000 | 62,200 | 1,322 |
| 17.1.1995 | Earthquake | Japan: Hyogo, Kobe, Osaka, Kyoto | 100,000 | 3,000 | 6,430 |
| 12.5.2008 | Earthquake | China: Sichuan, Mianyang, Beichuan, Wenchuan, Shifang, Chengdu, Guangyuan, Ngawa, Ya'an | 85,000 | 300 | 84,000 |
| 23-31.10.2012 | Hurricane Sandy, storm surge | Bahamas, Cuba, Dominican Republic, Haiti, Jamaica, Puerto Rico, USA, Canada | 68,500 | 29,500 | 210 |
| 17.1.1994 | Earthquake | USA: CA, Northridge, Los Angeles, San Fernando Valley, Ventura, Orange | 44,000 | 15,300 | 61 |
| 1.8-15.11.2011 | Floods | Thailand: Phichit, Nakhon Sawan, Phra Nakhon Si Ayuttaya, Pathumthani, Nonthaburi, Bangkok | 43,000 | 16,000 | 813 |
| 6-14.9.2008 | Hurricane Ike | USA, Cuba, Haiti, Dominican Republic, Turks and Caicos Islands, Bahamas | 38,000 | 18,500 | 170 |
| 27.2.2010 | Earthquake, tsunami | Chile: Concepción, Metropolitana, Rancagua, Talca, Temuco, Valparaiso | 30,000 | 8,000 | 520 |
| 23.10.2004 | Earthquake | Japan: Honshu, Niigata, Ojiya, Tokyo, Nagaoka, Yamakoshi | 28,000 | 760 | 46 |

Source: Munich Re, NatCatSERVICE, 2015

As at: January 2015

# Earthquake Hazard – Forecasting

Reduction of fatalities could ideally be carried out through short-term forecasting with:

- Analysis of precursors (highly debatable)
- Early warning systems (large investment, practical limitations)
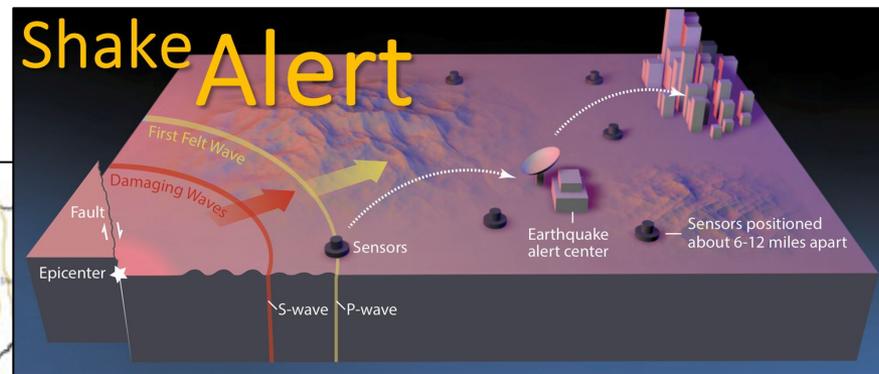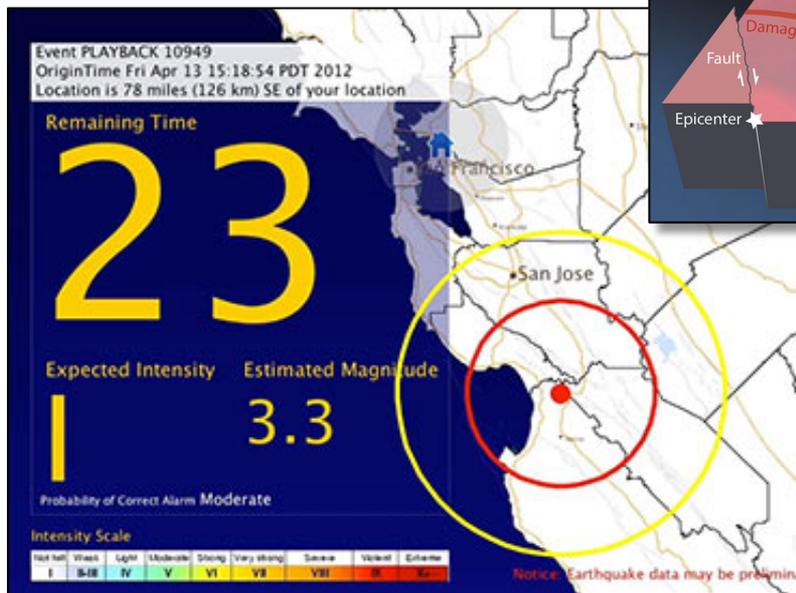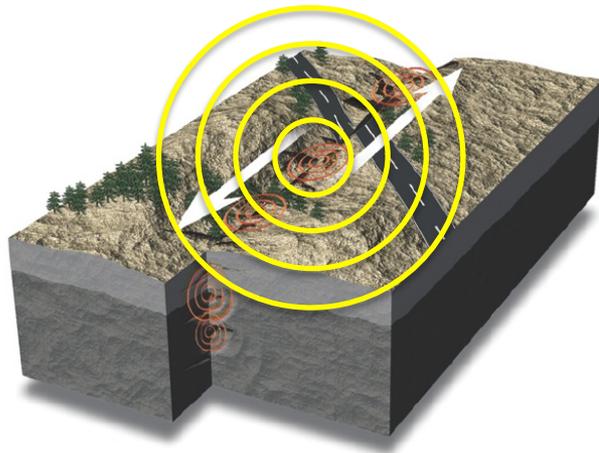


USGS ShakeAlert
EEW Program

# Earthquake Hazard – Ground Shaking Level

Reduction of losses should be properly done by preemptive design and reinforcement of new and existing building and infrastructures

This requires, however, a proper estimation of the **ground shaking level likely expected at a site within a given interval of time**

Question is: how and how precisely this level can be defined, given the little knowledge we have of the earthquake process?
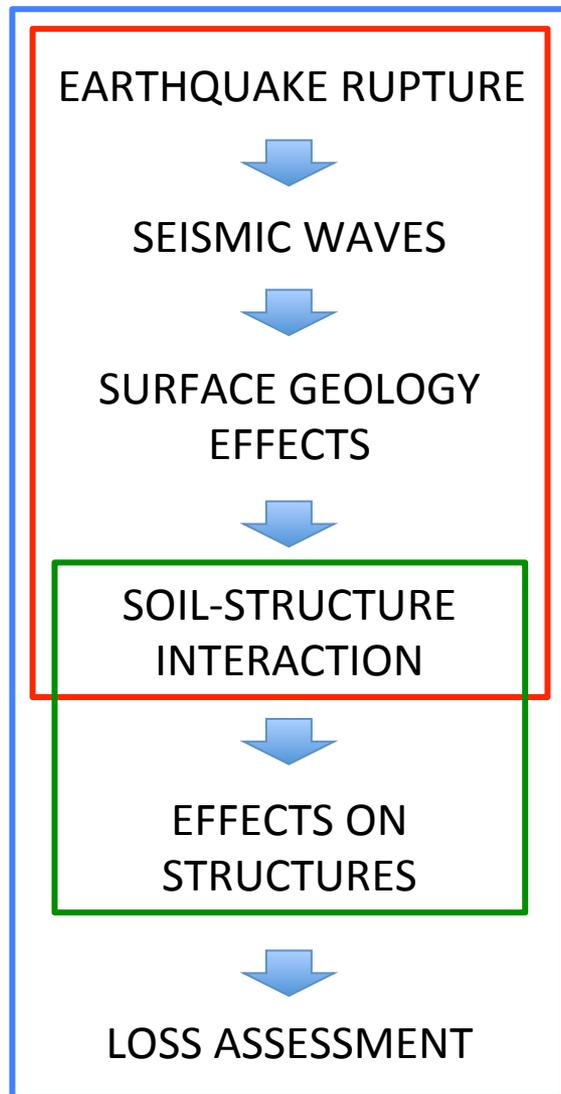
This is the task of
Seismic Hazard Analysis
(SHA)....

http://www.howitworksdaily.com/

# Earthquake Hazard and Risk

EARTHQUAKE RUPTURE

⬇

SEISMIC WAVES

⬇

SURFACE GEOLOGY EFFECTS

⬇

SOIL-STRUCTURE INTERACTION

⬇

EFFECTS ON STRUCTURES

⬇

LOSS ASSESSMENT

Seismic Hazard is therefore an essential component of Earthquake Risk Assessment

$$R = H * E * V$$

**Seismic Hazard (H)**

**Physical Vulnerability (V)**
**Exposure/Inventory (E)**

**Risk (R)**

# End-Users Perspective

**1) Engineers**
o   For what level of ground motion should I design my structure?
o   What are the possible earthquake scenarios that may pose a threat to my structure?
o   The Building Standard says I should ensure this performance level – how do I know how resistant to make my structure to ensure this?
o   What if I want to achieve different performance objectives (e.g. "operational", "life-safety", "no-collapse")?

**2) Insurers**
o   What is the probability of my exceeding X amount of loss from my portfolio in the next T years?
o   The Catastrophe Bond will trigger when "... earthquake occurs in this cell ... ground shaking exceed this value here..." – how likely is this to happen?
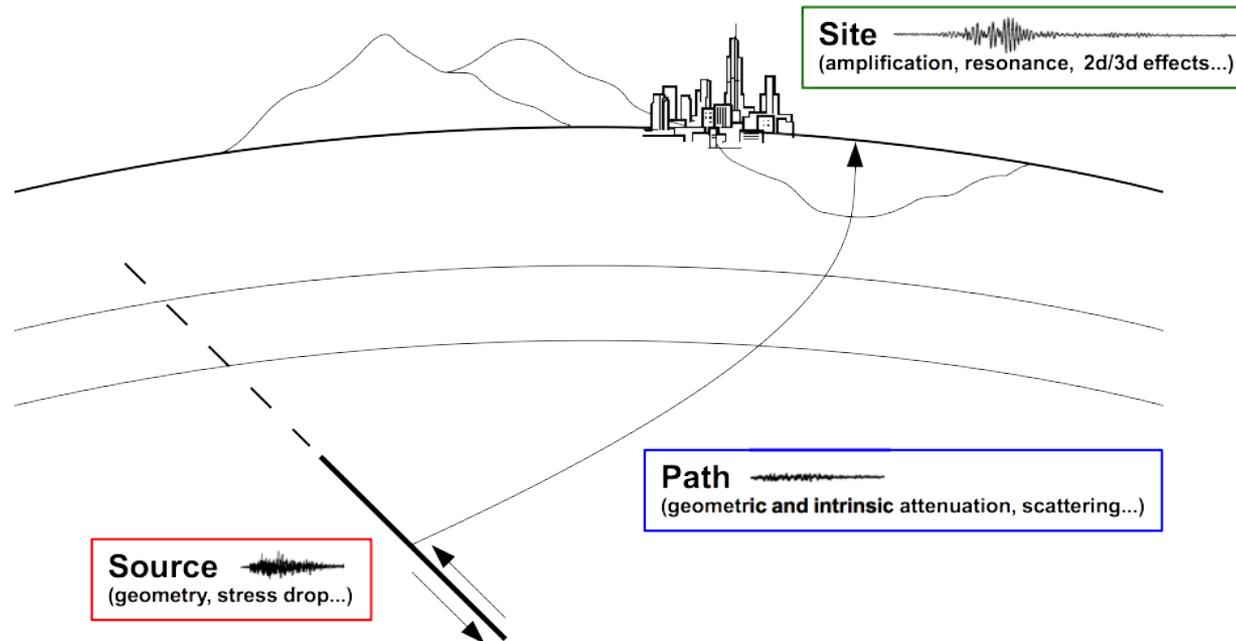
**3) Decision Makers & Public**
o   Will this property be damaged/destroyed?
o   How likely is this to happen?
o   What is the best course of action to take (cost-benefit)?
o   What sort of earthquakes can occur? What might happen when they do?

# SHA Requirements

For the calculation of hazard associated to a region is essential to know:

- o **Where** the earthquakes occur and the geometry of the seismic sources
- o **How often** earthquakes occur on each seismic source
- o **The size** of the earthquakes generated by each source
- o **Mechanical properties** of geological materials through which seismic waves will propagate (including surface geology)



**Site** (amplification, resonance, 2d/3d effects...)

**Path** (geometric **and intrinsic** attenuation, scattering...)

**Source** (geometry, stress drop...)

# Deterministic vs. Probabilistic Approach

Two are the main methodologies currently adopted for seismic hazard analysis:

**Deterministic.** Also called the "_Worst Case Scenario_"
One or a few earthquake scenarios are selected and the corresponding ground motion computed assuming a level of uncertainty on ground motion (i.e. a number of standard deviations above the median value predicted by a Ground Motion Prediction Equation - GMPE).

**Probabilistic:** All possible scenarios of engineering relevance for the investigated site are considered in the analysis taking into account their probability of occurrence i.e. all ruptures (magnitude+distance) and levels of uncertainty on ground motion.

# Deterministic Approach – Defining the "worst case"



Scenario #1

http://eoimages.gsfc.nasa.gov

$M^{max}$

$R^{min}$

Many issues:

- Largest earthquake in the source?
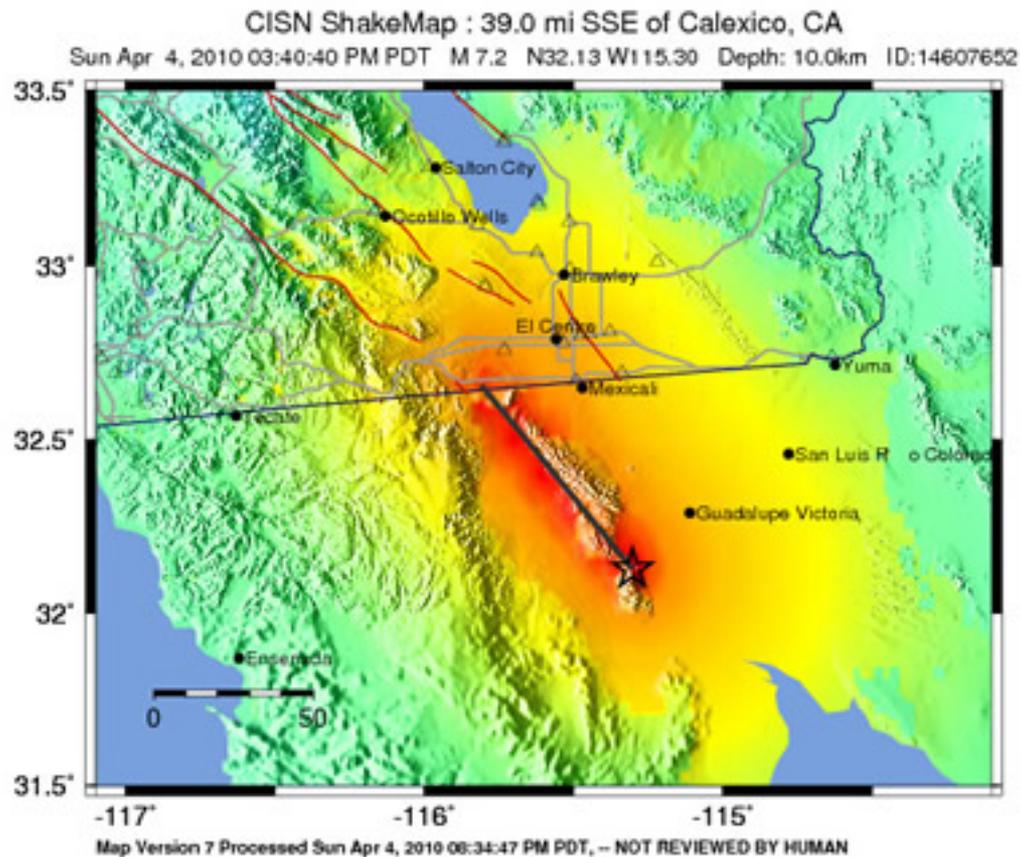- Closest earthquake to source?
- Worst possible or plausible scenario?

GMPE or Simulation

Modified from Field (USGS)

PGA @ 20Km + σ

Mag = 6.0

PGA (g)

Distance (Km)
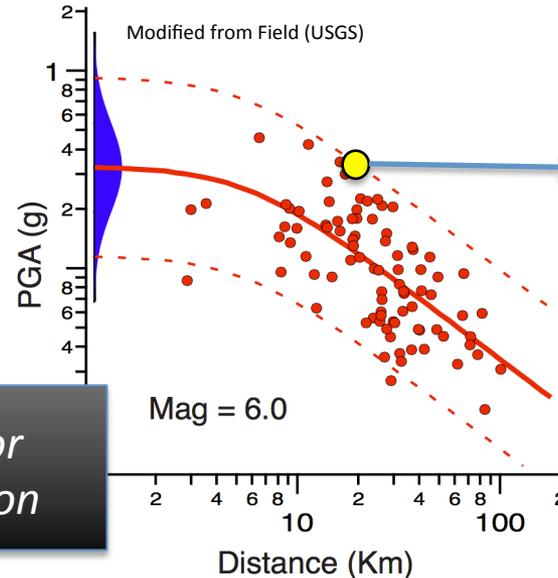
# Scenario Models - ShakeMap Example



CISN ShakeMap : 39.0 mi SSE of Calexico, CA
Sun Apr 4, 2010 03:40:40 PM PDT   M 7.2   N32.13 W115.30   Depth: 10.0km   ID:14607652

Map Version 7 Processed Sun Apr 4, 2010 06:34:47 PM PDT, -- NOT REVIEWED BY HUMAN

| PERCEIVED SHAKING | Not felt | Weak | Light | Moderate | Strong | Very strong | Severe | Violent | Extreme |
|---|---|---|---|---|---|---|---|---|---|
| POTENTIAL DAMAGE | none | none | none | Very light | Light | Moderate | Moderate/Heavy | Heavy | Very Heavy |
| PEAK ACC.(%g) | <.17 | .17-1.4 | 1.4-3.9 | 3.9-9.2 | 9.2-18 | 18-34 | 34-65 | 65-124 | >124 |
| PEAK VEL.(cm/s) | <0.1 | 0.1-1.1 | 1.1-3.4 | 3.4-8.1 | 8.1-16 | 16-31 | 31-60 | 60-116 | >116 |
| INSTRUMENTAL INTENSITY | I | II-III | IV | V | VI | VII | VIII | IX | X+ |

# PSHA - Basic Workflow

Probabilistic hazard is computed by taking into account **all the possible scenarios** generated by all the sources within a certain distance from the investigated site
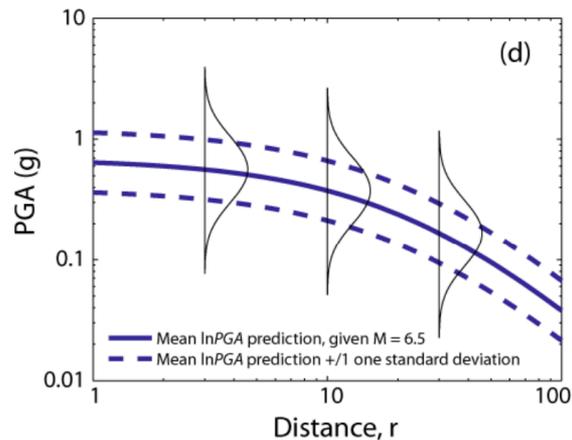
**Where**
Seismogenic Zone Models
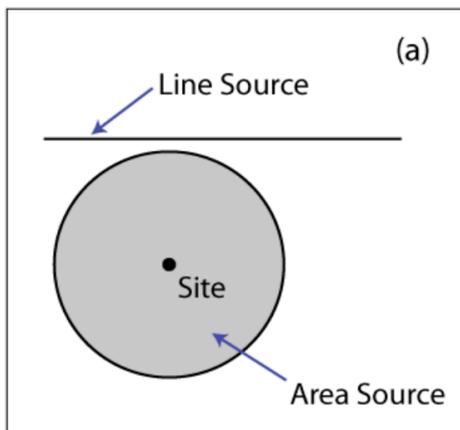


Modified from Baker (2008)

**When (how often)**
Recurrence Models
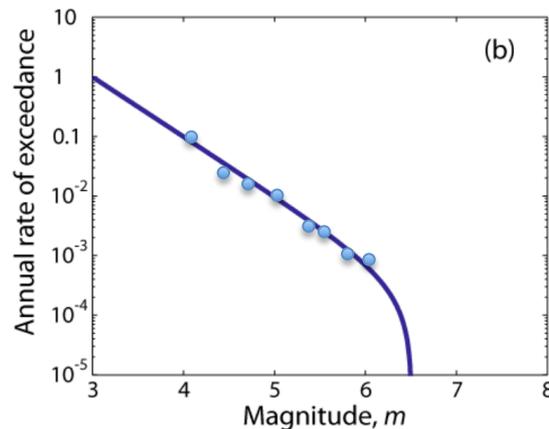


**How**
Ground Motion Models

# PSHA – Basic Equation

The rate λ of events with intensity (IM) larger than a value x experienced at a given site from the contribution of all sources can be formalized as:

$$\lambda(IM > x) = \sum_{i=1}^{n_{sources}} \lambda(M_i > m_{min}) \int_{m_{min}}^{m_{max}} \int_{r_{min}}^{r_{max}} P(IM > x \mid m, r) f_{M_i}(m) f_{R_i}(r \mid m) \, dr \, dm$$

Loop over distances

Loop over magnitudes

Loop over sources

The annual rate λ is then translated into probability by assuming a **Poisson recurrence model** (independent events):

$$P(IM > x) = 1 - e^{-\lambda(IM > x)t}$$
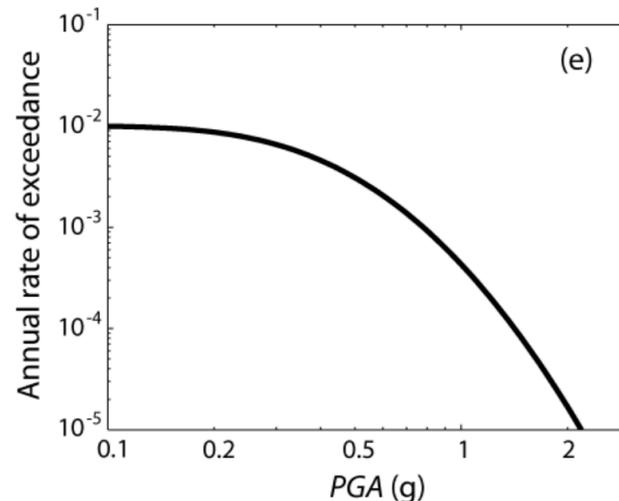
# Seismogenic Zones

Distributed Seismicity:

- Single points
- Grid representations (e.g. smoothed seismicity)
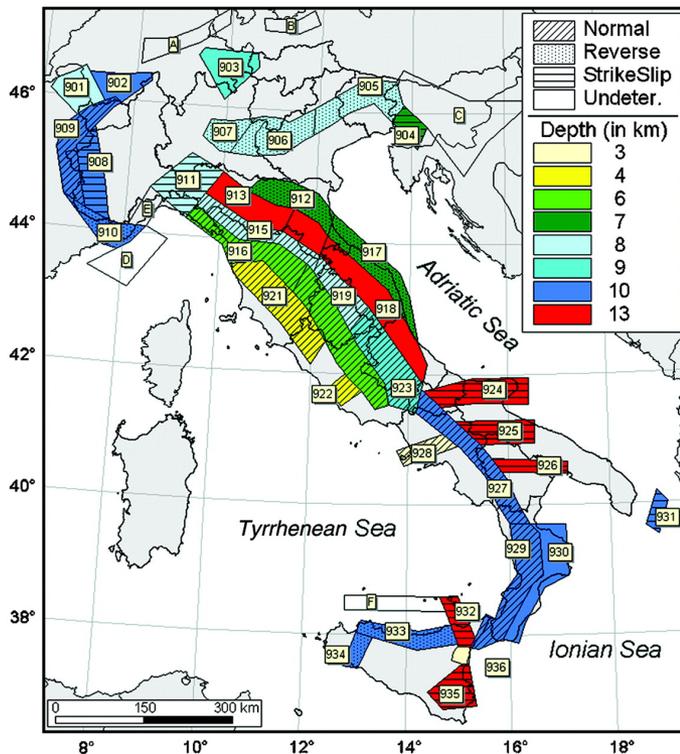- Polygon of Uniform Seismicity (so far the most widely used approach)
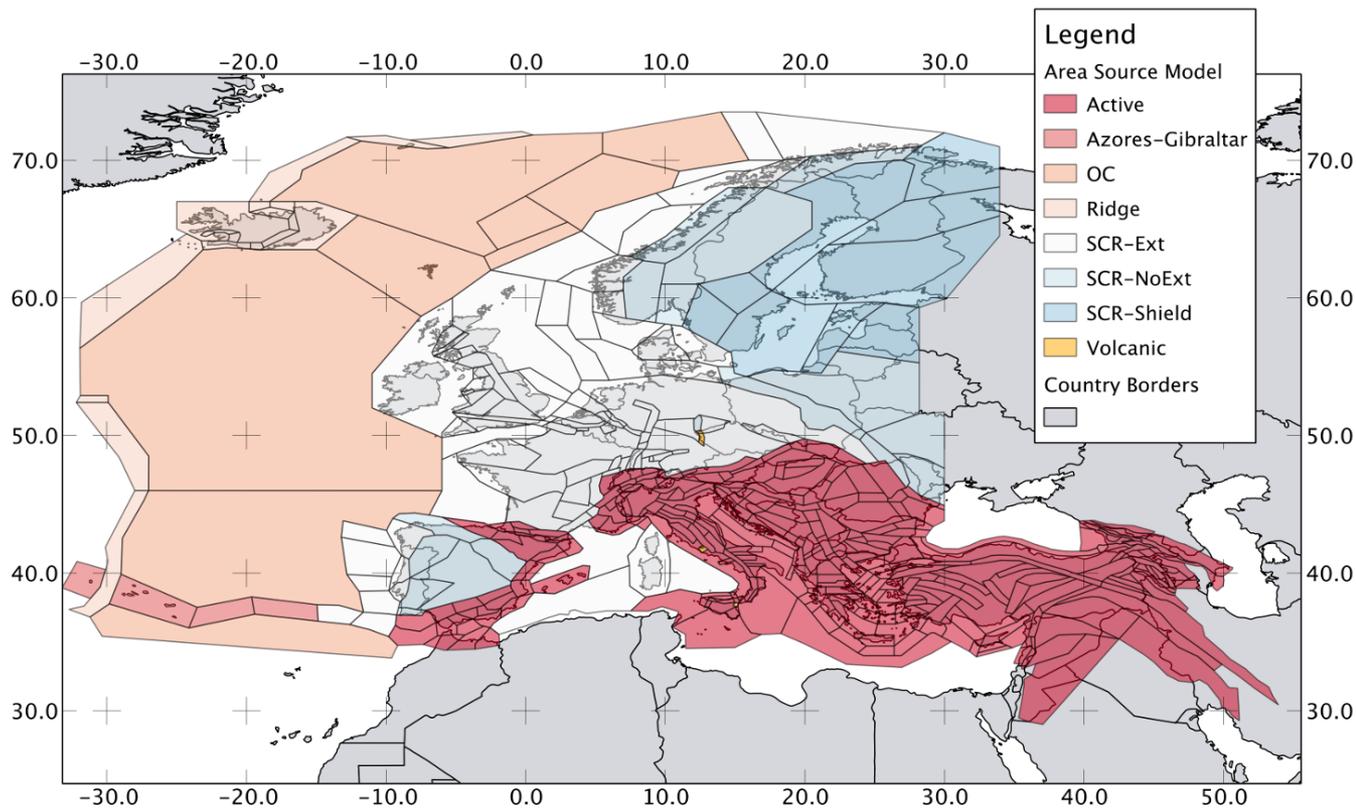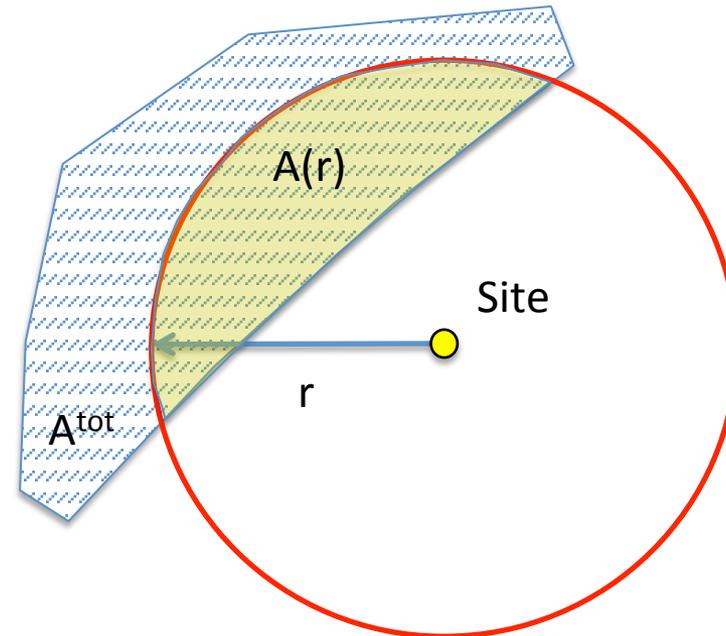
SHARE Area Source Zonation Model

# Area Sources Zones

Source Zone 1

Uniform Area Source Model of Italy
(modified from Meletti et al., 2008)





The cumulative probability P(R < r) can be seen as the area of the sub-zone within a distance r from the site, divided by the area of the total source zone

# Active Faults

o   If fault geometry is sufficiently known, it can be modeled as a three-dimensional surface

o   Such approach can be used for active shallow faults as well as larger subduction interfaces

**Complex fault**

**SARA Model**

**Segmented planar fault**
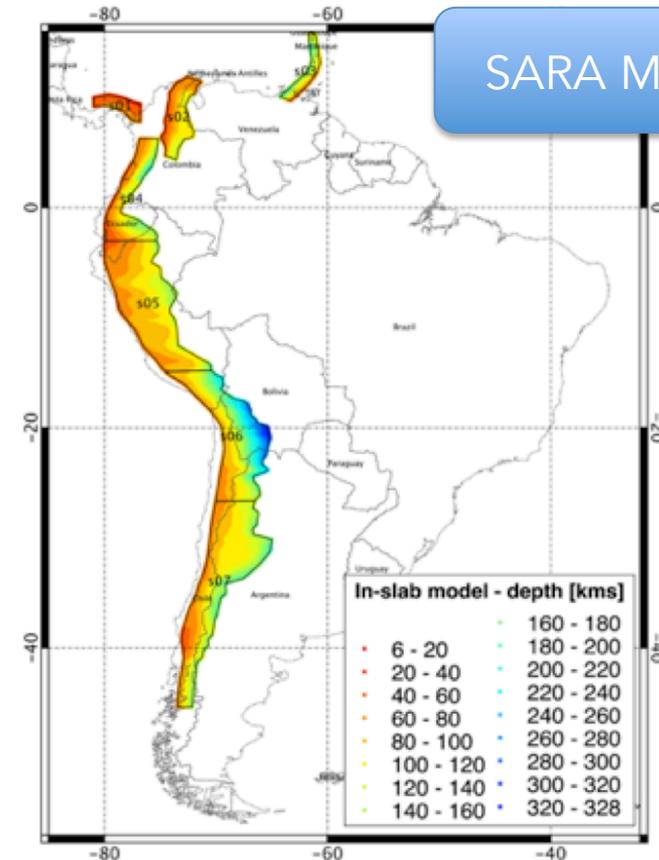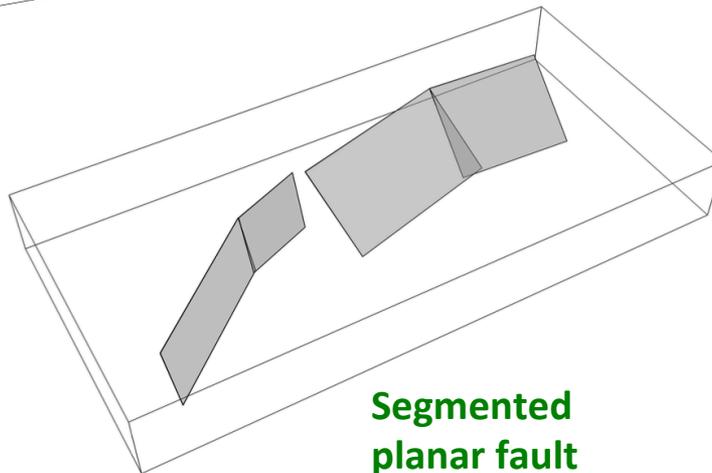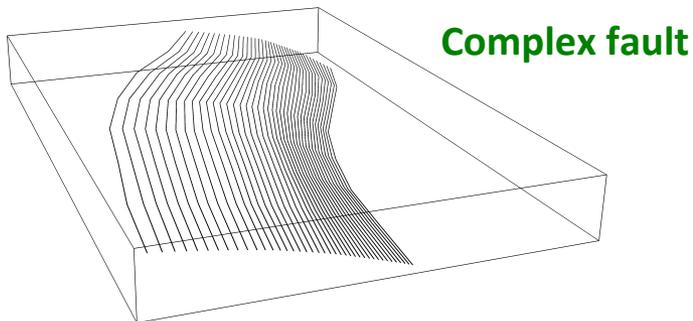
# Building a Seismic Source Model

o  Primary data resource is the **homogenized earthquake catalogue**
o  Models of recurrence often determined from observed (instrumental and historical seismicity) within the source



SSA-GEM Catalogue

Faults + Plate Boundaries

Area Source Model

Macgregor (2015)
Saria et al. (2014)
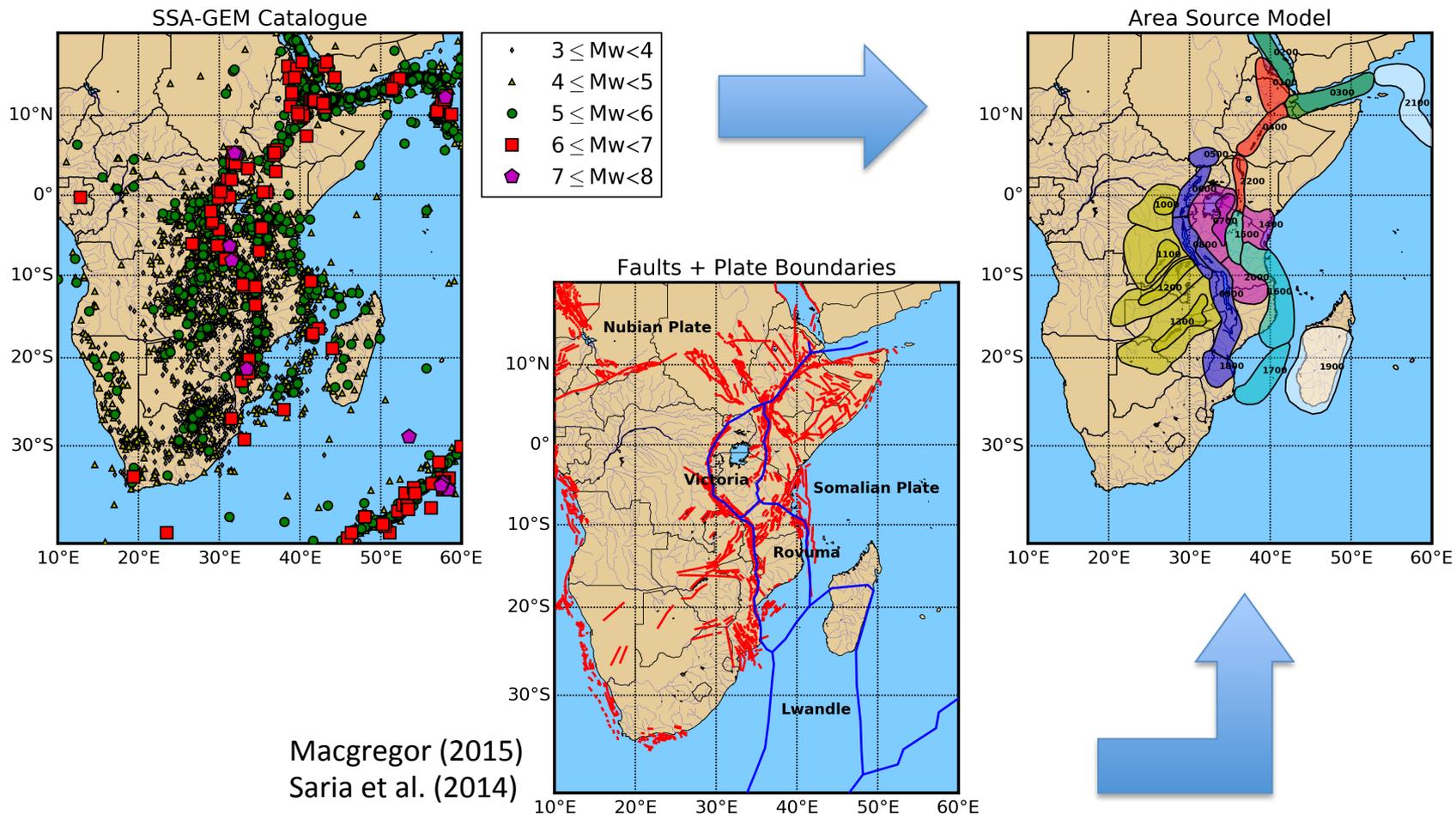
# Seismicity Analysis

To obtain estimates of stationary seismicity rates the recurrence models need to be fit to earthquake catalogues that are:
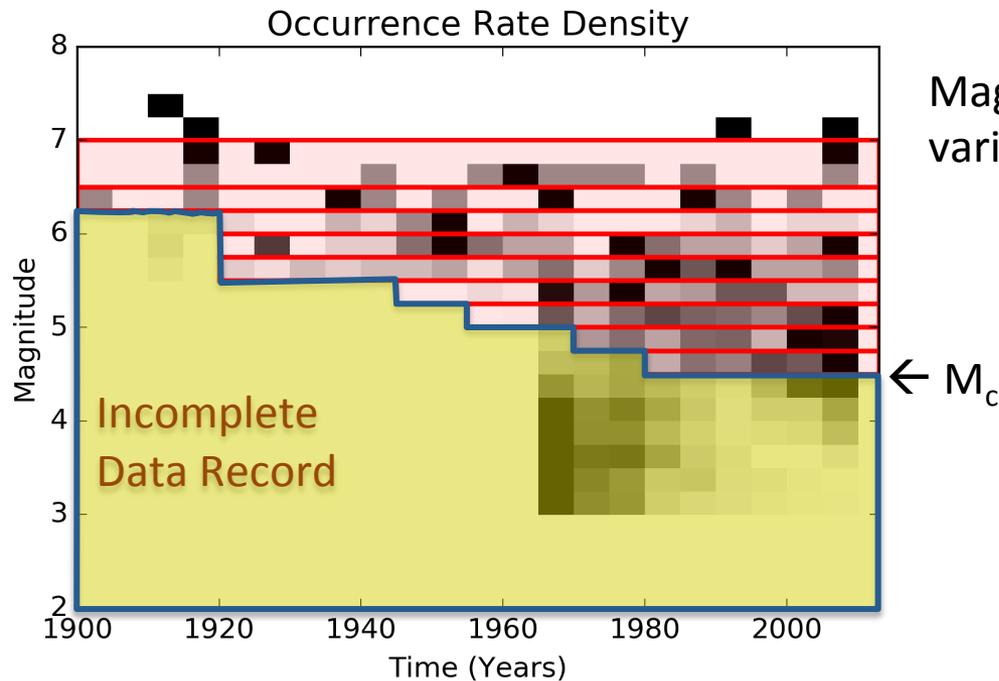
1) Purged of non-Poissonian Events (i.e. foreshocks and aftershocks) which are dependent ➔ **Declustering**
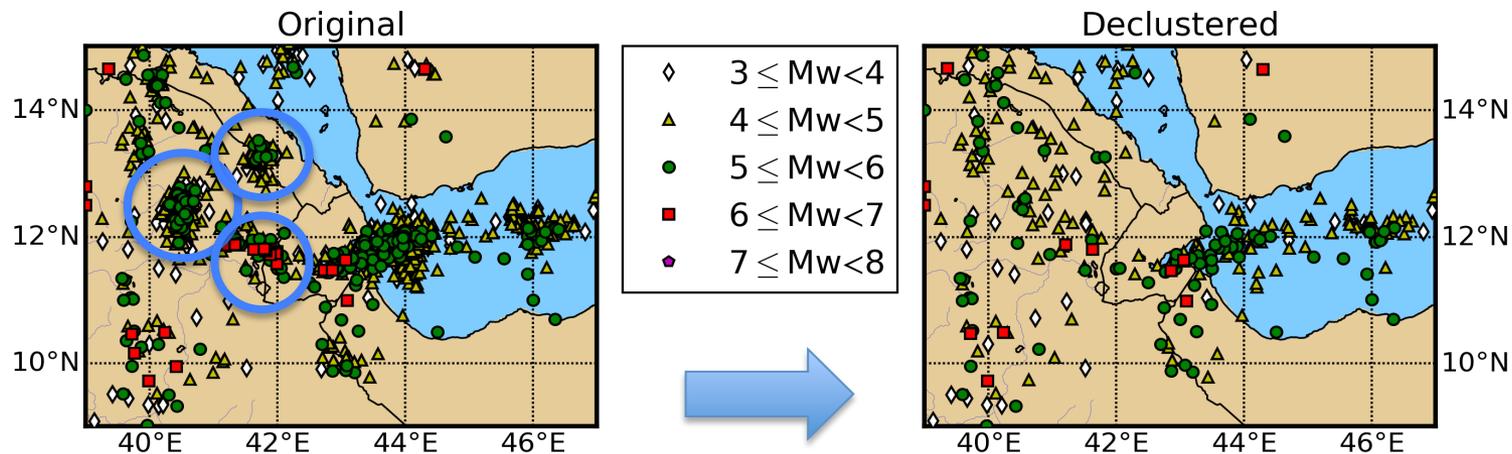
# Seismicity Analysis

2) Spatially and temporally complete (i.e. are recording all events above a given magnitude for a particular space-time window)

➔ **Completeness Analysis**



Occurrence Rate Density

Magnitude of completeness varies as function of time
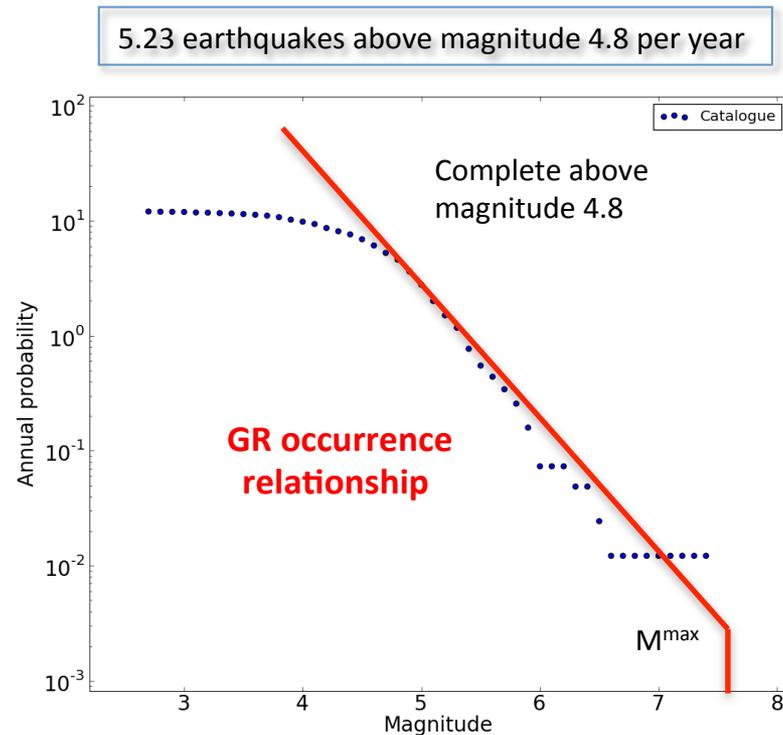
Incomplete Data Record

← $M_c$

# Magnitude occurrence relations

Temporal distribution of seismicity is modeled assuming a given magnitude occurrence relation

The most widely used relation is the **Gutenberg-Richter exponential law**:

$$N(M > m) = e^{a-bM}$$

Calibration of coefficients **a** and **b** is a key issue in PSHA



5.23 earthquakes above magnitude 4.8 per year

Complete above magnitude 4.8

GR occurrence relationship

$M^{max}$
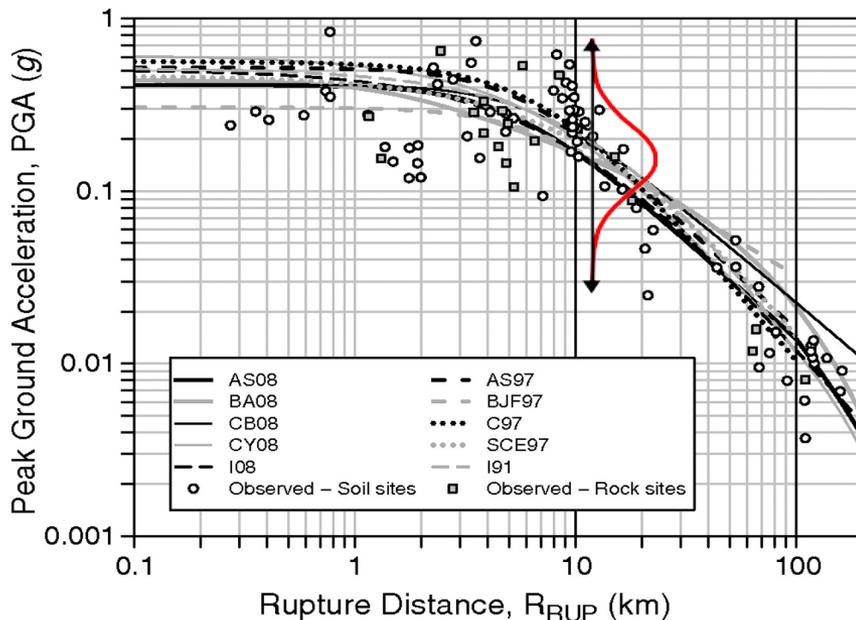
Catalogue

Annual probability

Magnitude

Recurrence models typically fit to catalogue using maximum likelihood techniques

# Ground Motion Modeling

The easiest way to model ground motion is perhaps the use of Ground Motion Prediction Equations (GMPEs)

$$\log IM_{ij} = f\left(M_i\right) + f\left(R_{ij}, M_i\right) + f\left(R_{ij}\right) + f\left(S_j\right) + f\left(F_{ij}\right) + z_{E,i}\tau + z_{A,ij}\sigma$$



GMPE terms are representations of a given physical model, whose reliability can be increased with the availability of new empirical information
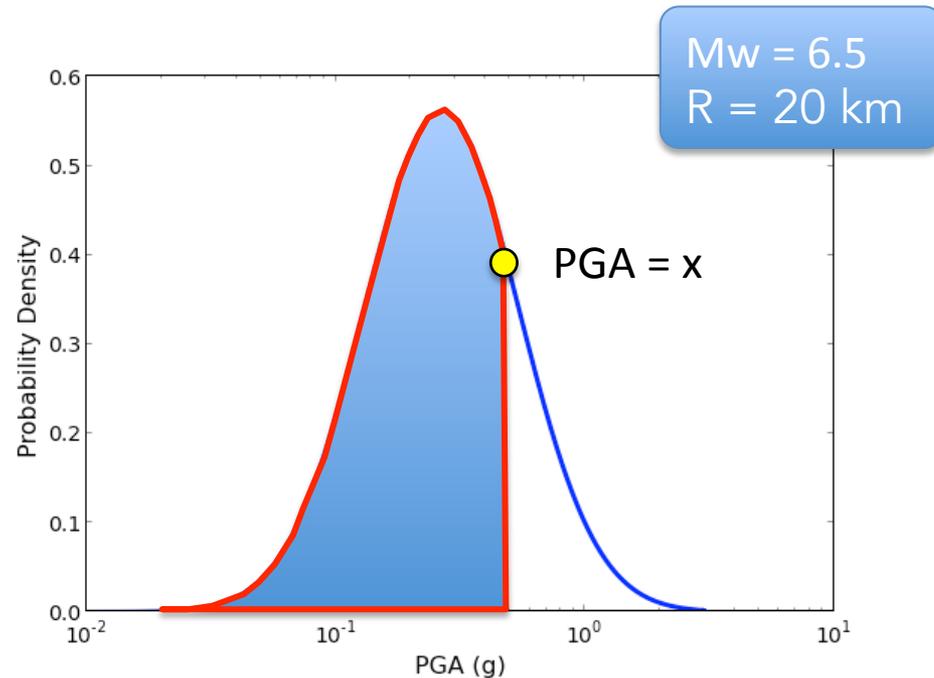
$$IM = PGA, PGV, SA...$$

# Ground Motion Prediction

A fundamental property of GMPEs is the assumption that the aleatory variability can be represented by a **lognormal distribution** characterized by a **median** ground motion and the corresponding **standard deviation**

**P(IM > x | M, R)** can then be easily determined as the probability that IM will exceed the value x



Mw = 6.5
R = 20 km

PGA = x

# Variability and Uncertainty

Uncertainty and variability are concepts tightly linked with seismic hazard analysis

Two are the typologies of uncertainty considered:

- *Aleatory*
- *Epistemic*

Aleatory uncertainty is connected with the intrinsic randomness and the nature of the earthquake process

Epistemic uncertainty on the contrary depends on our limited knowledge the phenomenon (e.g. lack of observation data)

This means that: aleatory uncertainty is irreducible whereas epistemic uncertainty can be potentially reduced

# Variability and Uncertainty

Epistemic and aleatory variability are nonetheless handled separately into the hazard analysis process:

1) Aleatory uncertainty is usually incorporated in the PSHA integrals

*Examples: Earthquake location, uncertainty on ground motion estimates*

2) Epistemic uncertainty is formally taken into account by using alternative models (or parameterizations) within a <u>logic-tree</u> structure

*Examples: ground motion models, recurrence parameters (b-value, maximum magnitude), style of faulting….*

# Logic- Tree Strategy – Weights and Branches

Epistemic uncertainties modeled by including multiple models in logic trees
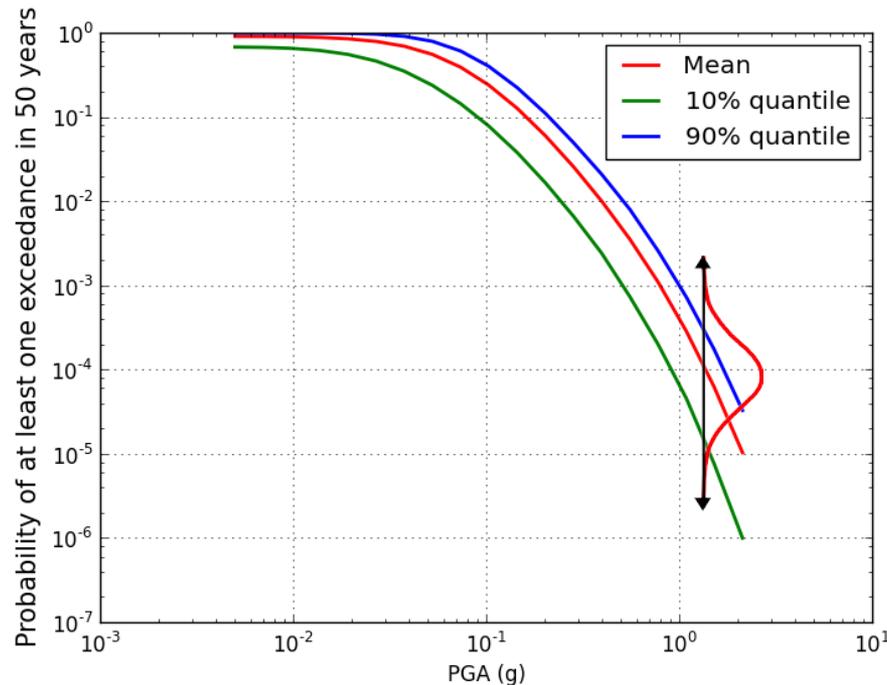Each model is assigned weights
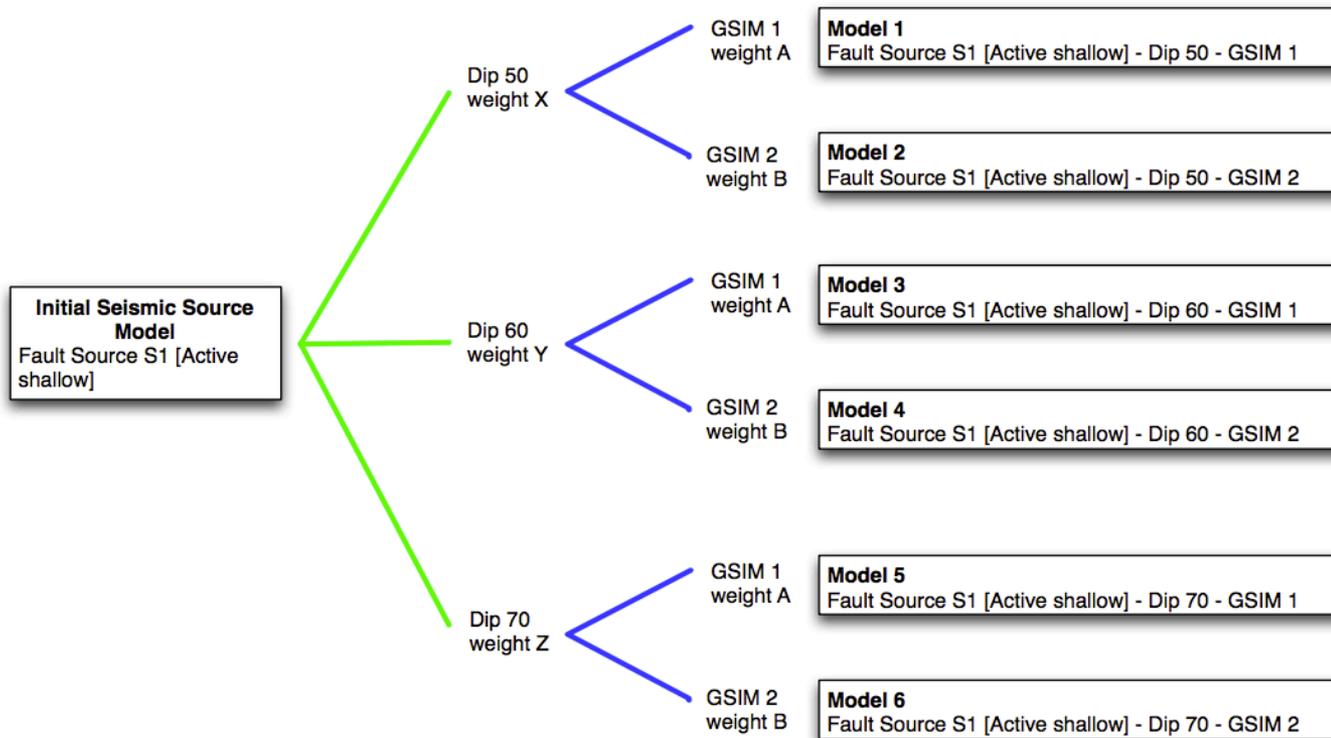


How to assign weights?
o  Based on fits to observed data? (**Empirical approach**)
o  Based on theoretical representation of the physics of the process?
   (**Physical approach**)

# Logic-Tree Strategy – A Posteriori Statistic

From the ensemble of all hazard curves from each log-tree realization, **mean** and **percentile curves** can be computed



Note: Less data or knowledge should imply greater epistemic uncertainty

**HOWEVER**

Use of additional "conflicting" models (from newly available data) can increase epistemic uncertainty
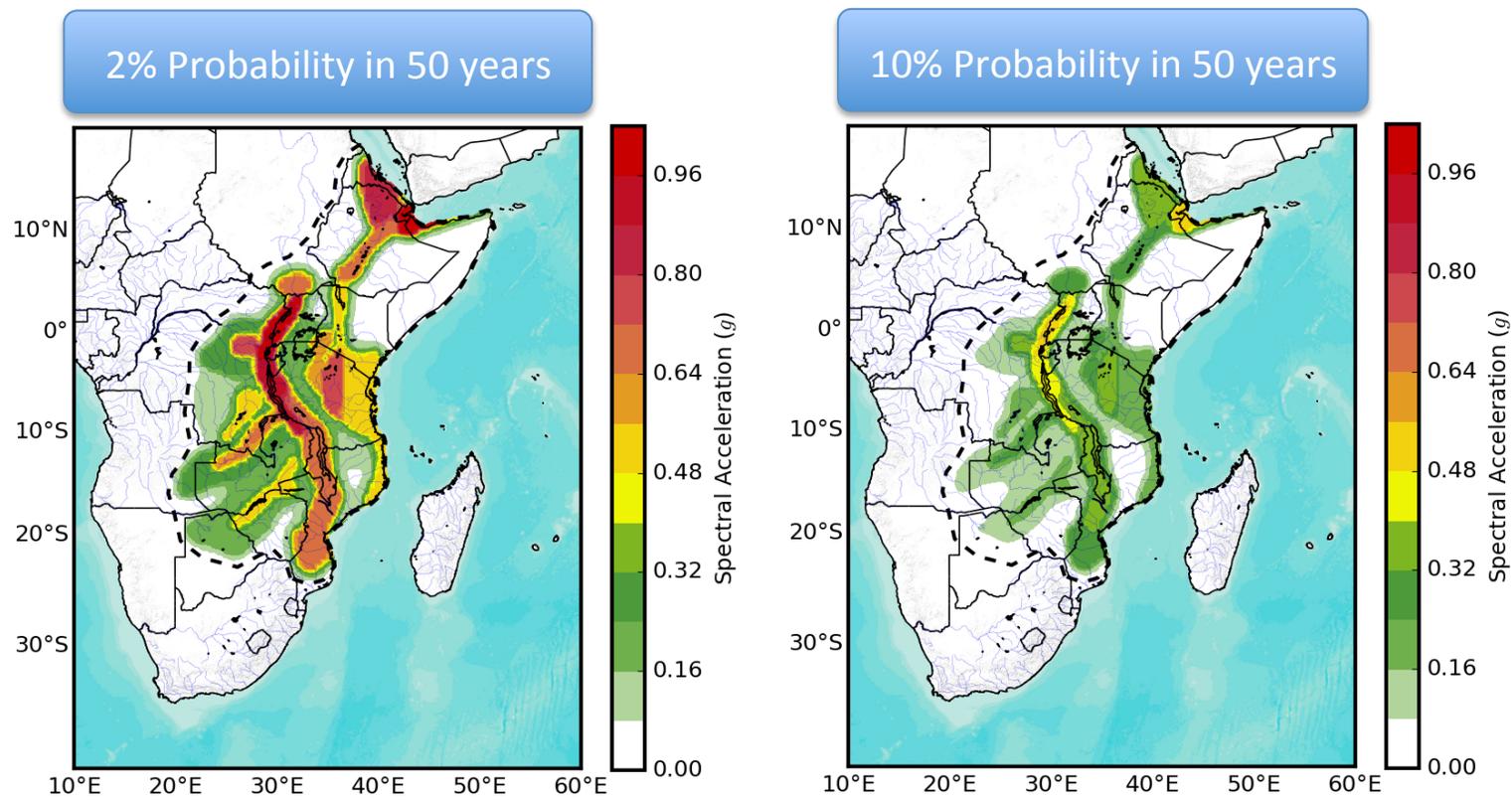
Epistemic uncertainty might be (paradoxically) lower in regions with less data!

# PSHA Outputs – Hazard Maps

Shows the uniform probability of exceedance of a given ground motion measure for a given return period
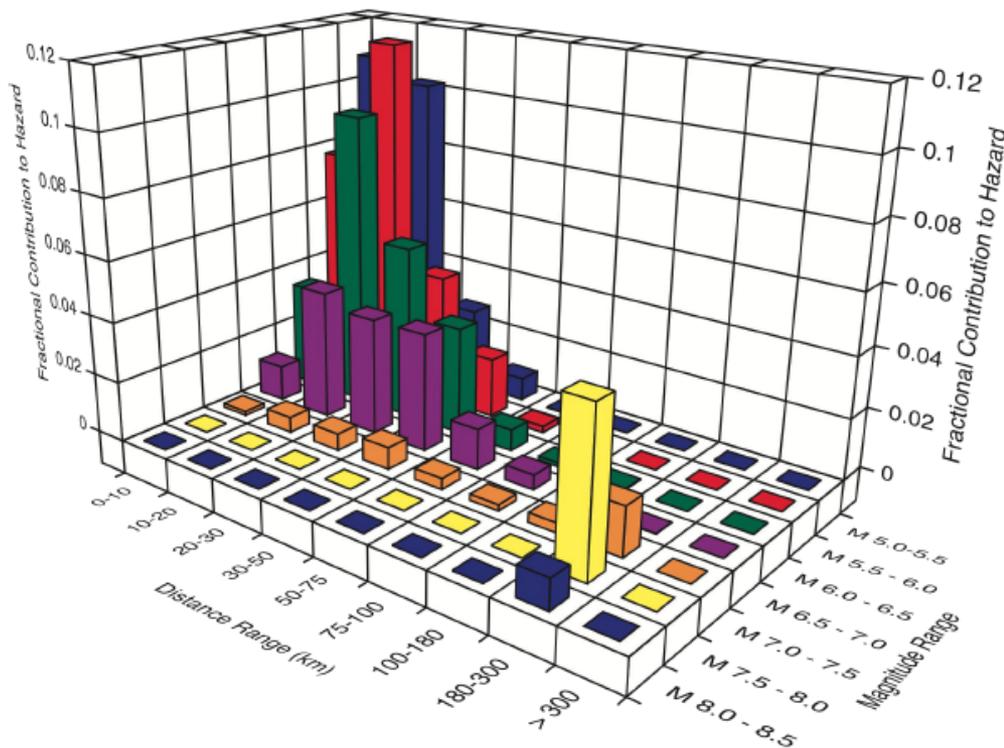


2% Probability in 50 years

10% Probability in 50 years

Spectral Acceleration @ 2 seconds

# PSHA Outputs - Disaggreagation

For a given site, ground motion intensity measure and return period the fractional contribution of specific scenarios to the hazard can be extracted from the hazard analysis via disaggregation
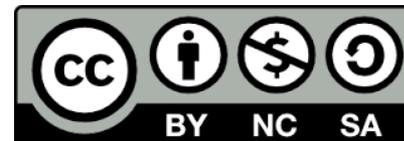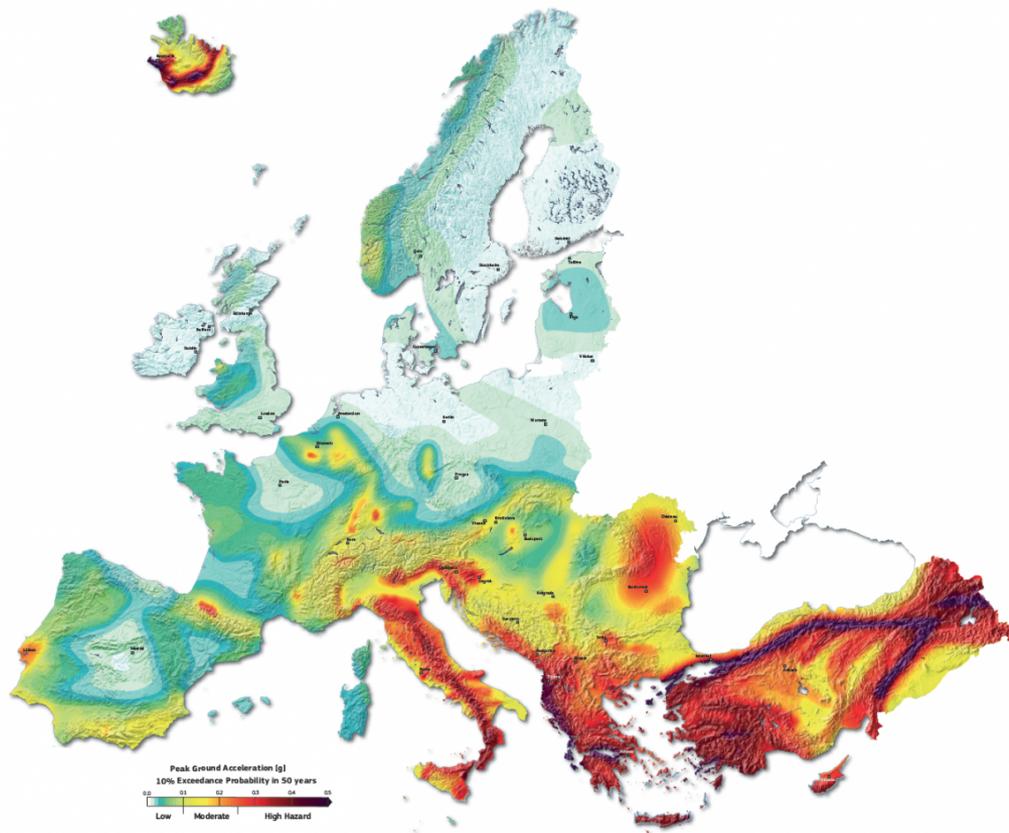


Can identify scenarios that represent the greatest likelihood of contributing to the hazard

# Thank you!

Peak Ground Acceleration [g]
10% Exceedance Probability in 50 years
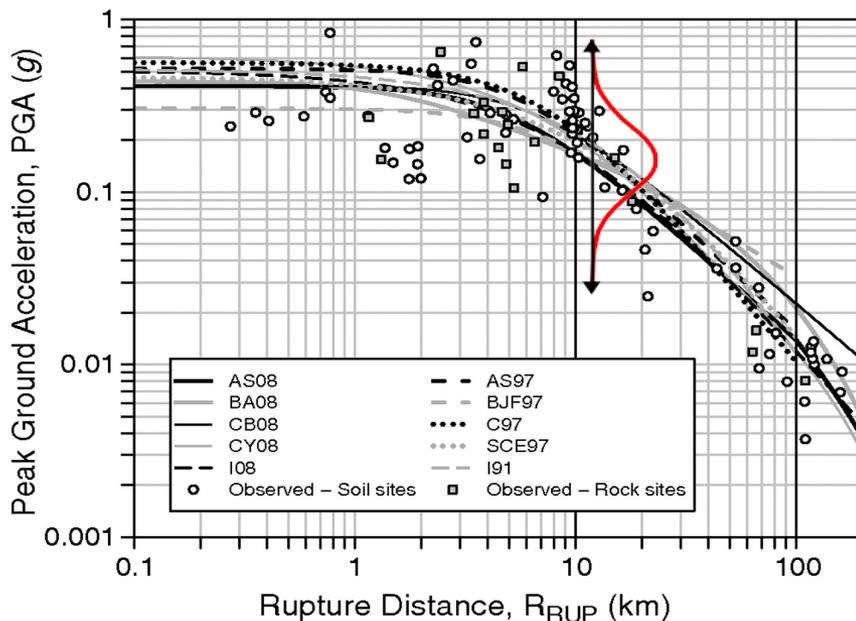
Low    Moderate    High Hazard

# Ground Motion Prediction

The easiest way to model ground motion is perhaps the use of Ground Motion Prediction Equations (GMPEs)

$$\Omega_{ij}(f,r) = \underbrace{\omega \cdot \Omega_i \cdot f_c^{\gamma}/(f_c^{\gamma} + f^{\gamma})}_{\text{Source Spectrum}} \cdot \underbrace{S_{ij}(r) \cdot \exp(-\pi \cdot f^{1-\alpha} \cdot t_{ij}^*)}_{\text{Path Effects}} \cdot \underbrace{A_j(f) \cdot \exp(-\pi \cdot f^{1-\alpha} \cdot K_j)}_{\text{Site Effects}}$$



GMPE terms are representations of a given physical model, whose reliability can be increased with the availability of new empirical information

# Logic-Tree Strategy – Over Reliance?

The problem:

o Less data/knowledge implies greater epistemic uncertainty

o But if considering published (e.g. peer-reviewed) models, usually the case that more models will be available from regions with more data (e.g. more GMPEs for active shallow crust than for stable crust)

o More use of more available models increases epistemic uncertainty in regions with more data, and therefore epistemic uncertainty is lower in regions with less data!

o Need for a "minimum generic uncertainty" for regions with sparse data