Engineering Seismology and Seismic Hazard – 2019

Lecture 18

Seismic Hazard Analysis

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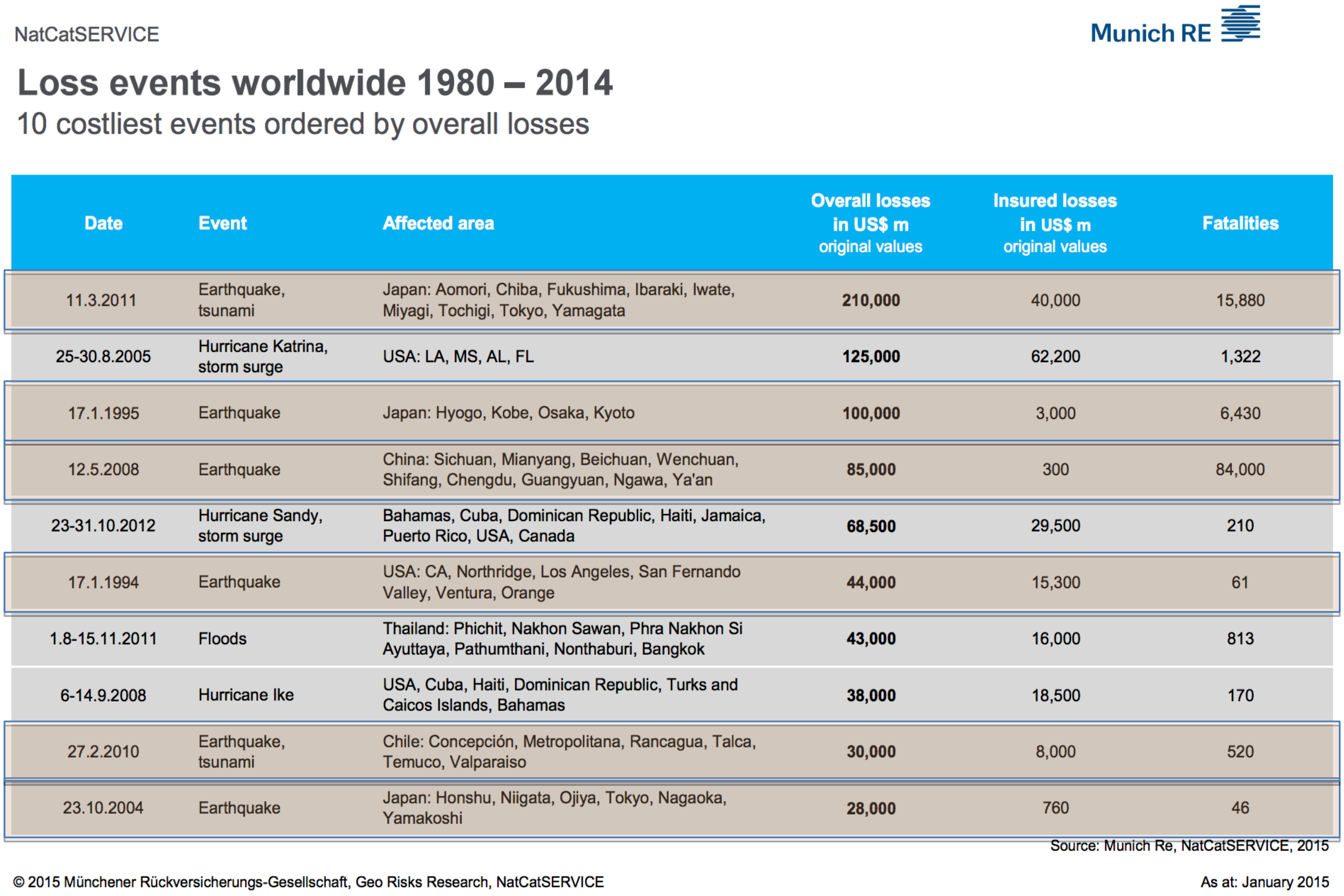
A widespread danger

As we have learned from the previous lectures, earthquakes are one of the most costly natural hazards worldwide.



NatCatSERVICE

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

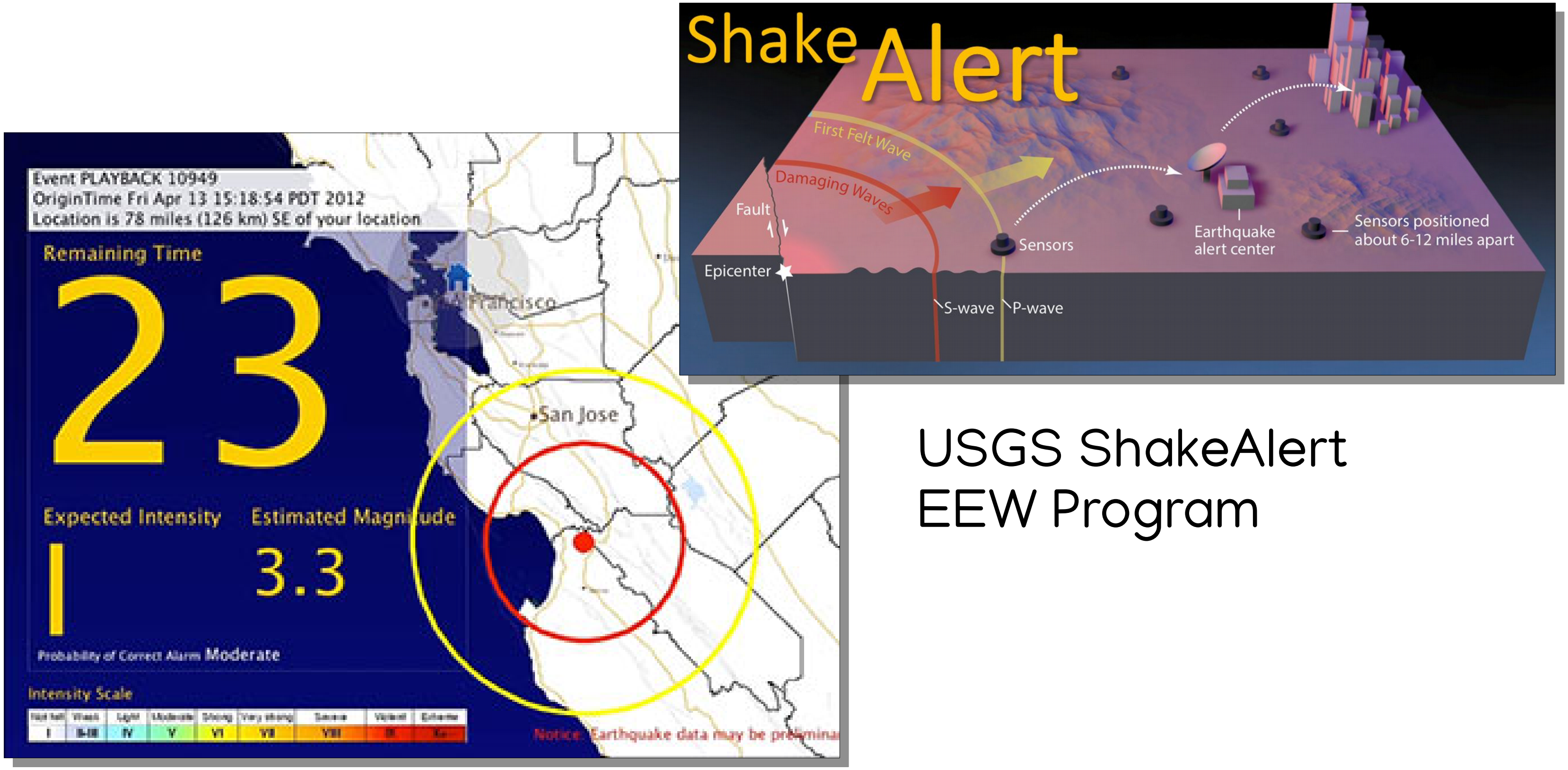
Source: Munich Re, NatCatSERVICE, 2015

As at: January 2015

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)



Event PLAYBACK 10949
OriginTime Fri Apr 13 15:18:54 PDT 2012
Location is 78 miles (126 km) SE of your location

Remaining Time
23

Expected Intensity
I

Estimated Magnitude
3.3

Probability of Correct Alarm Moderate

Intensity Scale

Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
I	II-III	IV	V	VI	VII	VIII	IX	X+

Notice: Earthquake data may be prelimina

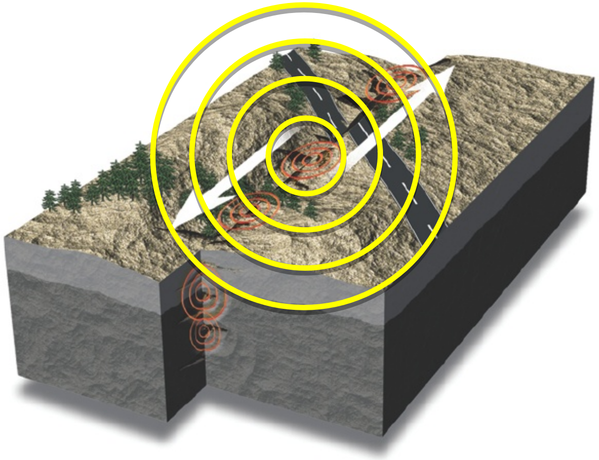
USGS ShakeAlert EEW Program

Expected 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

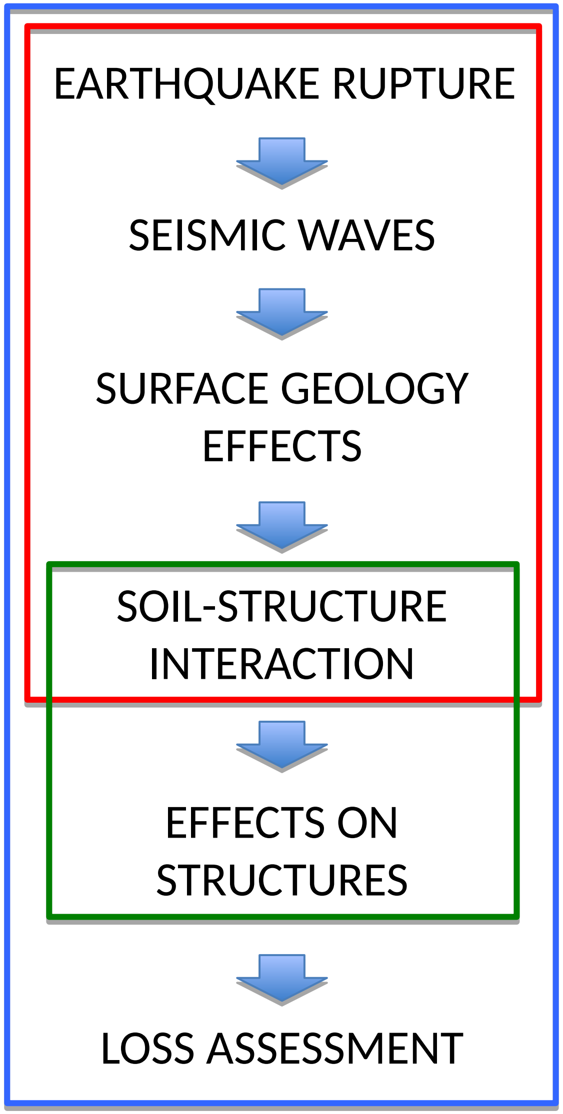
Question is: how and how precisely this level can be defined, given the little knowledge we have of the earthquake process?



http://www.howitworksdaily.com/

This is the task of Seismic Hazard Analysis (SHA)....

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-User Prospective

1) **Engineers**

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

2) **Insurers**

- What is the probability of my exceeding X amount of loss from my portfolio in the next T years?
- The Catastrophe Bond will trigger when “... earthquake occurs in this cell ... ground shaking exceed this value here...” – how likely is this to happen?

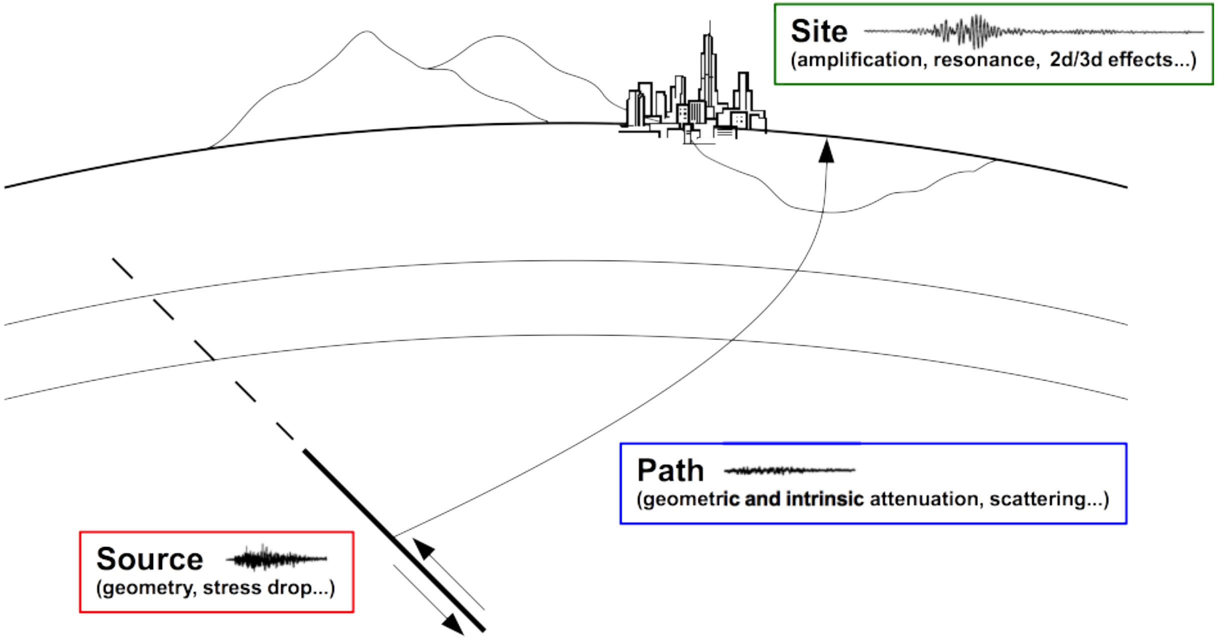
3) **Decision Makers, Politicians & Public**

- Will this property be damaged/destroyed?
- How likely is this to happen?
- What is the best course of action to take (cost-benefit)?
- 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:

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



Deterministic vs Probabilistic

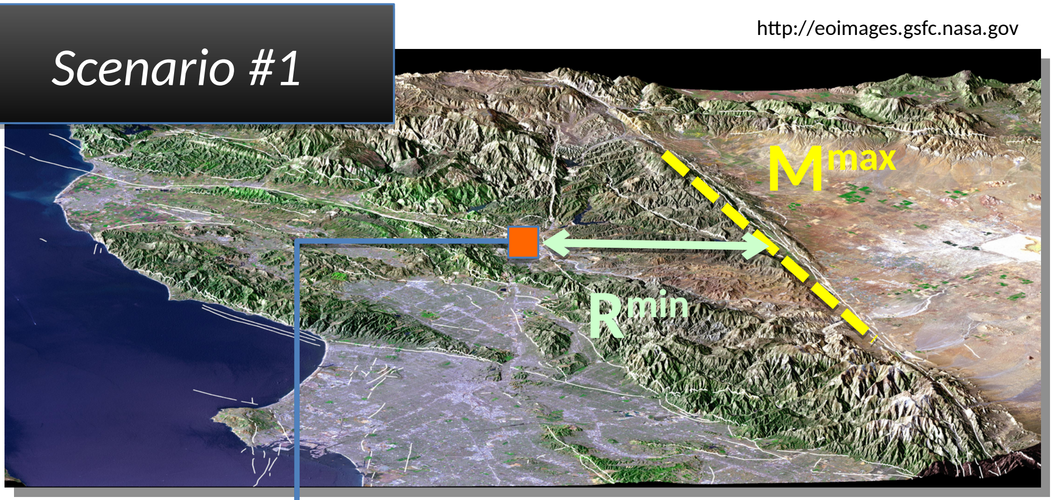
Two are the main methodologies currently adopted for seismic hazard analysis:

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.

Scenario Based Approach

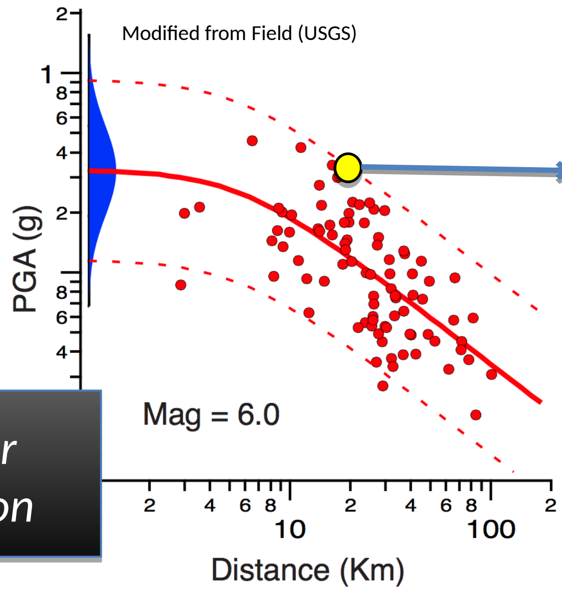
Scenario #1



1) Select one or more sources through specific magnitude and distance combinations

2) Compute expected ground motion (accounting for variability)

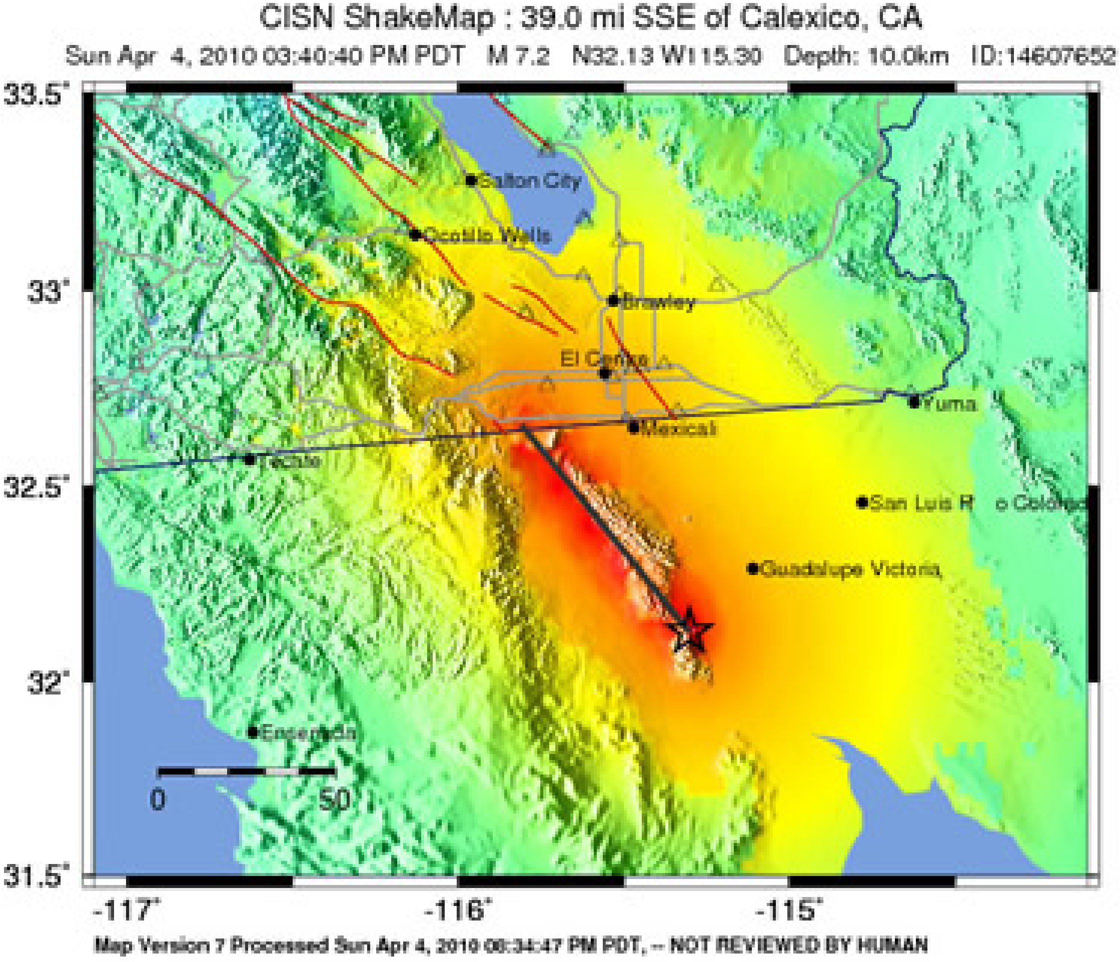
3) Retain greatest shaking for engineering design



GMPE or Simulation

PGA @ 20Km + σ

Example – ShakeMaps



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+

Main Issues of DSHA

1) Which scenario to be used?

- For dams, typically the "worst-case" earthquake
- Maximum Credible Earthquake, MCE
- Maximum Observed Earthquakes (plus delta)

2) Largest vs closest earthquake to source?

3) Ground motion has large variability for a given magnitude, distance, and site condition. What ground motion level do we select? A too conservative choice is not acceptable for engineering purposes.

4) Expected ground motion at site is independent of time, therefore no concept of probability of exceedance.

DSHA becoming nowadays less and less acceptable

Reasonable Scenario(?)

Note that worst-case ground motion is generally NOT selected in deterministic approach.

Combing largest earthquake with the worst-case ground motion is too unlikely a case:

→ The occurrence of the maximum earthquake is rare, so it is not "reasonable" to use a worst-case ground motion for this earthquake.

→ Chose something smaller than the worst-case ground motion that is "reasonable", but reasonable is of difficult quantification.

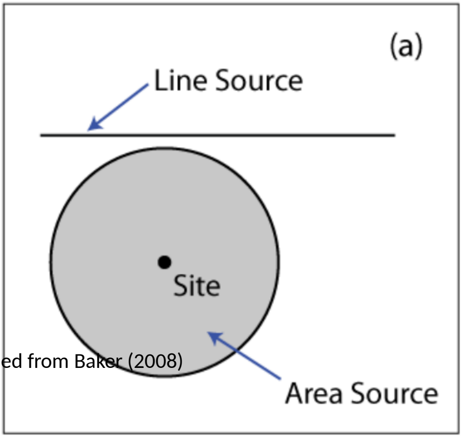
→ There is clear need to include for occurrence rate and the chance of ground motion exceedance!

PSHA – Basic Workflow

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

Where

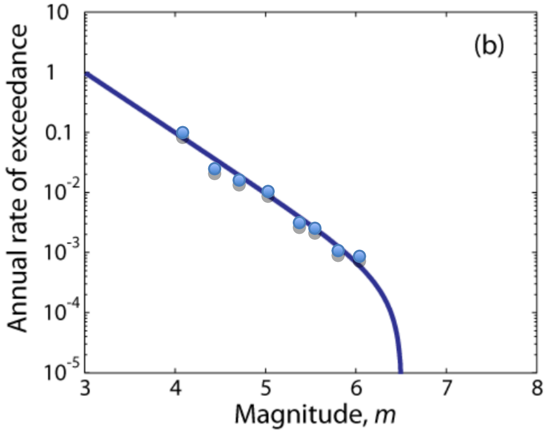
Seismogenic Zone Models



Modified from Baker (2008)

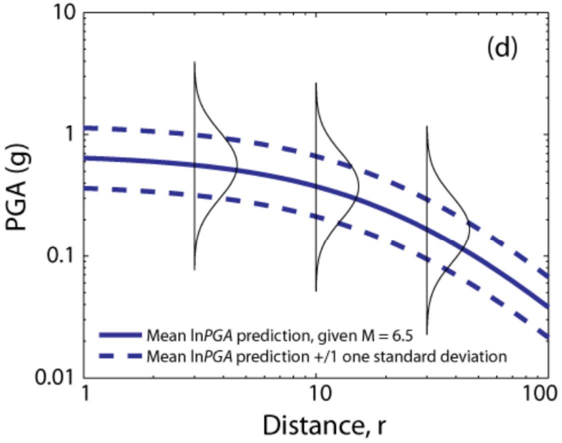
When (how often)

Recurrence Models



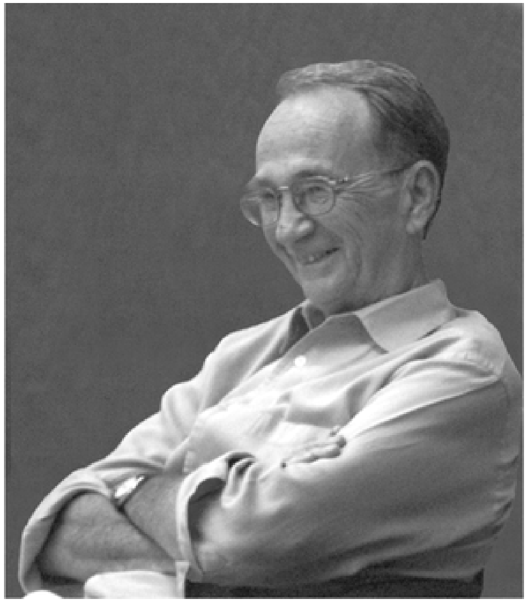
How (strong)

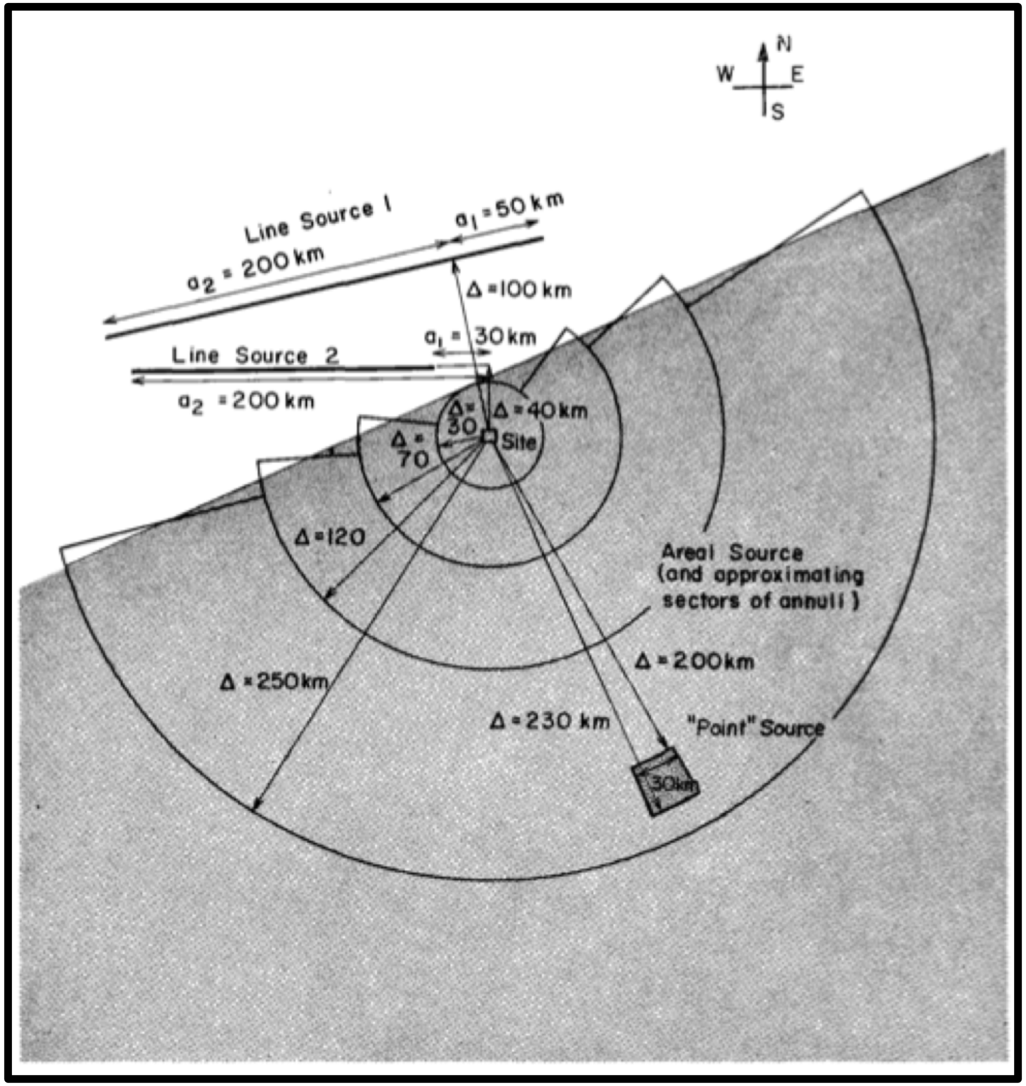
Ground Motion Models



Brief History of PSHA

Probabilistic seismic hazard analysis was discussed for the first time by **C.A. Cornell** in a paper published in 1968 on the Bulletin of the Seismological Society of America.





Brief History of PSHA

Several contributions to the definition of the PSHA methodology came also from the work of **Luis Esteva** (UNAM, Mexico), who published the first probabilistic hazard map:

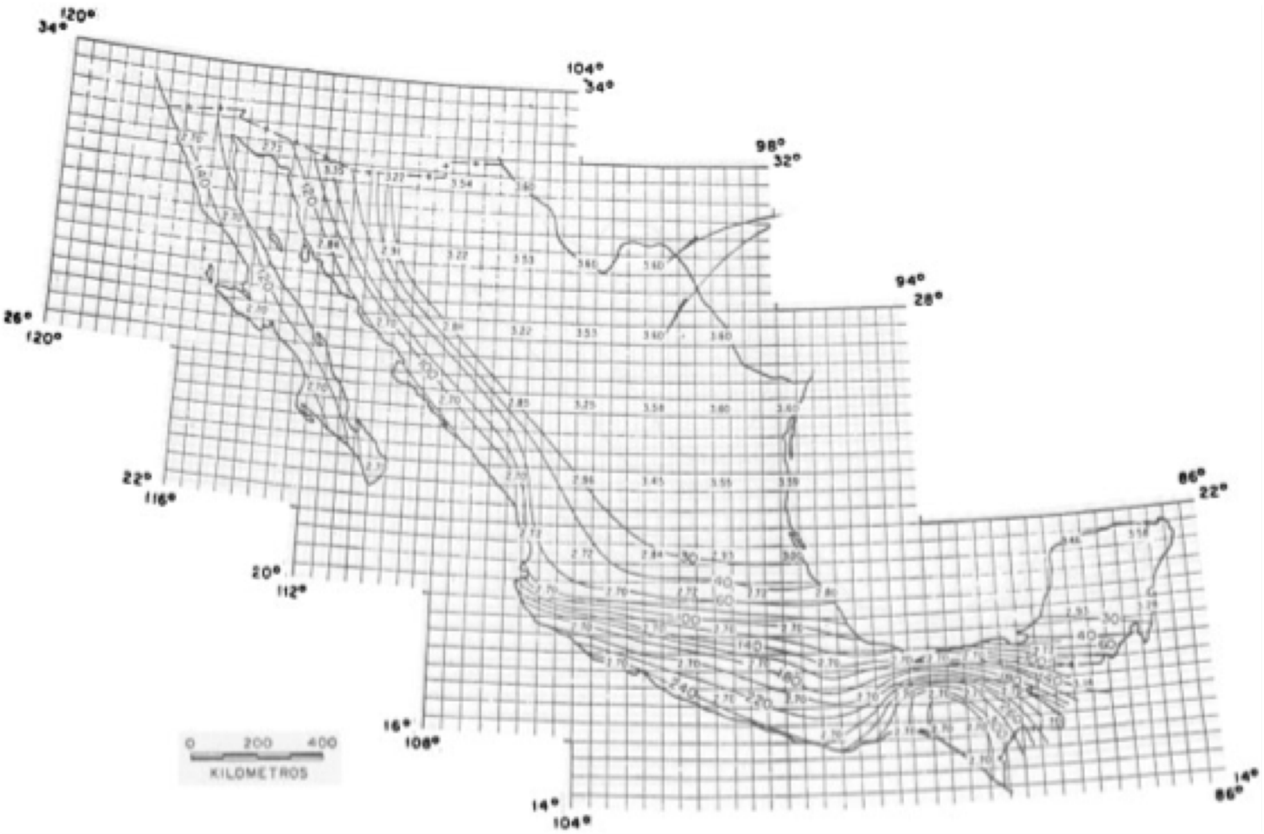


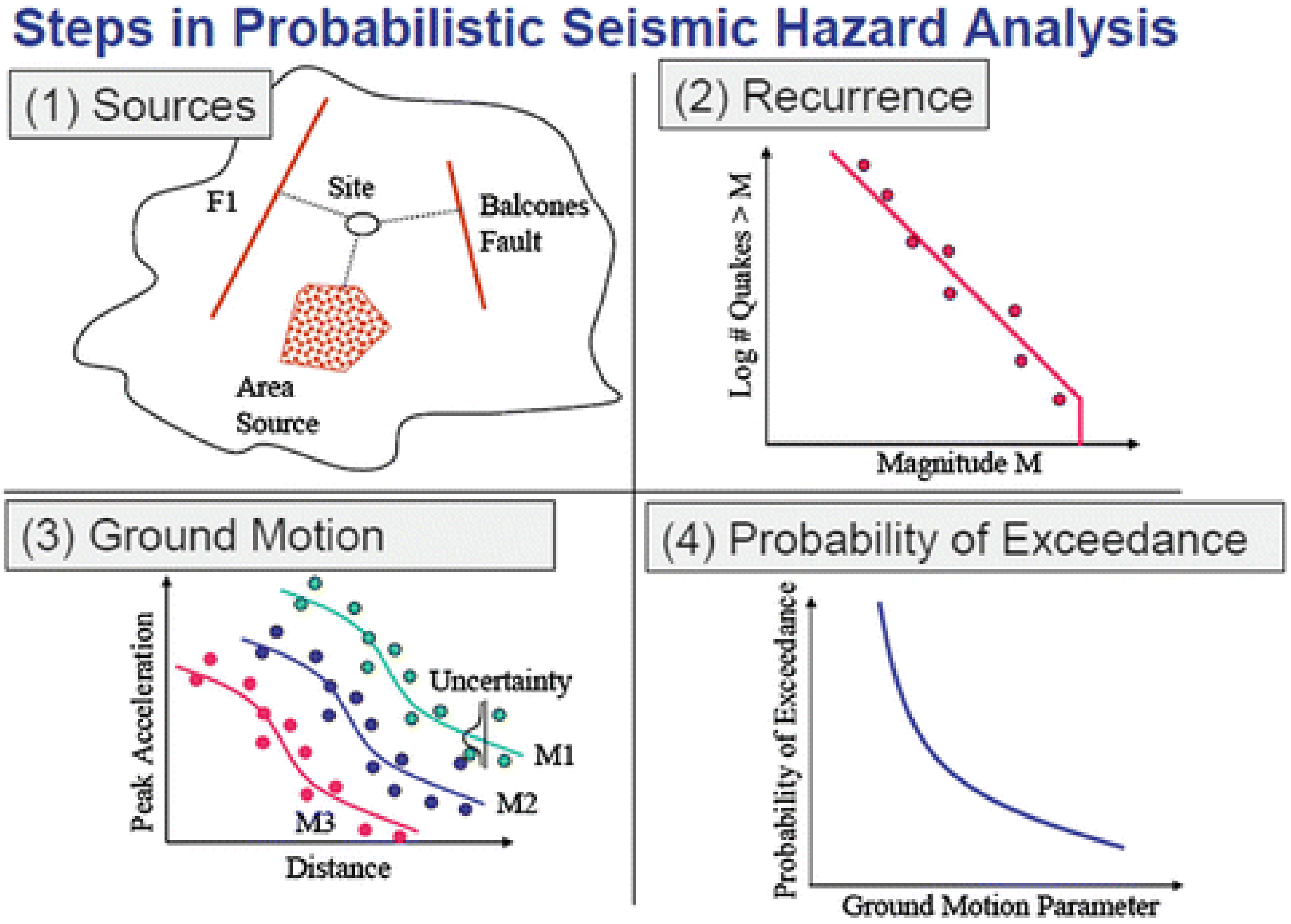
Figure 2. National seismic hazard map for Mexico showing PGA with a 500-year return period, published by Esteva [16] in 1970.

Some PSHA Milestones

- Cornell (1968) introduces the PSHA methodology. PSHA is computed using closed form solutions.
- Esteva (1970) publishes the first PSHA maps for Mexico.
- Johnson (1973) publishes the first GMPE using spectral ordinates
- McGuire (1976) issues a USGS Open File report describing a "Fortran computer Program for Seismic Risk Analysis". Hazard integral solved numerically in the Fortran code described in the report.
- Der Kiureghian and Ang (1977) recognize the importance of accounting for rupture finite dimension in PSHA calculations
- Kulkarni et al. (1984) introduce the logic tree methodology and the concepts of epistemic uncertainty and aleatory variability
- USGS produces in 1990 the first hazard maps incorporating ground motion variability
- 1996 First Hazard Maps in Spectral Acceleration published by USGS
- McGuire (1997) and Bazzurro and Cornell (1999) introduce the concept of disaggregation of hazard
- Bazzurro and Cornell (2002) publish the first paper on Vector Based PSHA

PSHA Workflow

In PSHA, hazard is computed by taking into account all the possible scenarios generated by all the sources within a certain distance from the investigated site.



Hazard Integral

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:

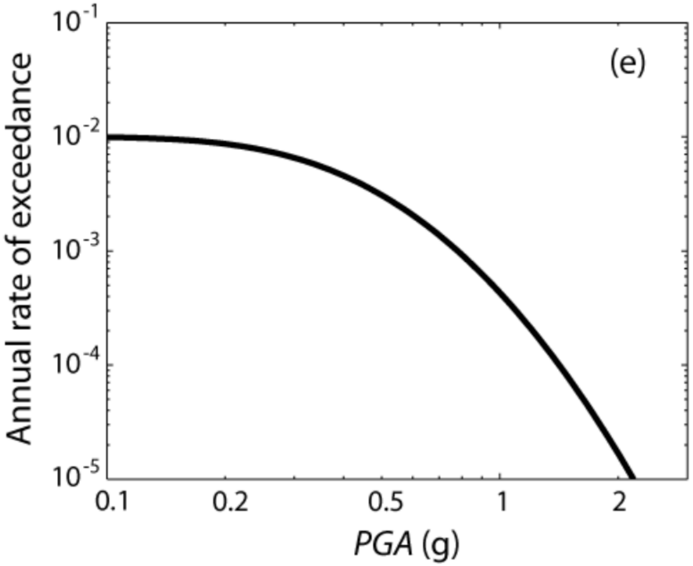
$$\lambda(\mathrm{IM}>x)=\sum_{i=1}^{n_{sources}}\lambda(M_i>m_{min})\int_{m_{min}}^{m_{max}}\int_{r_{min}}^{r_{max\,P}}\underline{(\mathrm{IM}>x\,|\,m,r)}\,\underline{f_{M_i}(m)}\,\underline{f_{R_i}(r\,|\,m)}\,dm\,dr$$

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)



Poisson Process

Poisson process – describes number of occurrences (n) of an event during a given time interval (t) or spatial region.

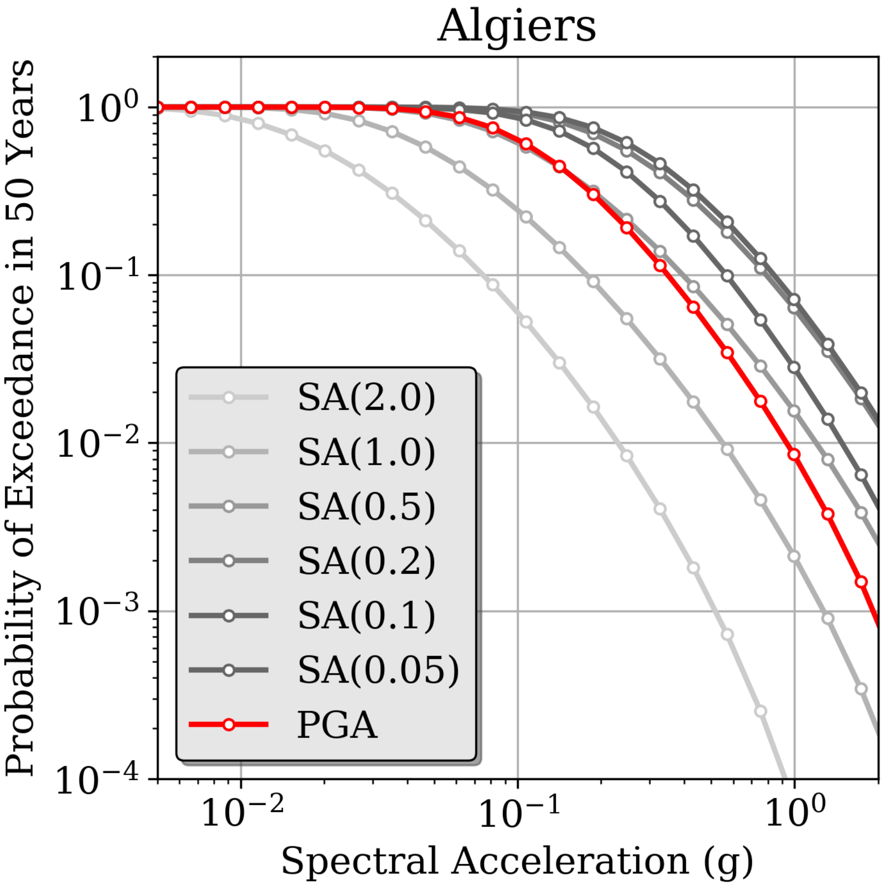
1. The number of occurrences in one time interval are independent of the number that occur in any other time interval.
2. Probability of occurrence in a very short time interval is proportional to length of interval.
3. Probability of more than one occurrence in a very short time interval is negligible.

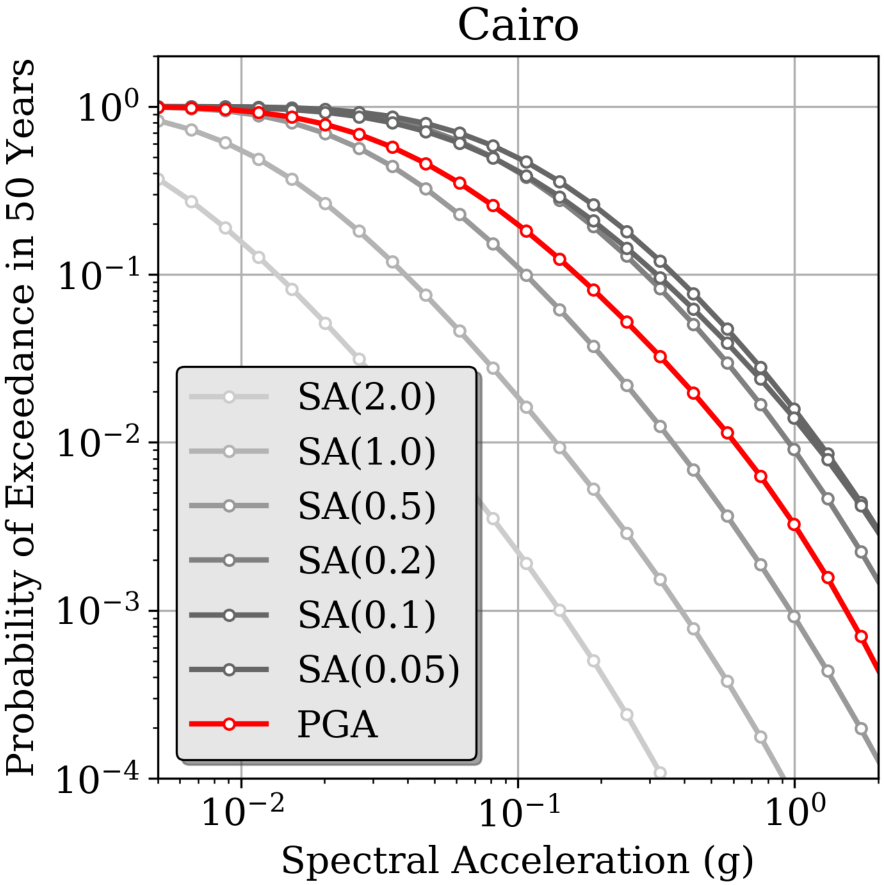
$$P(N=n)=\frac{(\lambda t)^n e^{-\lambda t}}{n!}$$

The probability of "at-least" one occurrence in time t is then expressed as the total probability (1) minus the probability of no successful events:

$$\boxed{P(N>1)=1-P(0)=1-e^{-\lambda t}}$$

Hazard Curves

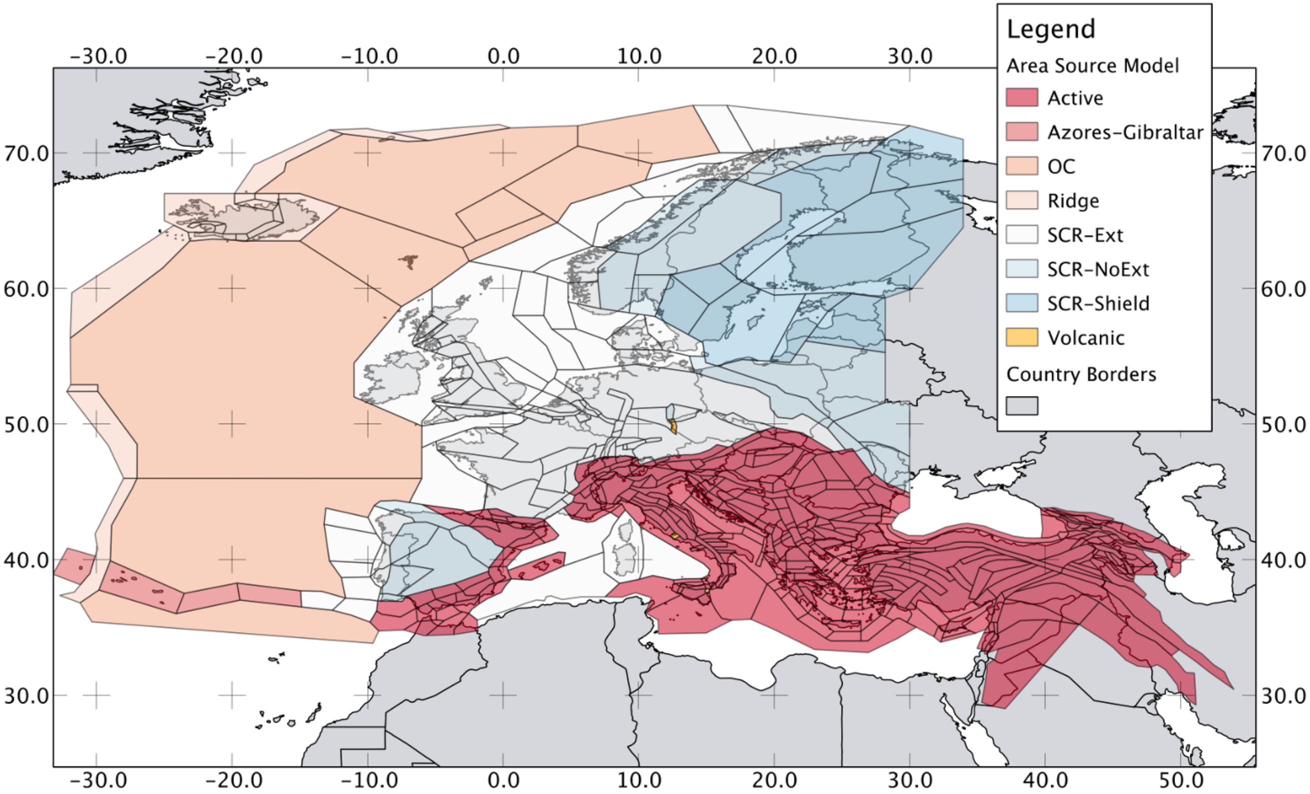




Seismogenic Zones

Distributed Seismicity:

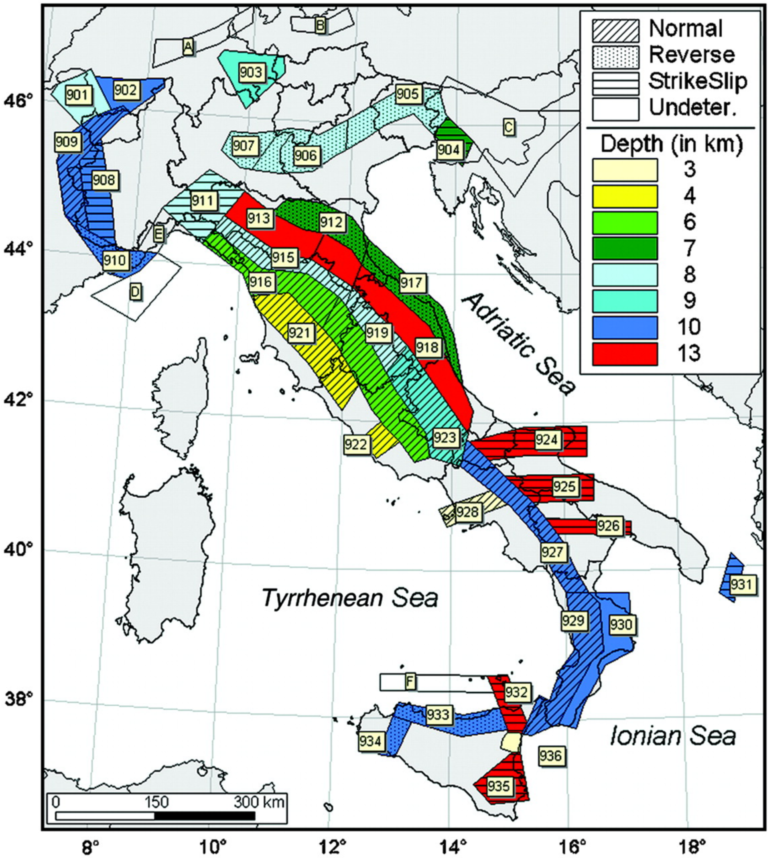
- Single points
- Grid representations (e.g. smoothed seismicity)
- Polygon of Uniform Seismicity (so far the most widely used approach)

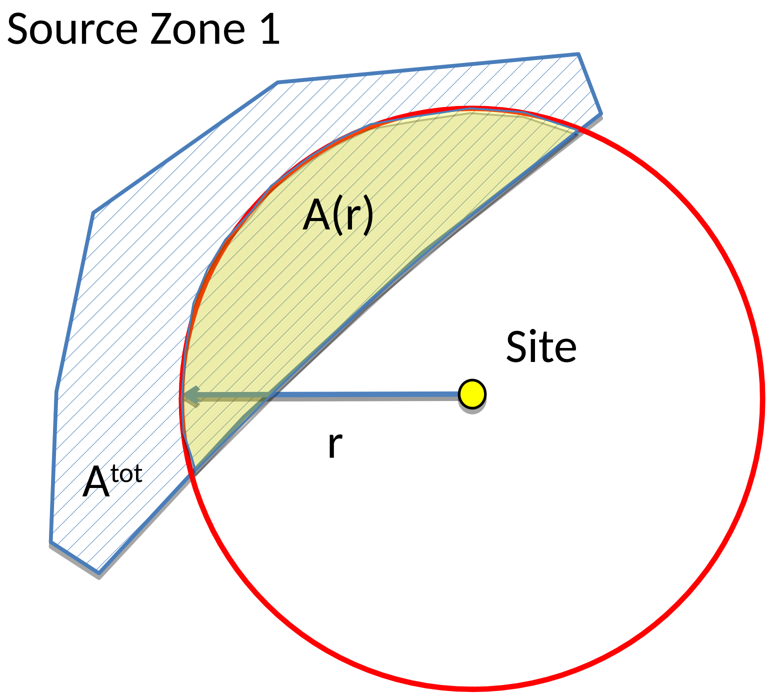


SHARE Area Source Zonation Model

Area Source Zones

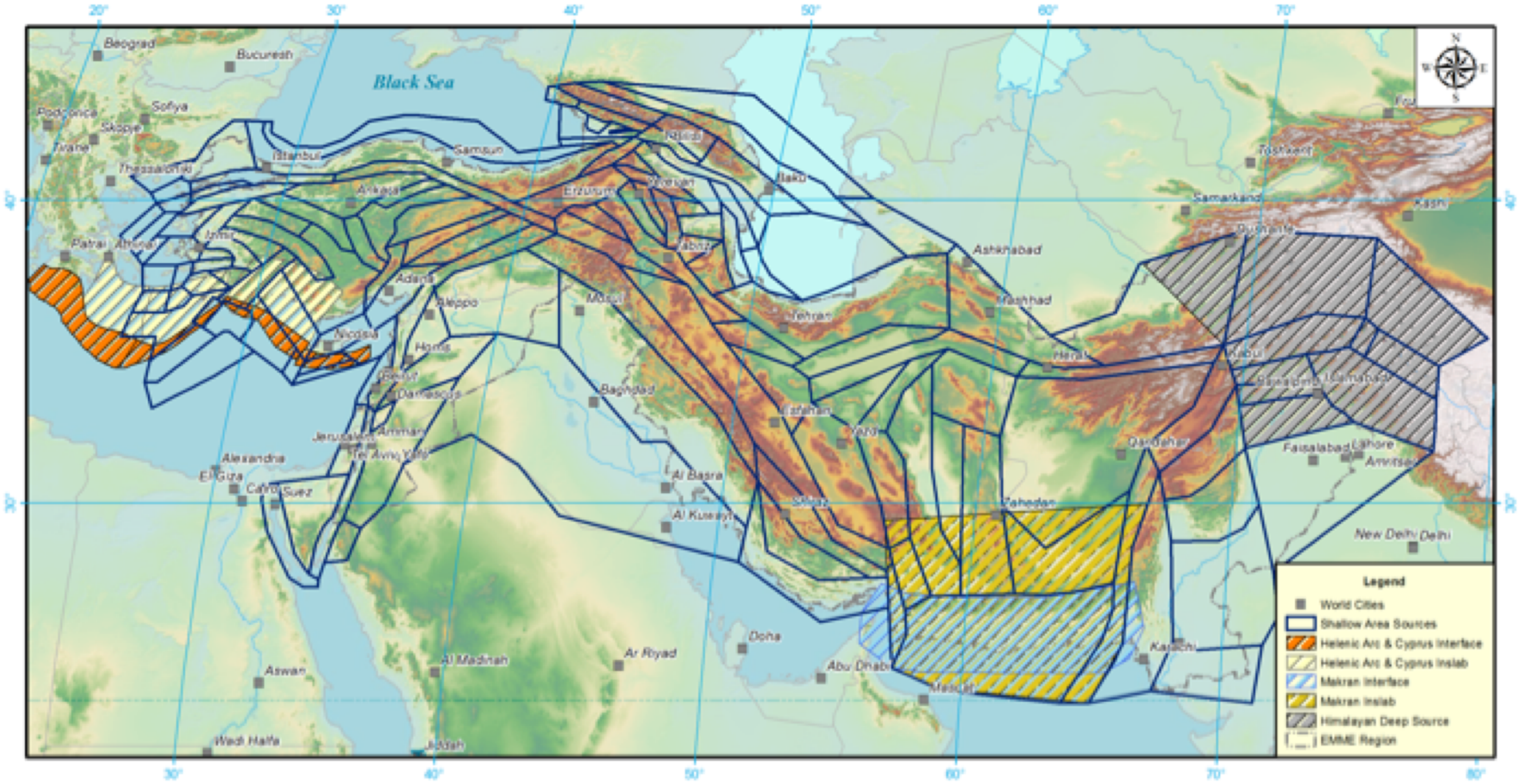
Uniform Area Source Model of Italy (modified from Meletti et al., 2008)





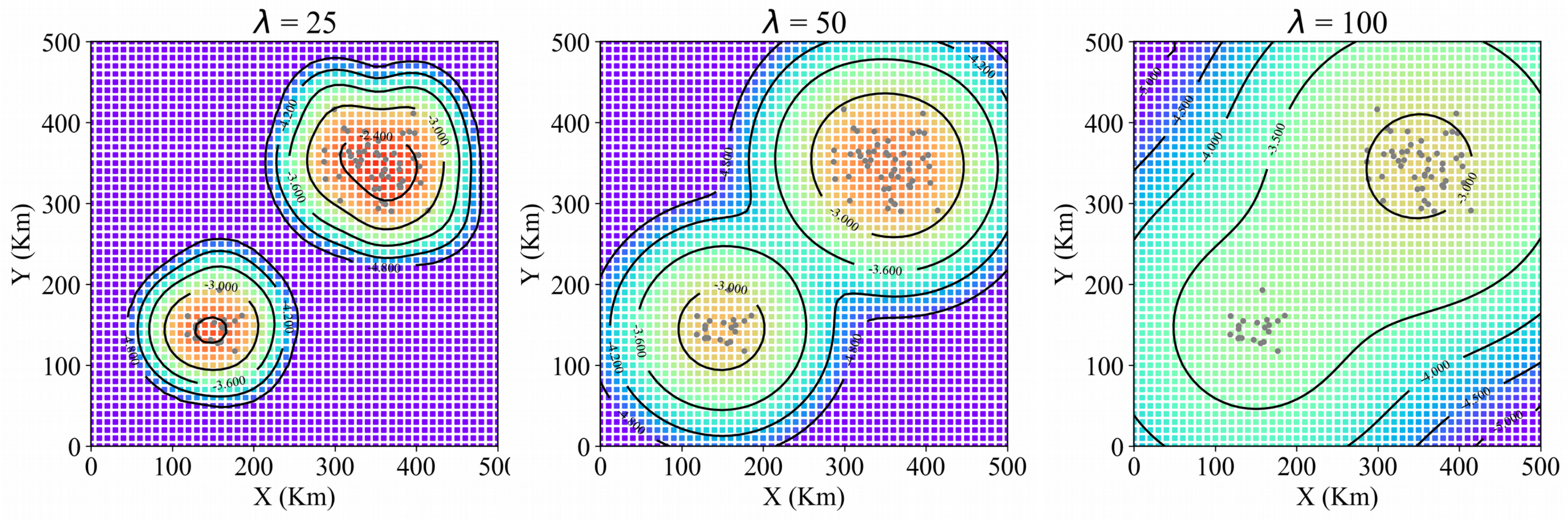
The probability density function (PDF) of an area source can be difficult to be computed analytically and numerical approximation is generally used instead.

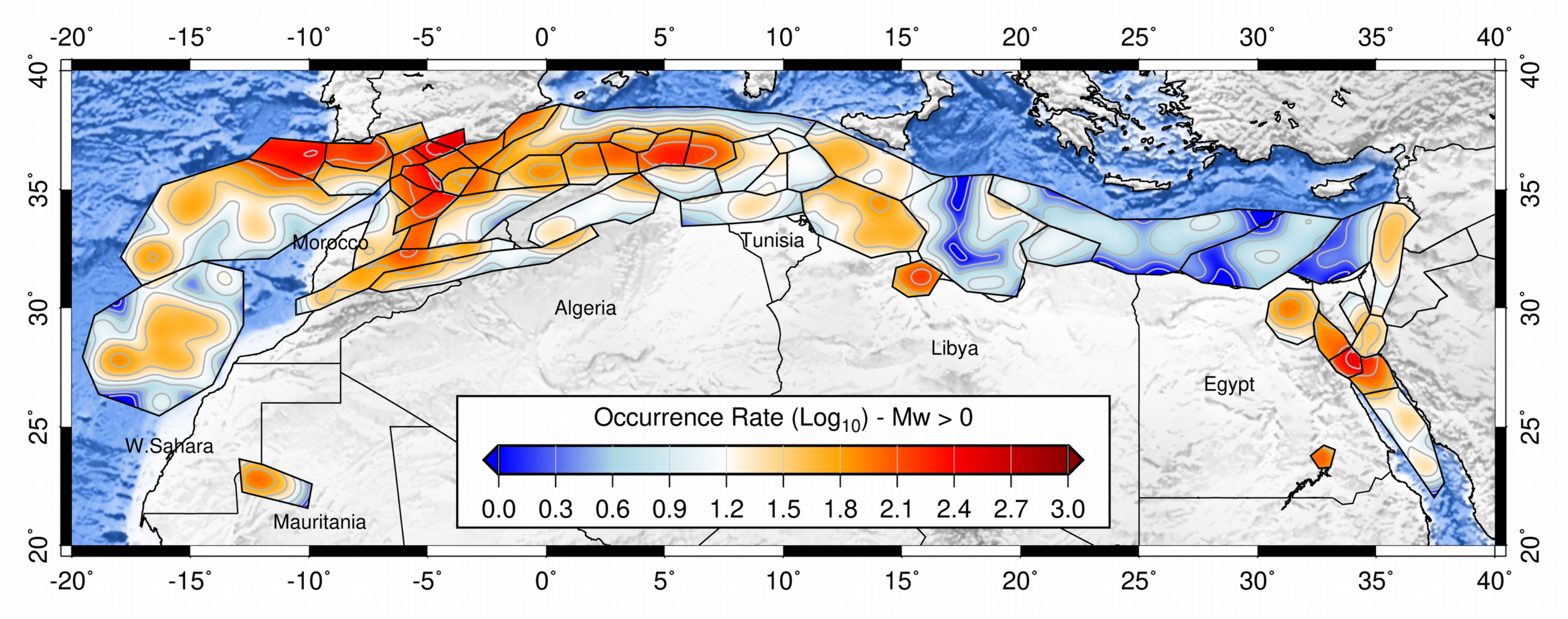
Example: EMME Model



EMME Area Source Model

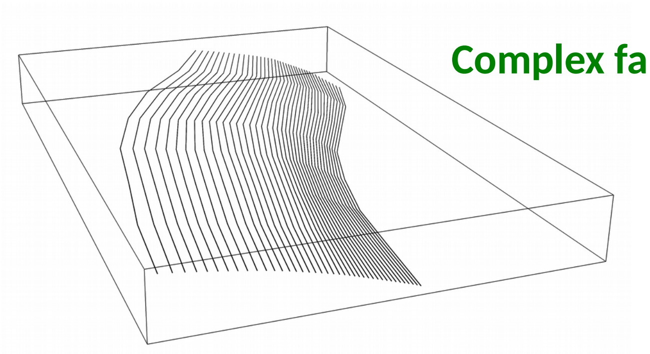
Smoothed Rates



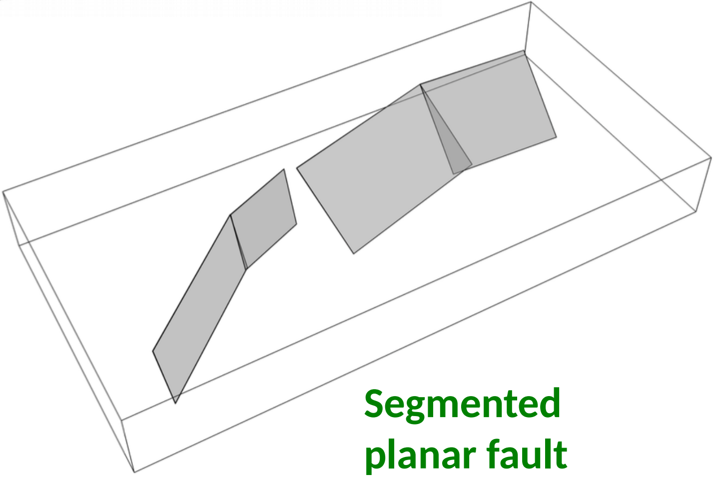


Fault Models

- If fault geometry is sufficiently known, it can be modeled as a three-dimensional surface
- Such approach can be used for active shallow faults as well as larger subduction interfaces

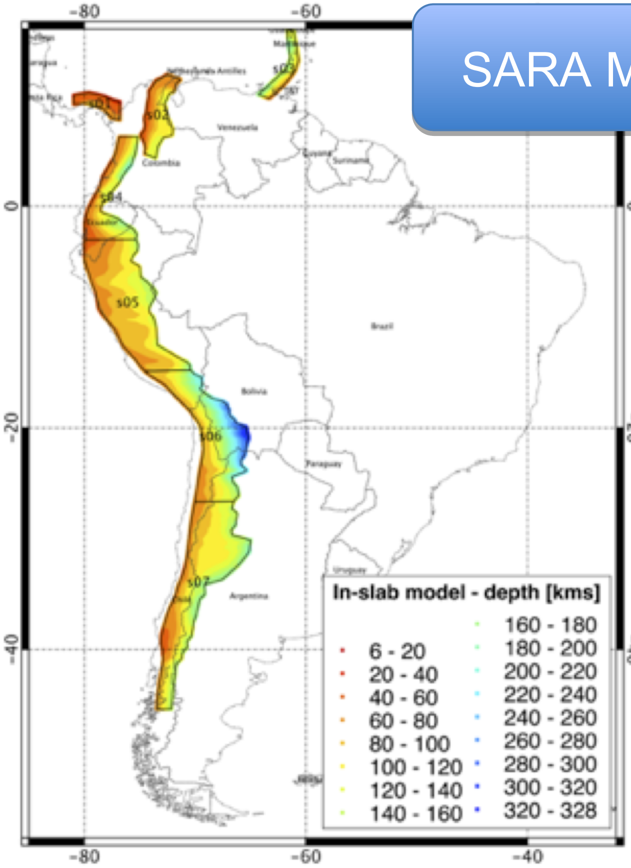


Complex fault

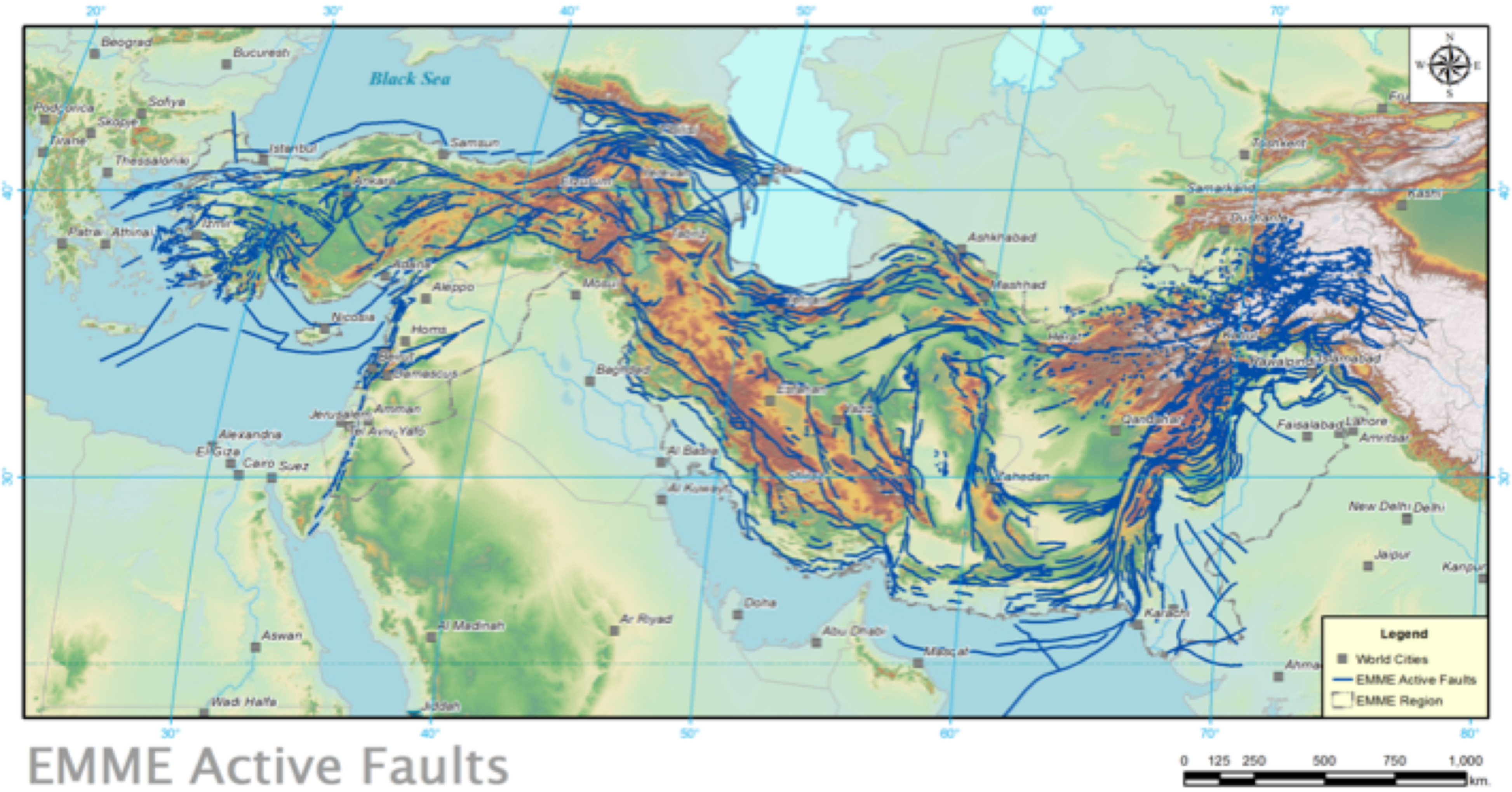


Segmented planar fault

SARA Model



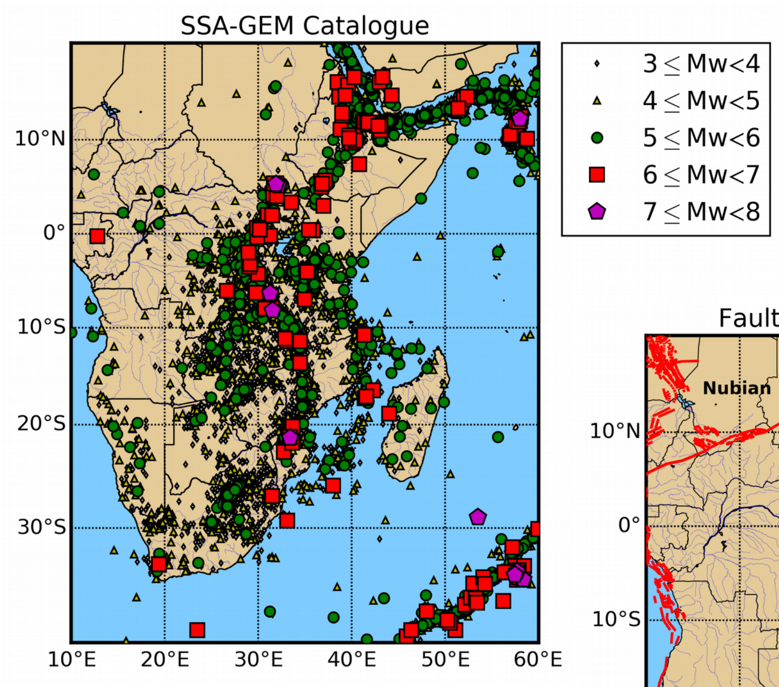
Example: EMME Model

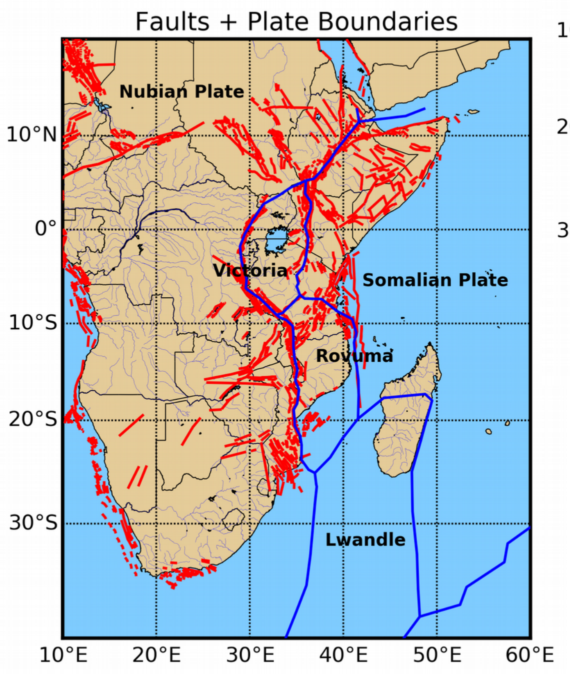


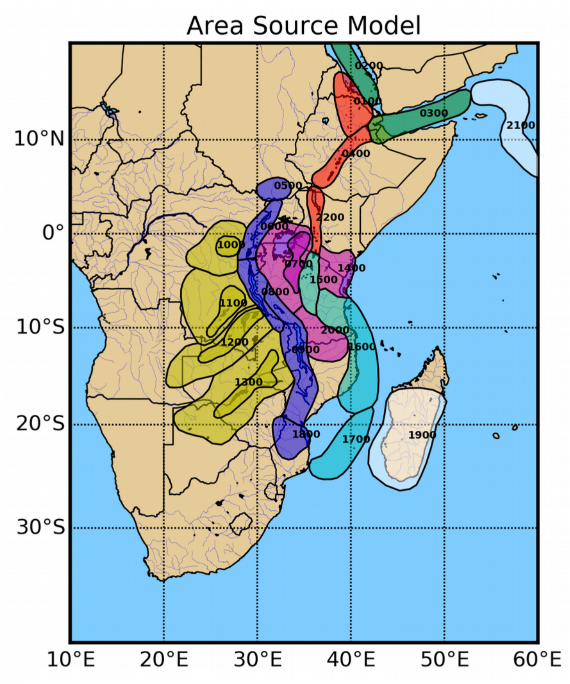
EMME Active Faults

Building the Source Model

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


SSA-GEM Catalogue


Faults + Plate Boundaries

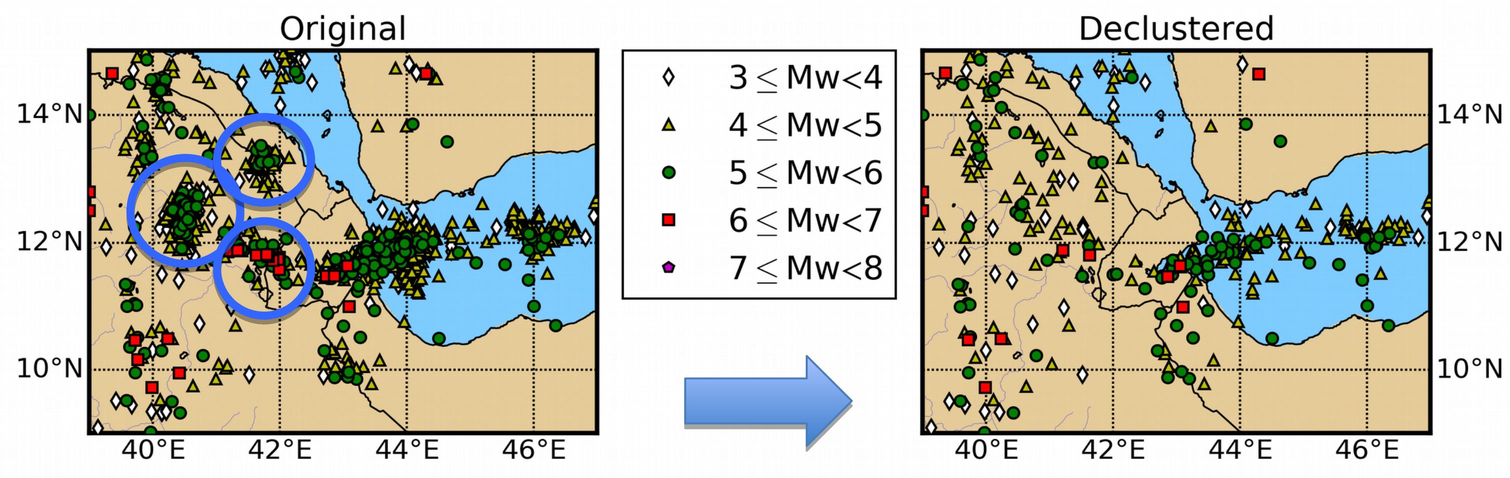

Area Source Model

Macgregor (2015)
Saria et al. (2014)

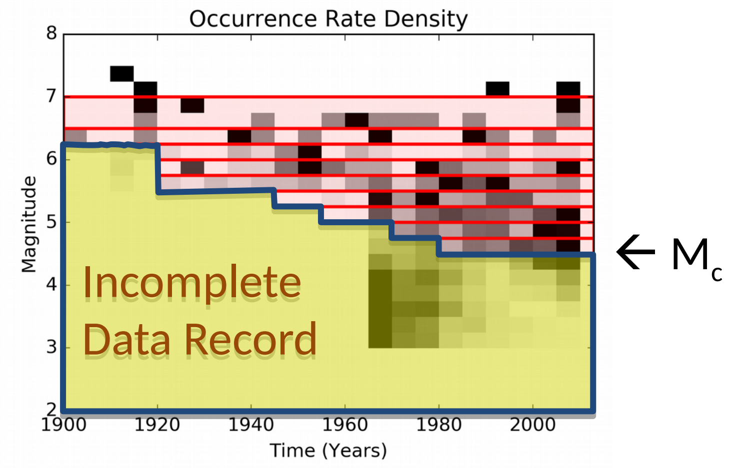
Seismicity Analysis

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



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



Magnitude Occurrence Relations

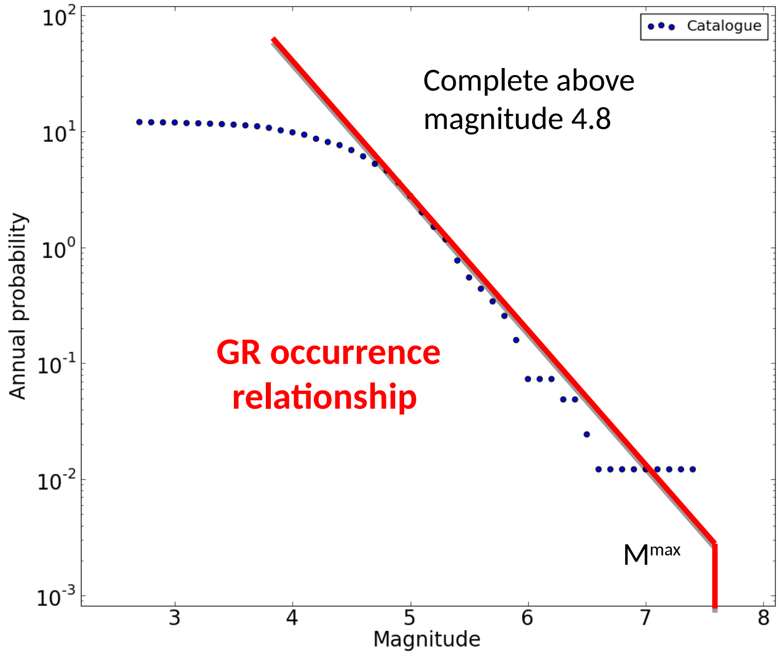
Temporal distribution of seismicity is modeled assuming a given magnitude occurrence relation

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

$$\lambda\left(M>m\right)=10^{a-bM}$$

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

5.23 earthquakes above magnitude 4.8 per year



Recurrence models typically fit to catalogue using maximum likelihood techniques

Occurrence Probability

The G-R relation can be used to compute a cumulative distribution function (CDF) for the magnitudes of earthquakes that are between some minimum (m_{min}) maximum magnitude (m_{max}):

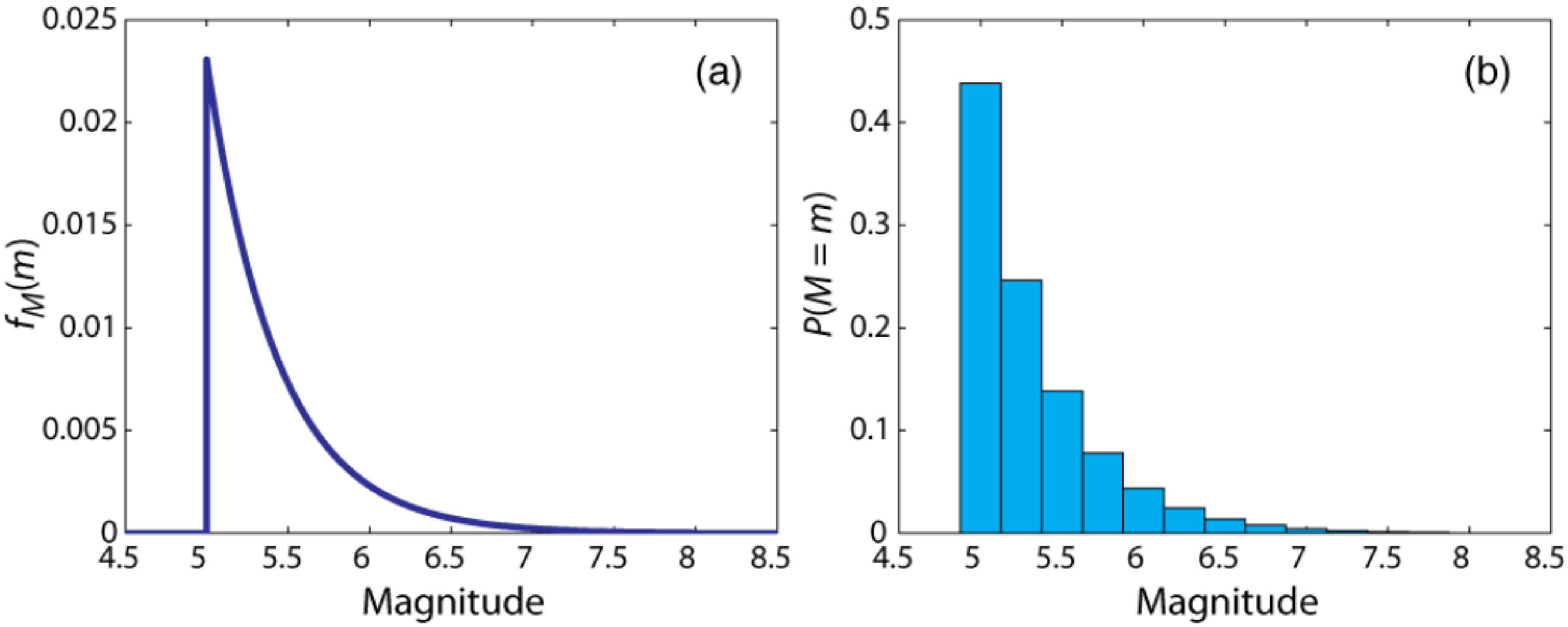
$$F_M(m) = \frac{\lambda_{M_{min}} - \lambda_m}{\lambda_{m_{min}} - \lambda_{m_{max}}} = \frac{1 - 10^{-b(m - m_{min})}}{1 - 10^{-b(m_{max} - m_{min})}}$$

Therefore the corresponding probability density function (PDF) will be:

$$f_M(m) = \frac{d}{dm} F_M(m) = \frac{b \ln(10) 10^{-b(m - m_{min})}}{1 - 10^{-b(m_{max} - m_{min})}}$$

Continuous vs Discrete

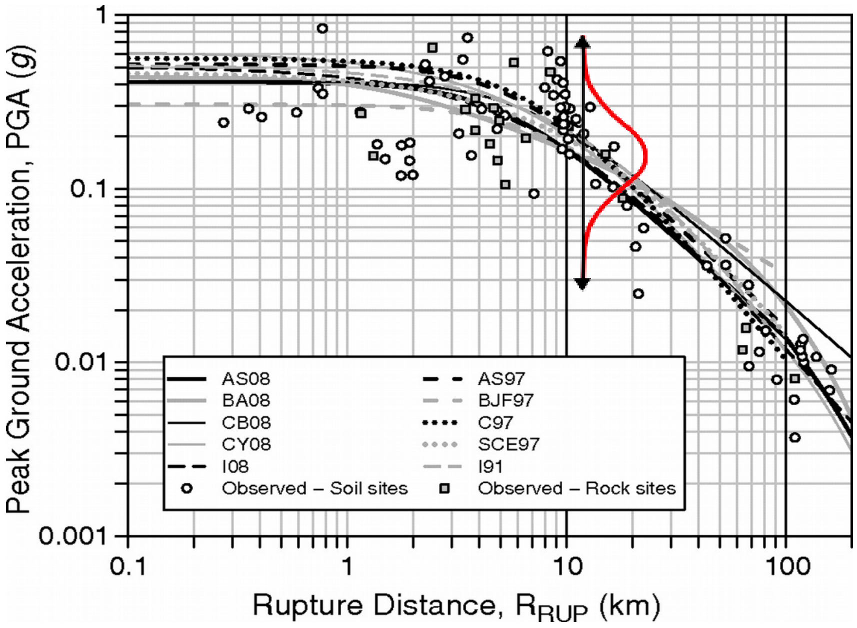
The PDF of the the Gutenberg-Richter can also be represented in discrete form by integration over magnitude binds of finite size (as it is implicitly done inside the hazard integral)



Ground Motion Modeling

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

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

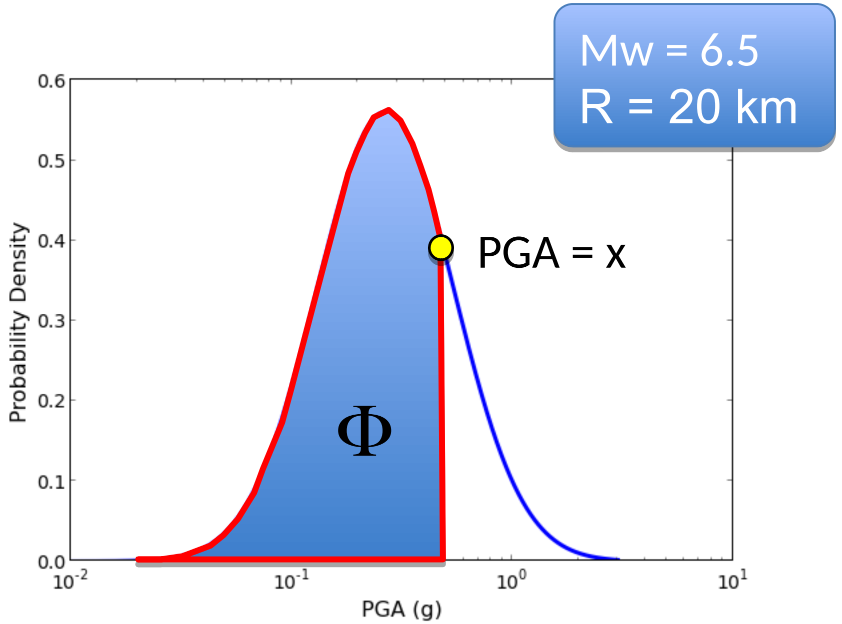


GMPE terms are representations of a given physical model, whose reliability can be increased with the availability of new empirical information

$$IM = PGA, PGV, SA...$$

Ground Motion Exceedance

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



Given M and R, the probability that IM will exceed the value x → P(IM > x | M, R) can then be determined from the CDF of the normal distribution of IM:

$$P(PGA > x \mid m, r) = 1 - \Phi\left(\frac{\ln x - \ln P\bar{G}A}{\sigma_{\ln PGA}}\right)$$

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: <u>aleatory uncertainty is irreducible whereas epistemic uncertainty can be potentially reduced</u>

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

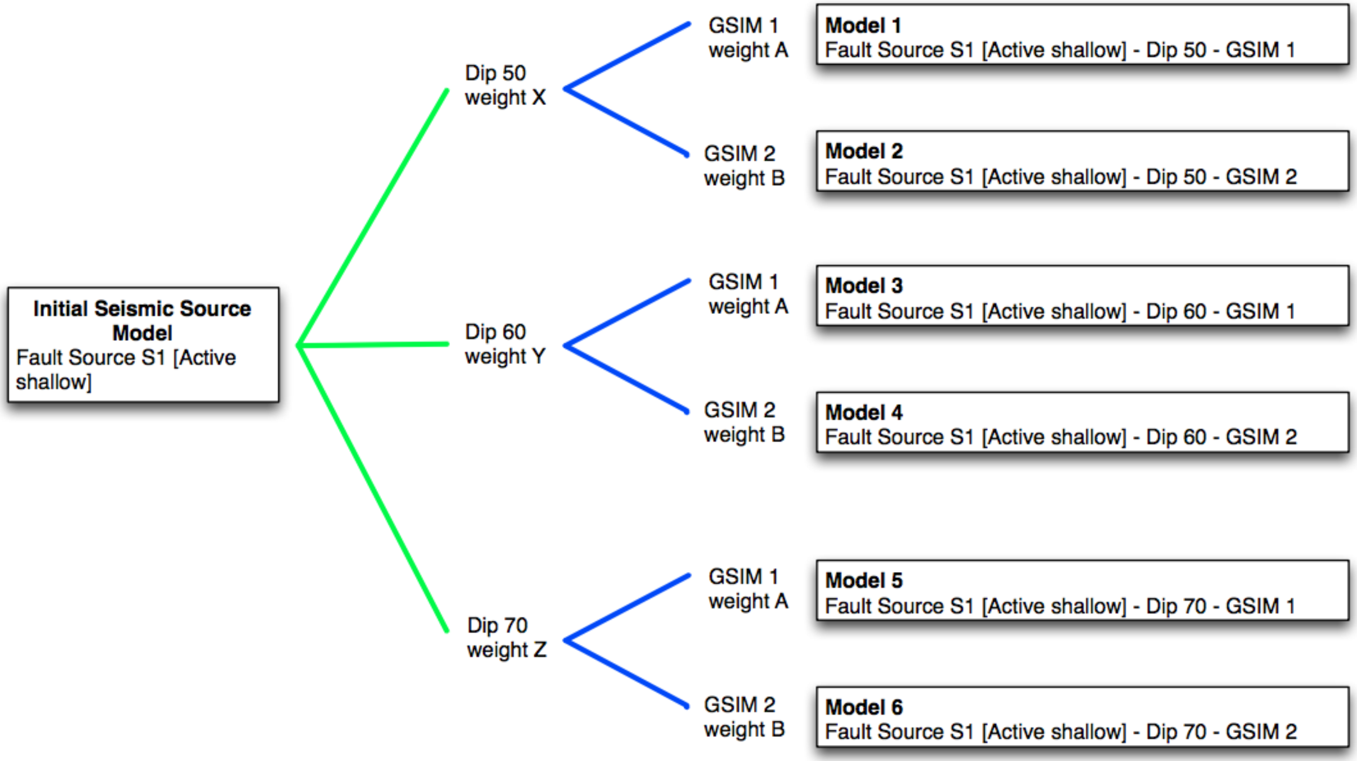
2) Epistemic uncertainty is formally taken into account by using alternative models (or parameterizations) within a logic-tree structure

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

Logic-Tree Strategy

A logic-tree consists of branches, which are independent, mutually exclusive and collectively exhaustive representations of the source and ground motion variability.

Commonly, several branching levels are used to combine uncertainties of different type.



Initial Seismic Source Model
Fault Source S1 [Active shallow]

Dip 50
weight X

Dip 60
weight Y

Dip 70
weight Z

GSIM 1
weight A

GSIM 2
weight B

Model 1
Fault Source S1 [Active shallow] - Dip 50 - GSIM 1

Model 2
Fault Source S1 [Active shallow] - Dip 50 - GSIM 2

Model 3
Fault Source S1 [Active shallow] - Dip 60 - GSIM 1

Model 4
Fault Source S1 [Active shallow] - Dip 60 - GSIM 2

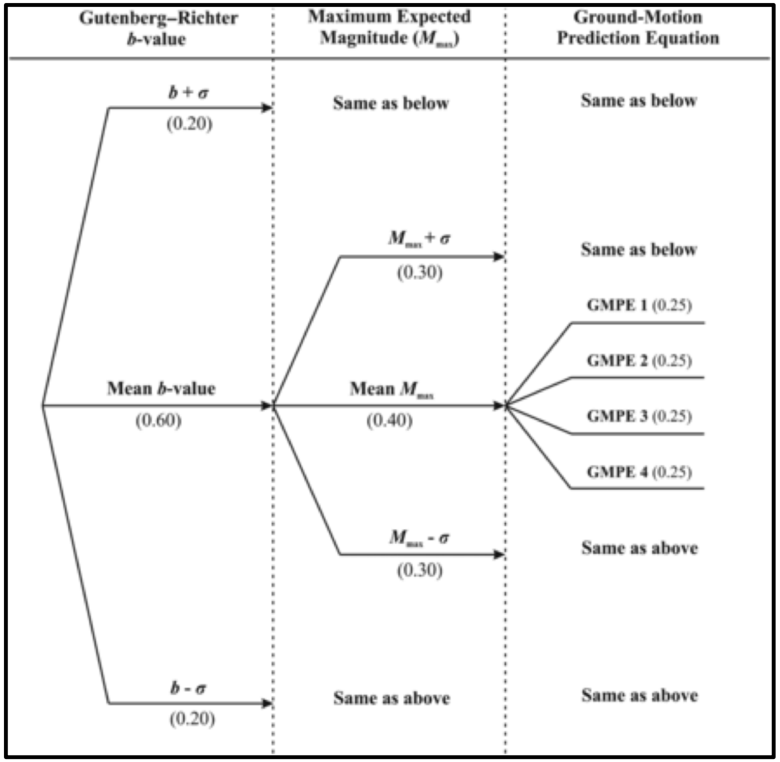
Model 5
Fault Source S1 [Active shallow] - Dip 70 - GSIM 1

Model 6
Fault Source S1 [Active shallow] - Dip 70 - GSIM 2

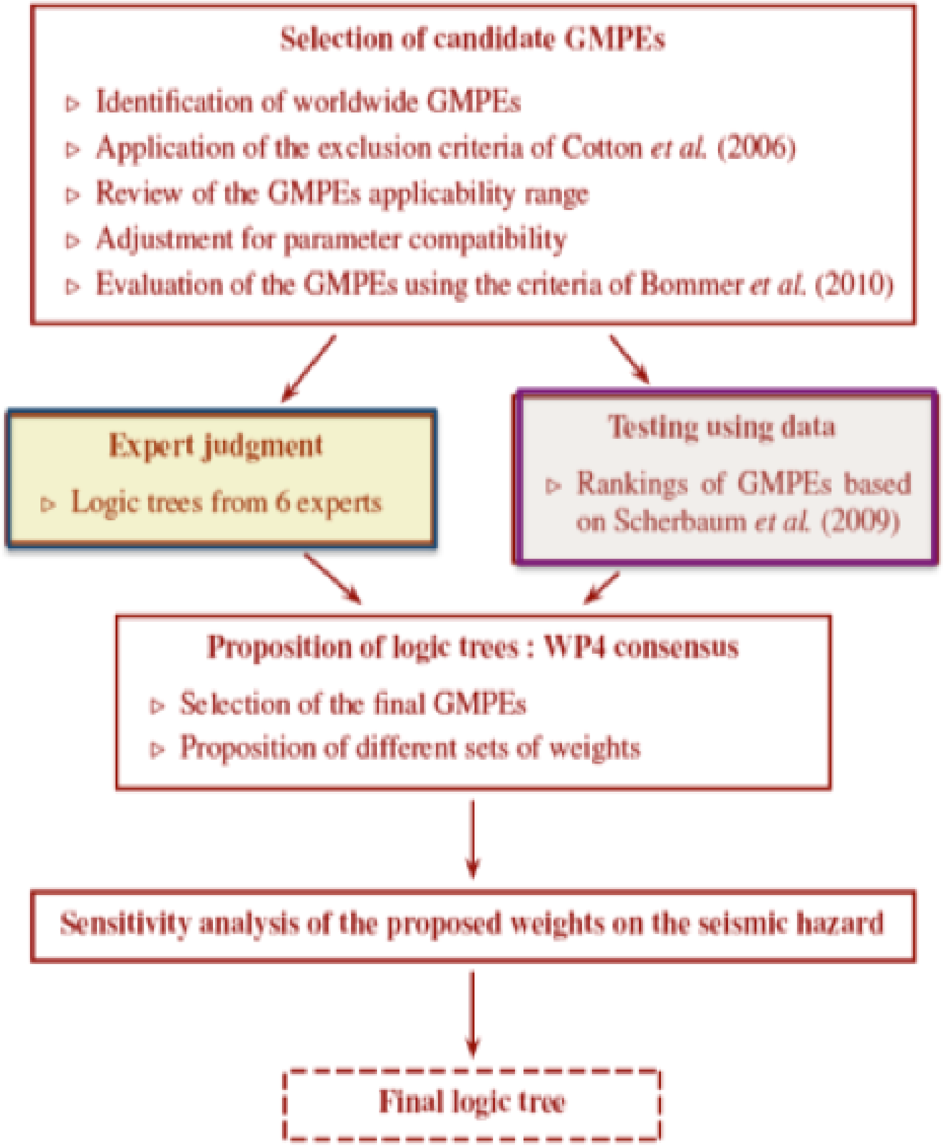
Assigning weights

Each model is assigned **weights**, which express the degree of belief on that model. But how to assign weights?

- Based on fits to observed data? (**Empirical approach**)
- Based on theoretical representation of the physics of the process? (**Physical approach**)
- Weights assignment could be (actually, often is) a subjective process based **expert judgement**.



Example: GMPE Selection



Selection of candidate GMPEs

- Identification of worldwide GMPEs
- Application of the exclusion criteria of Cotton *et al.* (2006)
- Review of the GMPEs applicability range
- Adjustment for parameter compatibility
- Evaluation of the GMPEs using the criteria of Bommer *et al.* (2010)

Expert judgment

- Logic trees from 6 experts

Testing using data

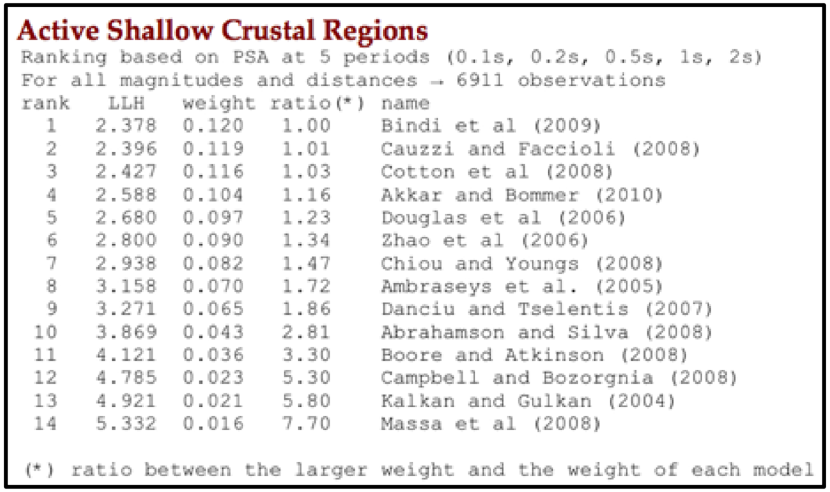
- Rankings of GMPEs based on Scherbaum *et al.* (2009)

Proposition of logic trees : WP4 consensus

- Selection of the final GMPEs
- Proposition of different sets of weights

Sensitivity analysis of the proposed weights on the seismic hazard

Final logic tree



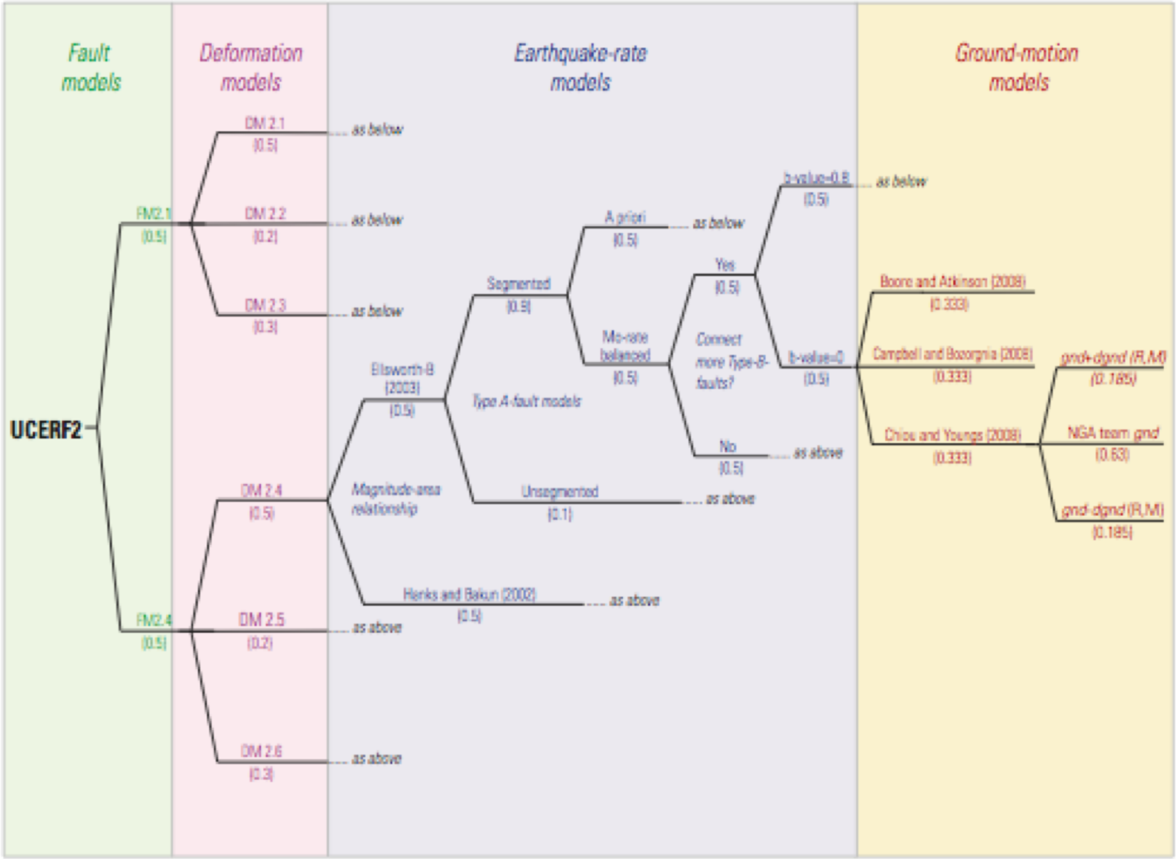
Active Shallow Crustal Regions

```
Ranking based on PSA at 5 periods (0.1s, 0.2s, 0.5s, 1s, 2s)
For all magnitudes and distances → 6911 observations
rank   LLH    weight ratio(*)  name
  1    2.378  0.120   1.00     Bindi et al (2009)
  2    2.396  0.119   1.01     Cauzzi and Faccioli (2008)
  3    2.427  0.116   1.03     Cotton et al (2008)
  4    2.588  0.104   1.16     Akkar and Bommer (2010)
  5    2.680  0.097   1.23     Douglas et al (2006)
  6    2.800  0.090   1.34     Zhao et al (2006)
  7    2.938  0.082   1.47     Chiou and Youngs (2008)
  8    3.158  0.070   1.72     Ambraseys et al. (2005)
  9    3.271  0.065   1.86     Danciu and Tselentis (2007)
 10    3.869  0.043   2.81     Abrahamson and Silva (2008)
 11    4.121  0.036   3.30     Boore and Atkinson (2008)
 12    4.785  0.023   5.30     Campbell and Bozorgnia (2008)
 13    4.921  0.021   5.80     Kalkan and Gulkan (2004)
 14    5.332  0.016   7.70     Massa et al (2008)

 (*) ratio between the larger weight and the weight of each model
```

Logic-tree sampling

PSHA softwares like OpenQuake make the use of logic-trees straightforward, but this strategy has be used carefully...

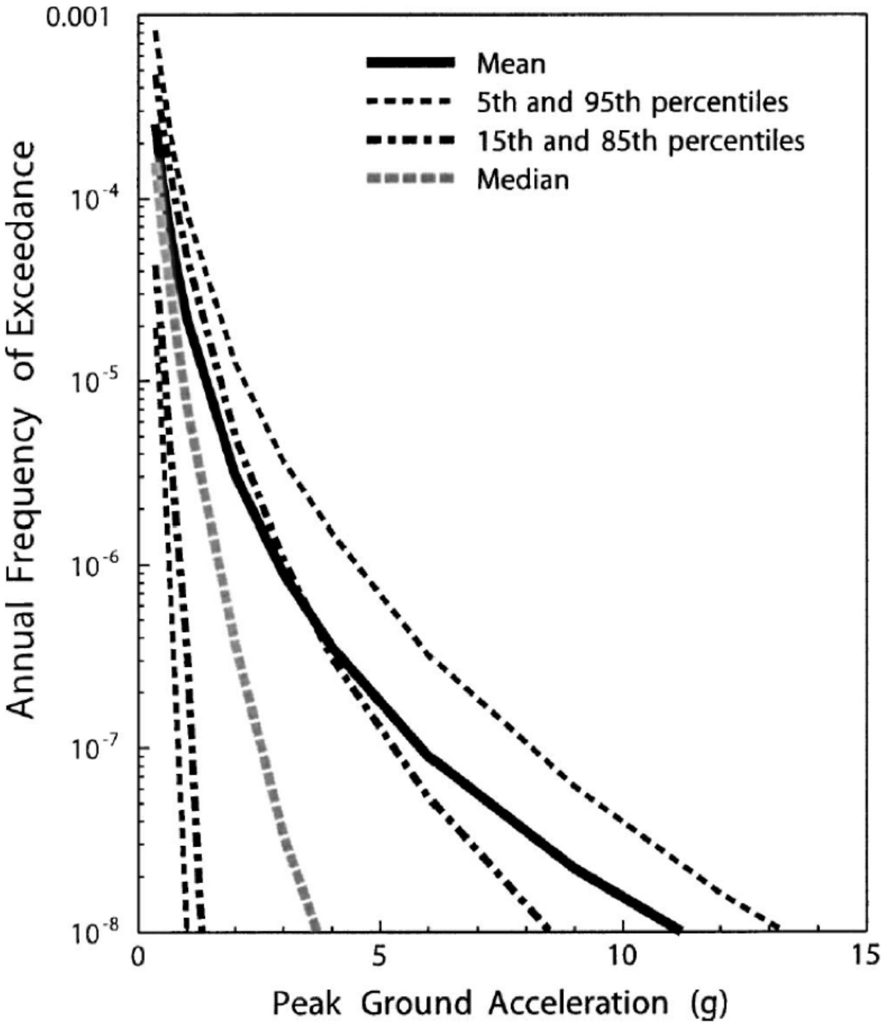


Calculation time can be prohibitive if number of branches and levels is too high!

<u>Sampling of the logic-tree might be necessary!</u>

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

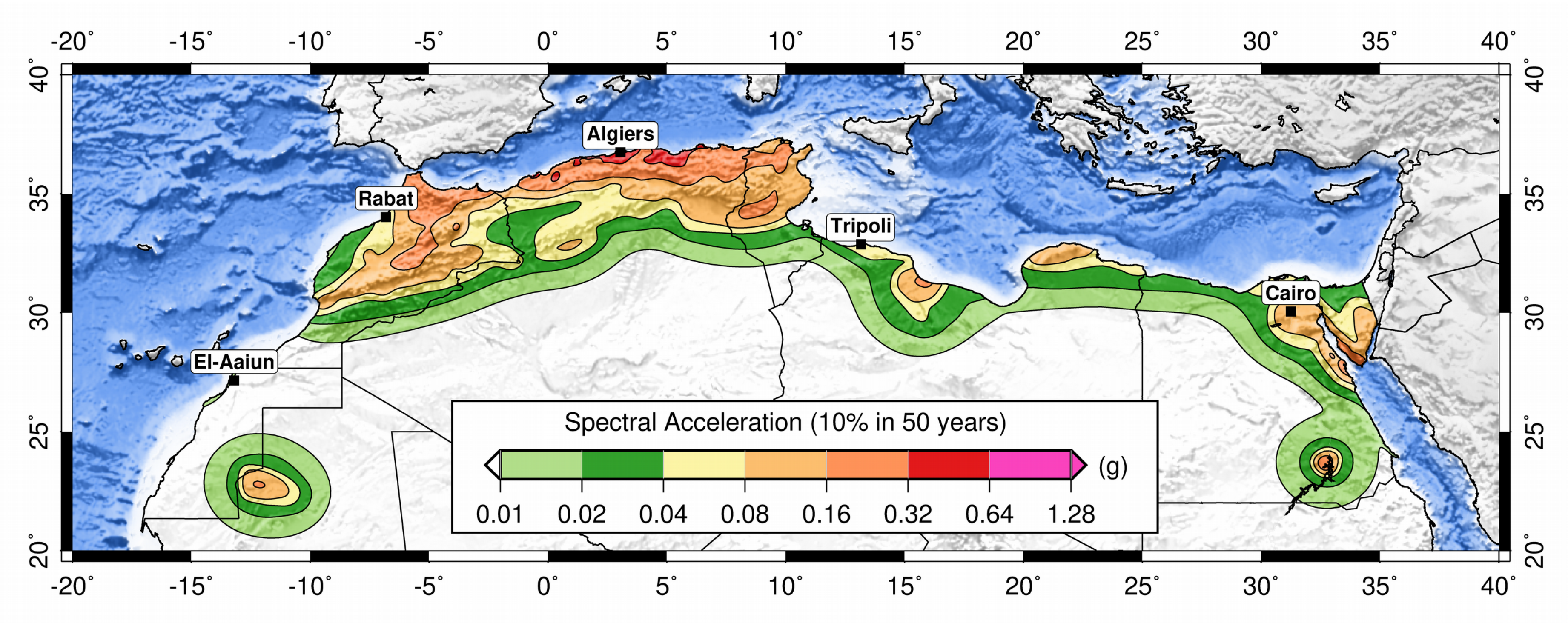
Use of additional "conflicting" models (from newly available data) can increase epistemic uncertainty

Epistemic uncertainty might be (paradoxically) lower in regions with less data!

PSHA Output: Hazard Maps

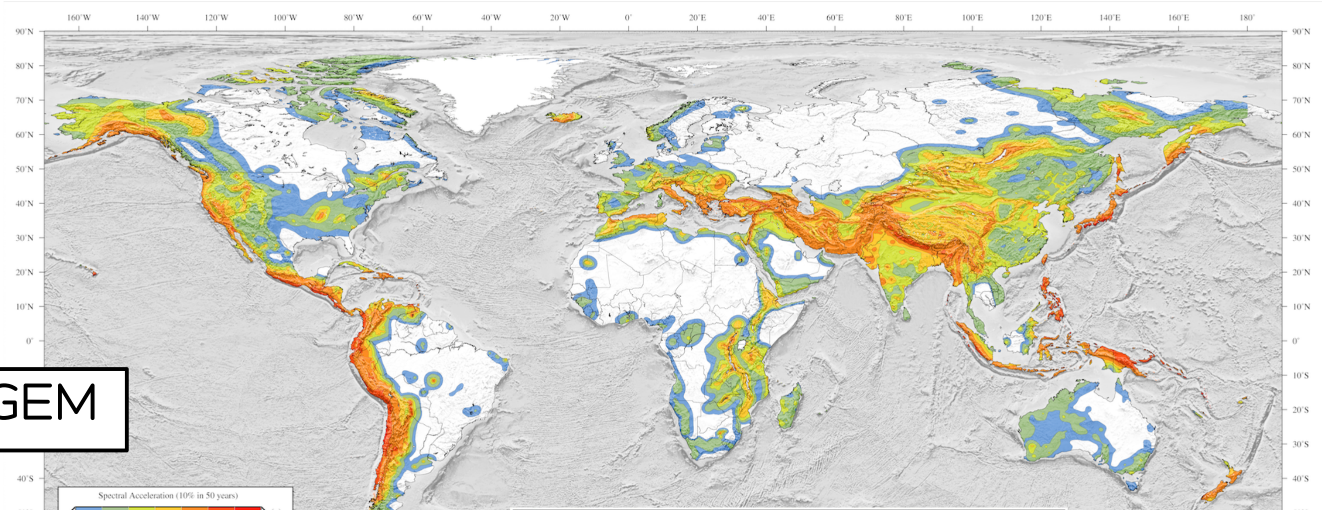
Hazard maps are used to show uniform probability of exceedance of a given ground motion measure for a given return period distributes over the area.

PGA @ 10% Probability in 50 years

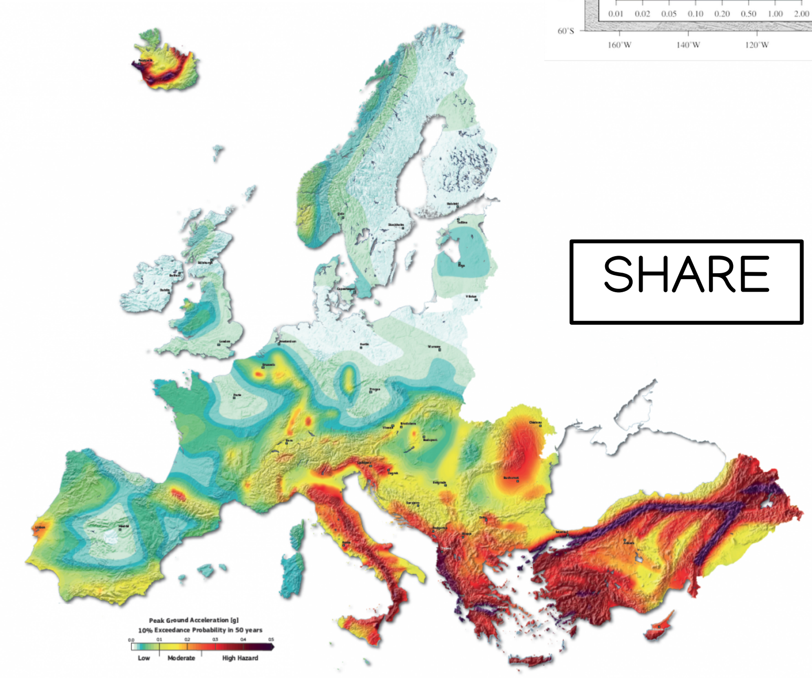


PSHA Output: Hazard Maps

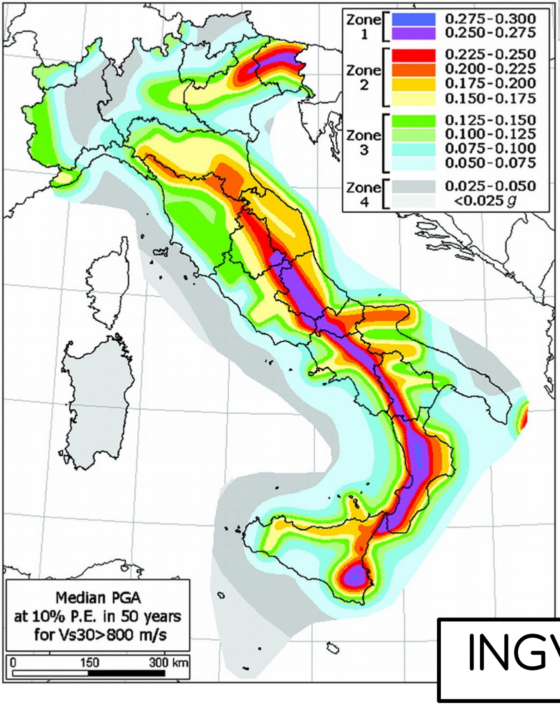
Different scales and resolutions:
- Global
- Continental
- National
- Regional
- Local



GEM



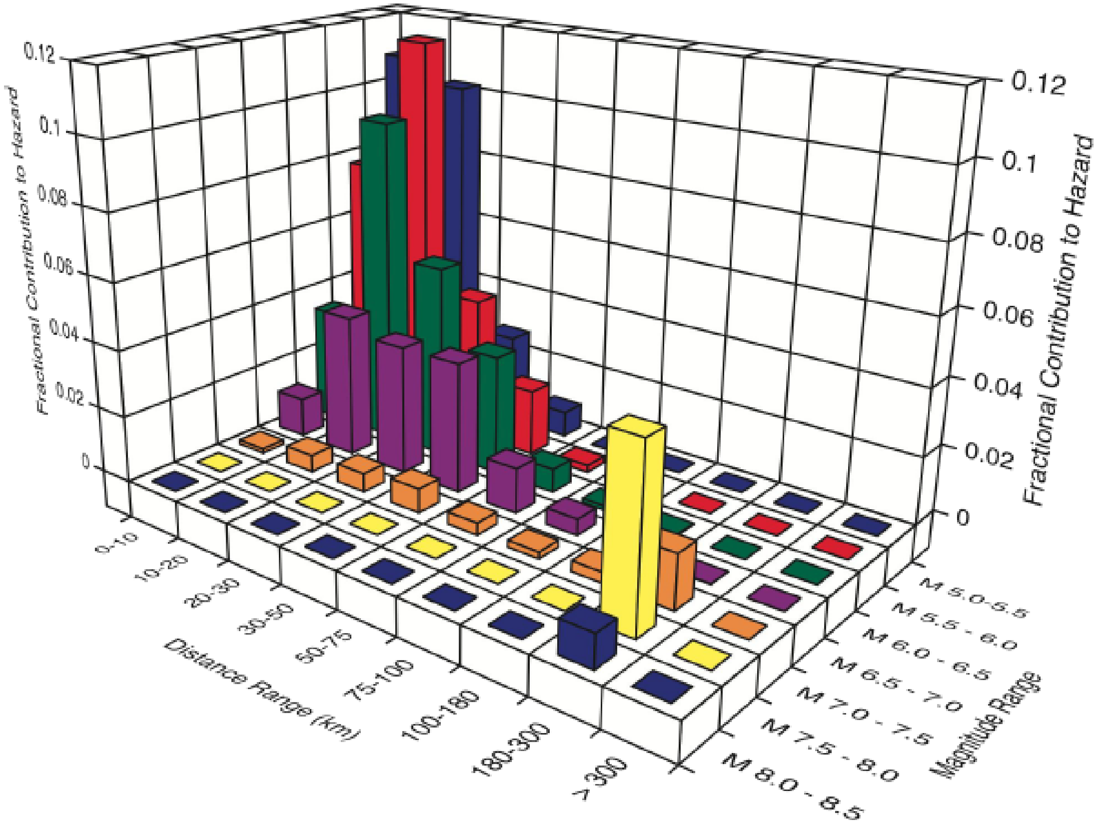
SHARE



INGV

Disaggregation

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.

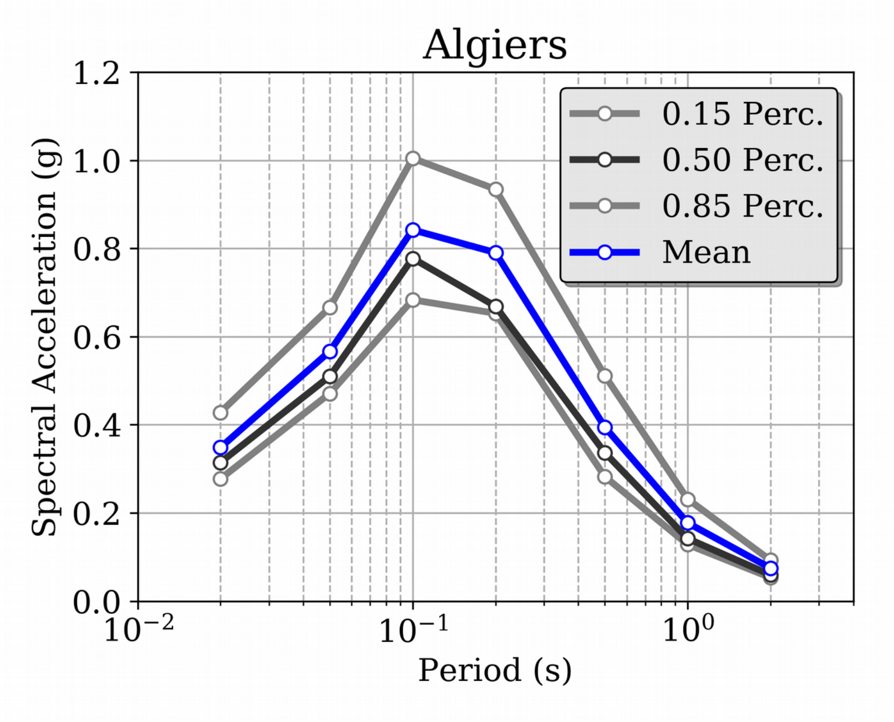


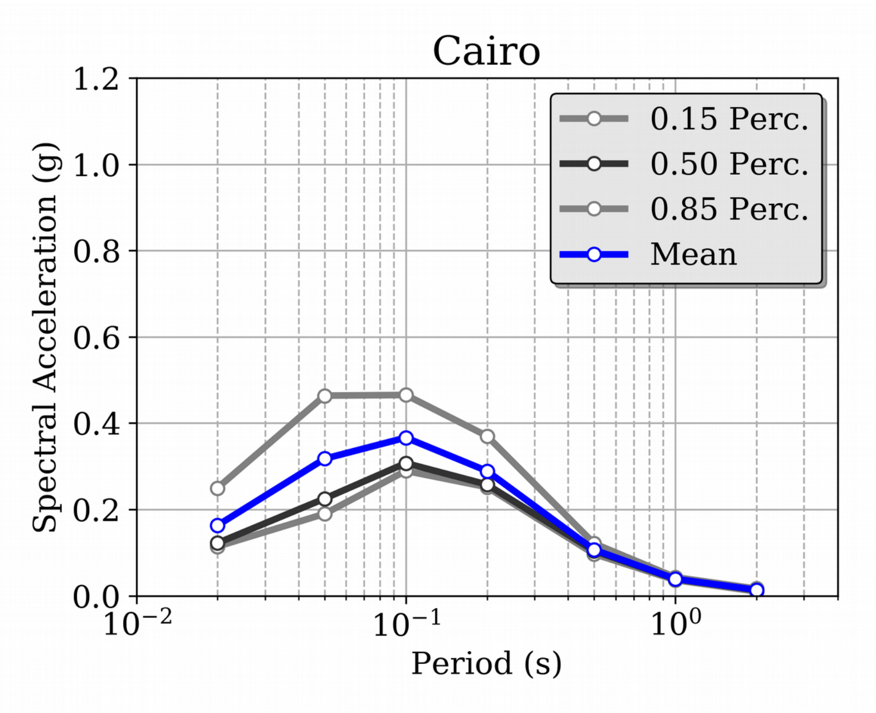
Can identify scenarios that represent the greatest likelihood of contributing to the hazard

Uniform Hazard Spectra

A common goal of PSHA is to identify a design response spectrum to use for both structural and geotechnical analysis.

Uniform hazard spectra (UHS) is used to represent ground motion that have an equal probability of being exceeded in a fixed time span.

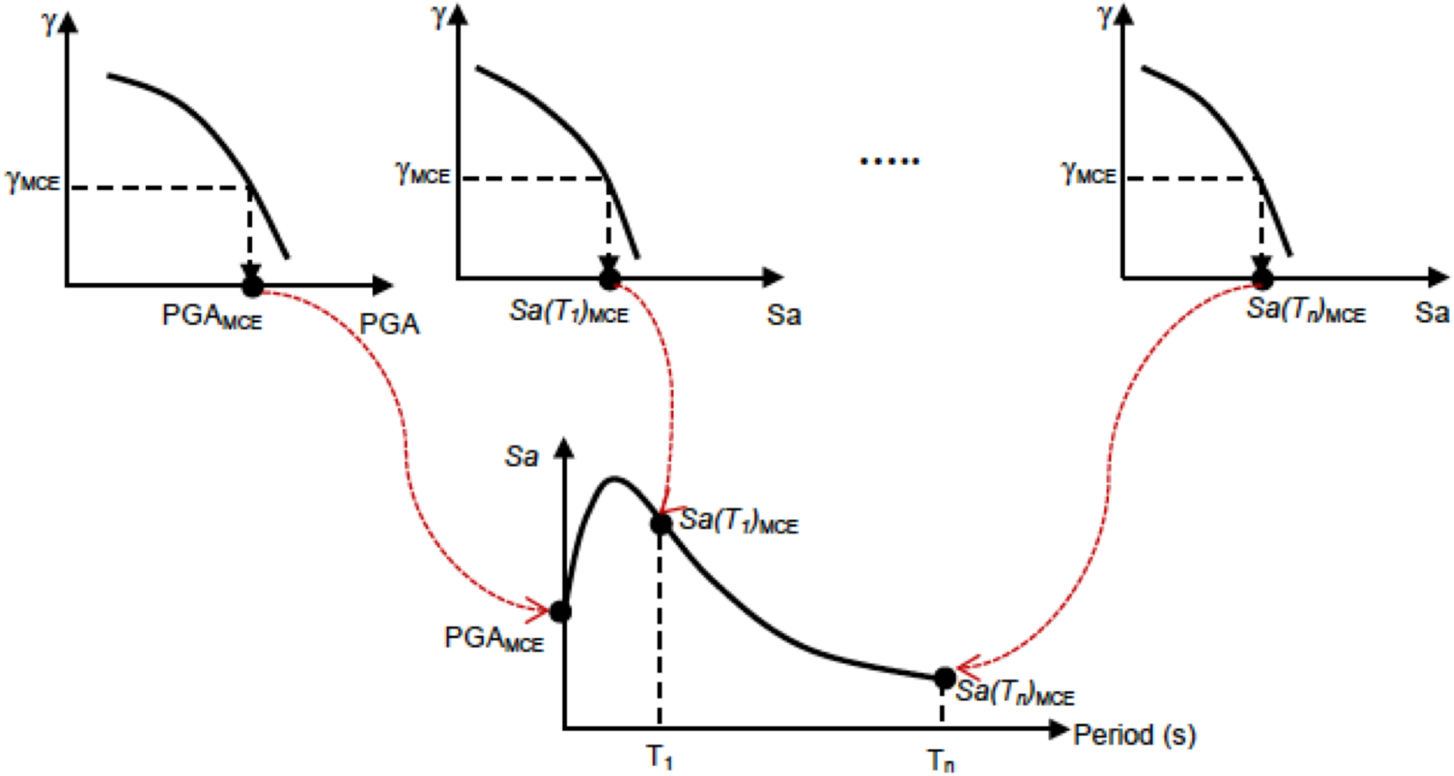




Uniform Hazard Spectra

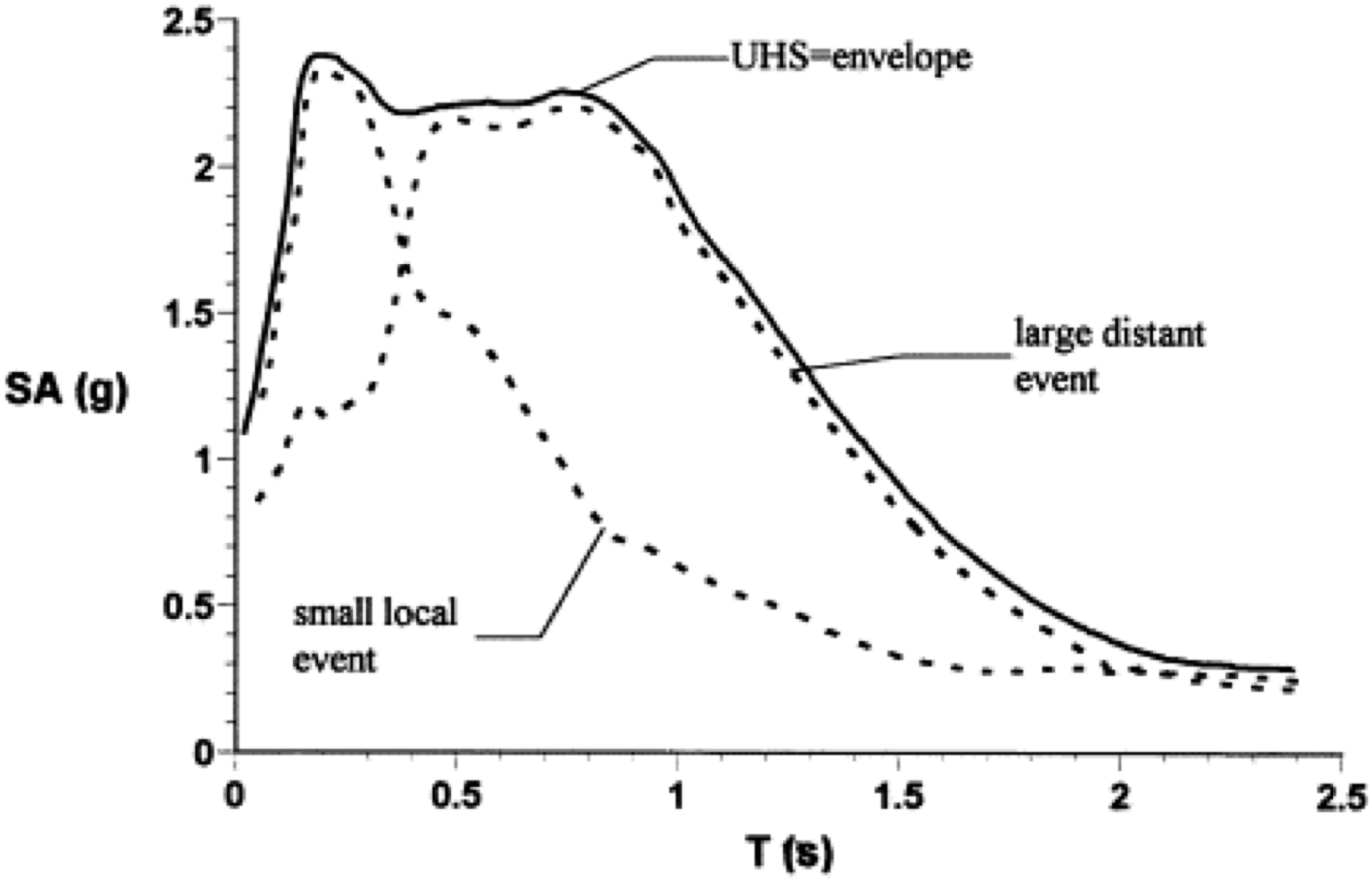
UHS can be computed using GMPEs that support several spectral periods in the following way:

1) Choose the target return period to use for the calculation of the UHS (e.g. 475 years)
2) Compute the hazard curve for each spectral ordinate
3) Select the Sa for the RP specified at point 1

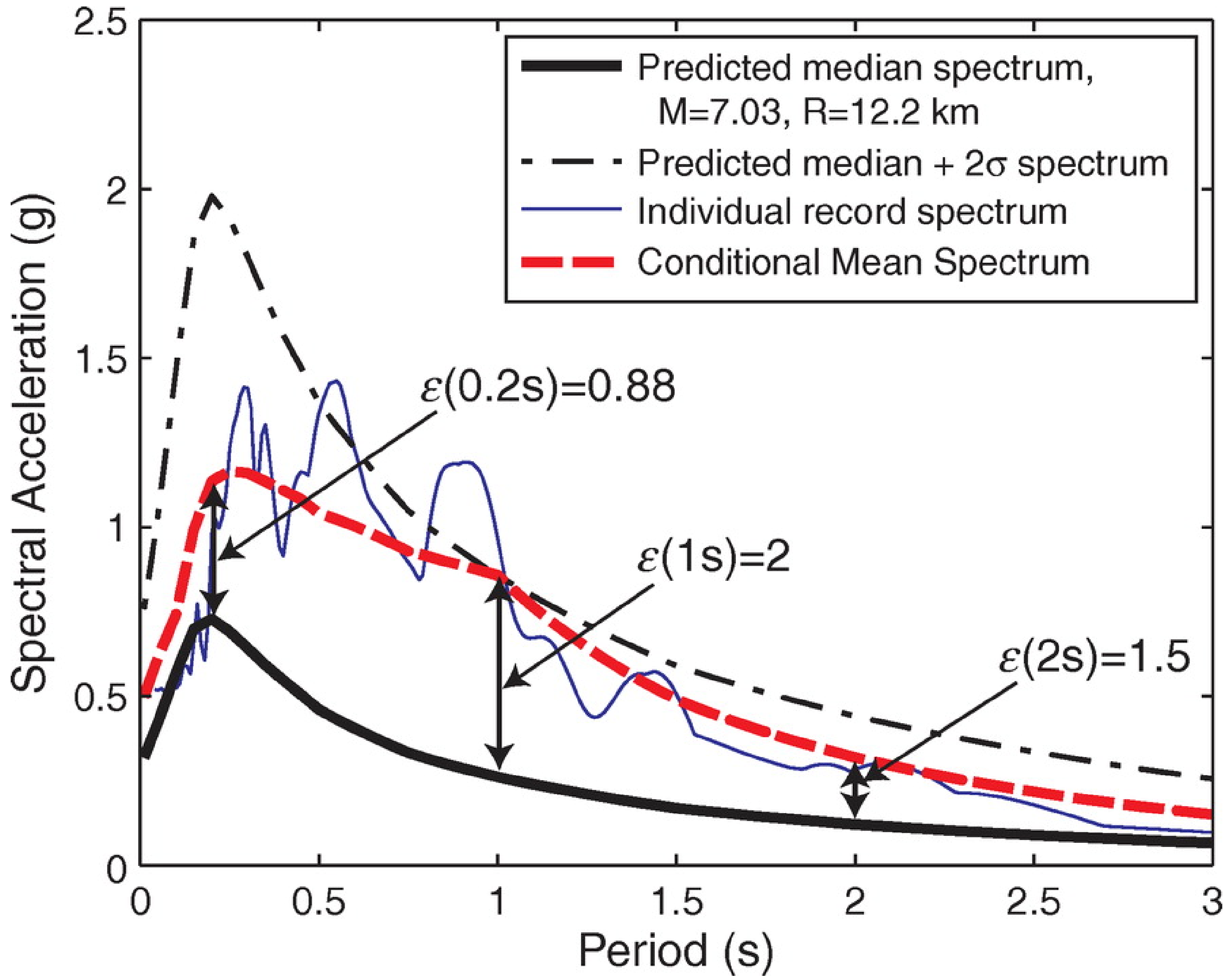


Uniform Hazard Spectra

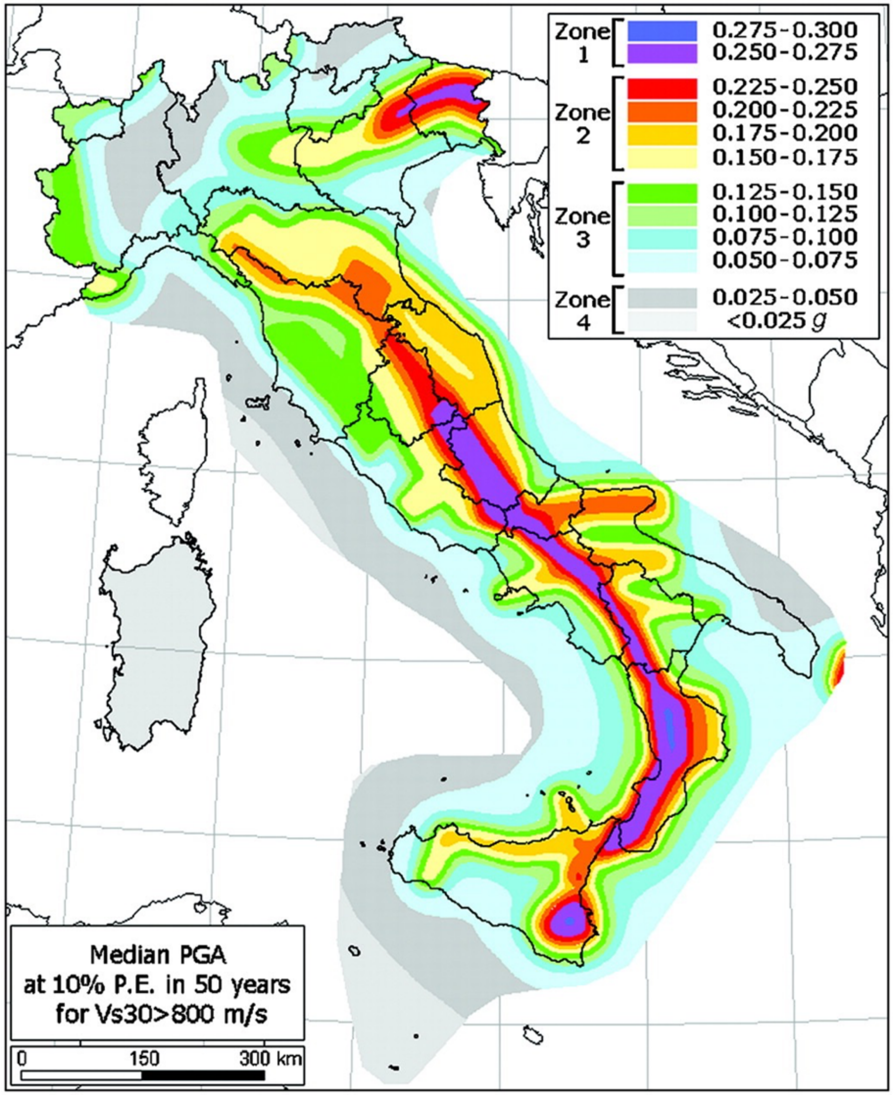
Note that each “part” of the spectrum is sensitive to a generally different controlling scenario.

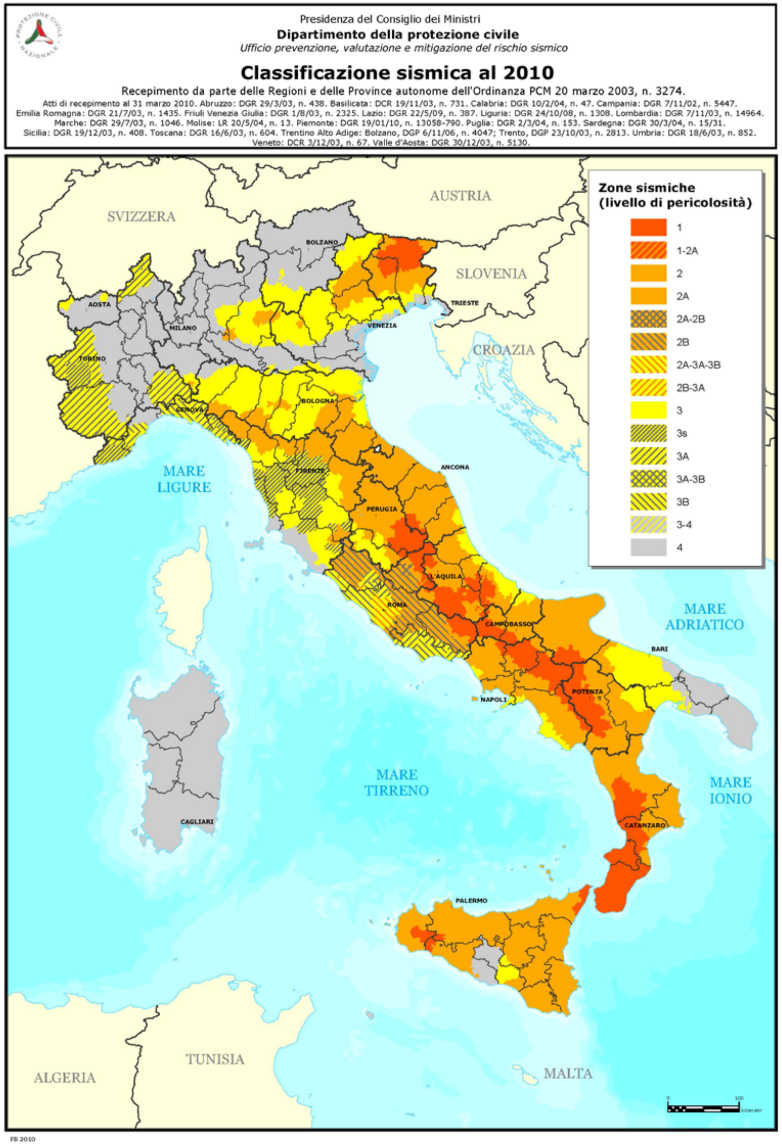


Conditional Mean Spectrum



Using PSHA: Seismic Zonation





Presidenza del Consiglio dei Ministri

Dipartimento della protezione civile

Ufficio prevenzione, valutazione e mitigazione del rischio sismico

Classificazione sismica al 2010

Recepimento da parte delle Regioni e delle Province autonome dell'Ordinanza PCM 20 marzo 2003, n. 3274.

Atti di recepimento al 31 marzo 2010. Abruzzo: DGR 29/3/03, n. 438. Basilicata: DCR 19/11/03, n. 731. Calabria: DGR 10/2/04, n. 47. Campania: DGR 7/11/02, n. 5447. Emilia Romagna: DGR 21/7/03, n. 1435. Friuli Venezia Giulia: DGR 1/8/03, n. 2325. Lazio: DGR 22/5/09, n. 387. Liguria: DGR 24/10/08, n. 1308. Lombardia: DGR 7/11/03, n. 14964. Marche: DGR 29/7/03, n. 1046. Molise: LR 20/5/04, n. 13. Piemonte: DGR 19/01/10, n. 13058-790. Puglia: DGR 2/3/04, n. 153. Sardegna: DGR 30/3/04, n. 15/31. Sicilia: DGR 19/12/03, n. 408. Toscana: DGR 16/6/03, n. 604. Trentino Alto Adige: Bolzano, DGP 6/11/06, n. 4047; Trento, DGP 23/10/03, n. 2813. Umbria: DGR 18/6/03, n. 852. Veneto: DCR 3/12/03, n. 67. Valle d'Aosta: DGR 30/12/03, n. 5130.

Title

Text