From data to decision-making
under conditions of uncertainty
August 26th to 28th, 2025

RISK
Summer
School
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Earth science data for estimation of probabilistic seismic hazard and risk

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ISTerre, IRD, Grenoble

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UGA
Université Grenoble Alpes

Outline of the presentation

- Introduction to the seismic hazard calculation
- Earthquake catalogs for hazard estimation
- Probabilistic seismic hazard assessment (PSHA) at the scale of a country, a complete seismic hazard analysis with illustration in Ecuador
- Testing PSHA against observations, some challenges, illustration in metropolitan France
- Conclusions

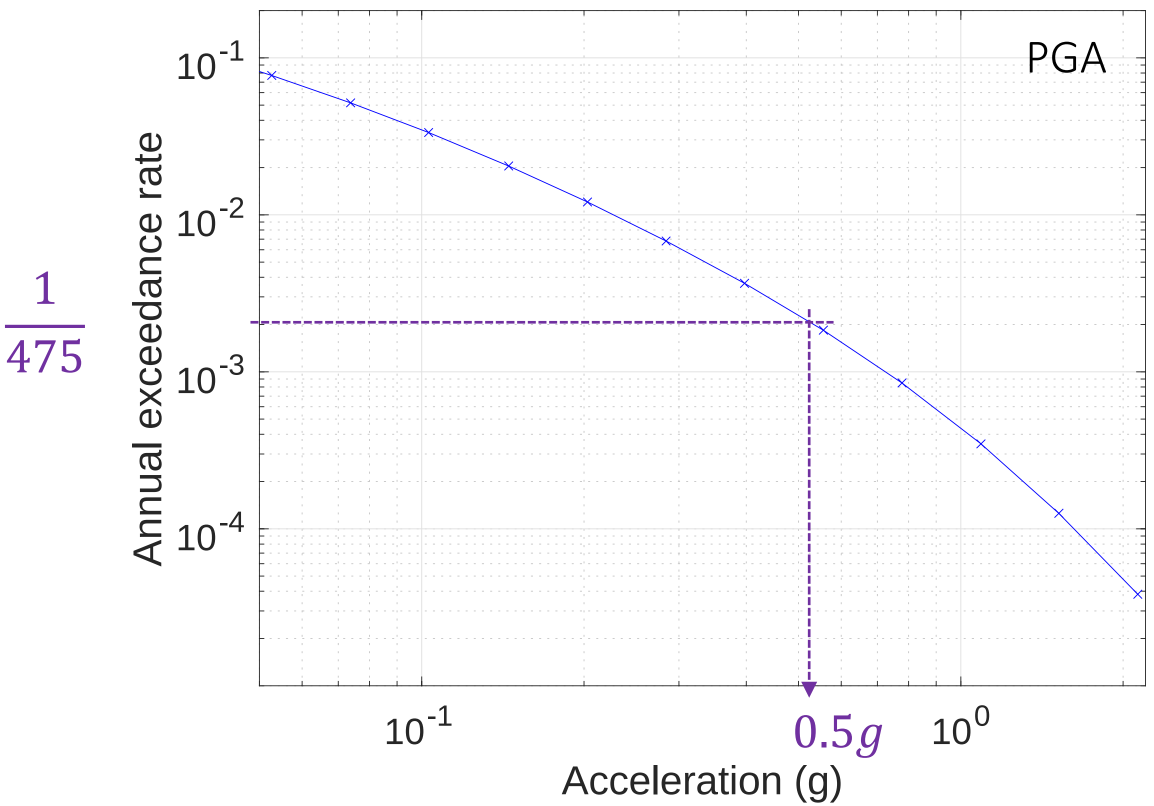
Introduction to PSHA

Determination of PSHA at a site: estimation of the hazard curve

Annual exceedance rate versus acceleration at a site

Required for:

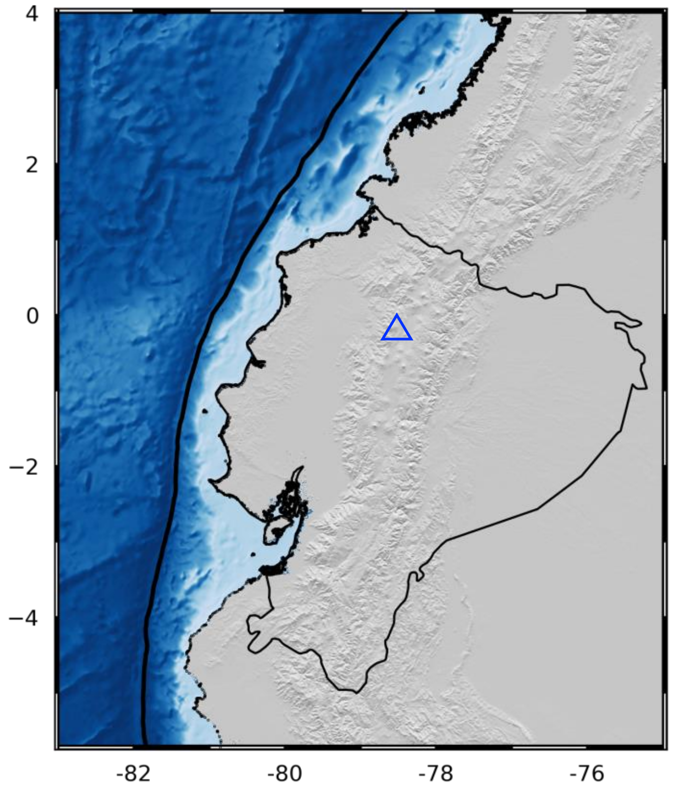
- Building design
- Disaster planning
- Insurance agencies



Céline Beauval, ISTerre, RISK Summer School, August 2025

Determination of PSHA at a site: estimation of the hazard curve

Seismic hazard curve for the city of Quito, capital of Ecuador ?



SOURCE MODEL

defines all earthquakes that may produce ground-motions of engineering significance in the city

GROUND-MOTION MODEL

predicts the ground-motions that these earthquakes will produce in the city

Determination of PSHA at a site: estimation of the hazard curve

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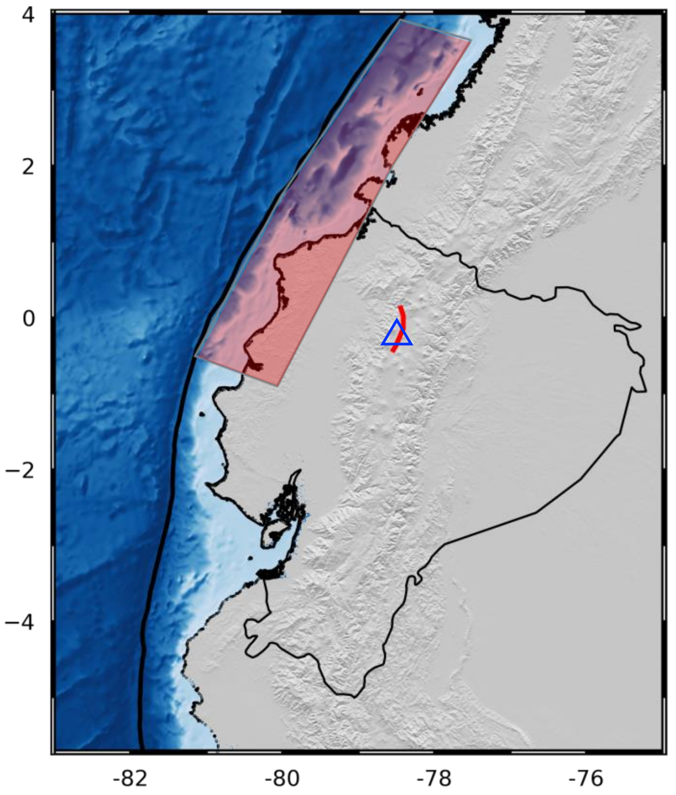
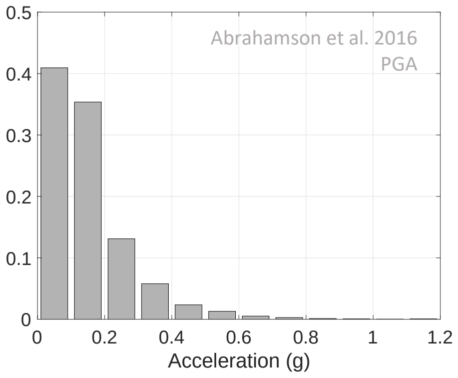


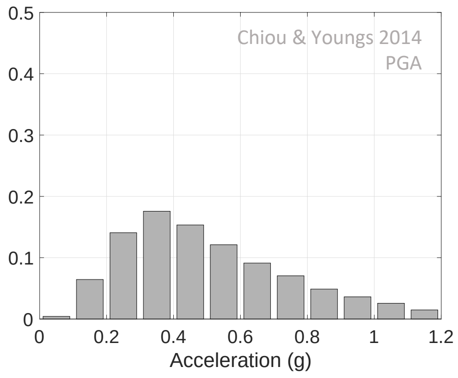
EARTHQUAKE FREQUENCIES

M_W 8.2 interface
1 every ~800 years

M_W 6.0 Quito fault
1 every ~600 years

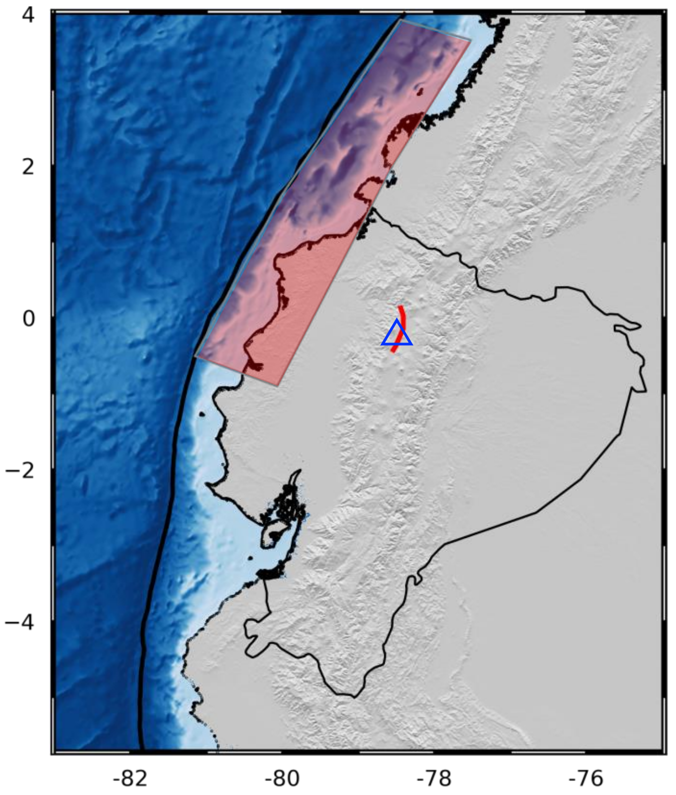
Acceleration predicted in Quito (PDF)

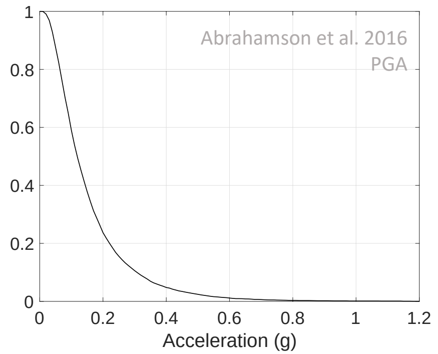
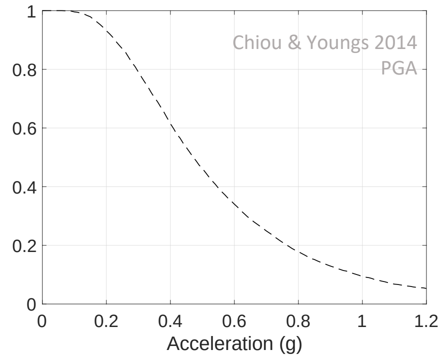




Determination of PSHA at a site: estimation of the hazard curve

Seismic hazard curve for the city of Quito, capital of Ecuador ?



EARTHQUAKE FREQUENCIES	Probability of exceedance in Quito
M_W 8.2 interface 1 every ~800 years	
M_W 6.0 Quito fault 1 every ~600 years	

Determination of PSHA at a site: estimation of the hazard curve

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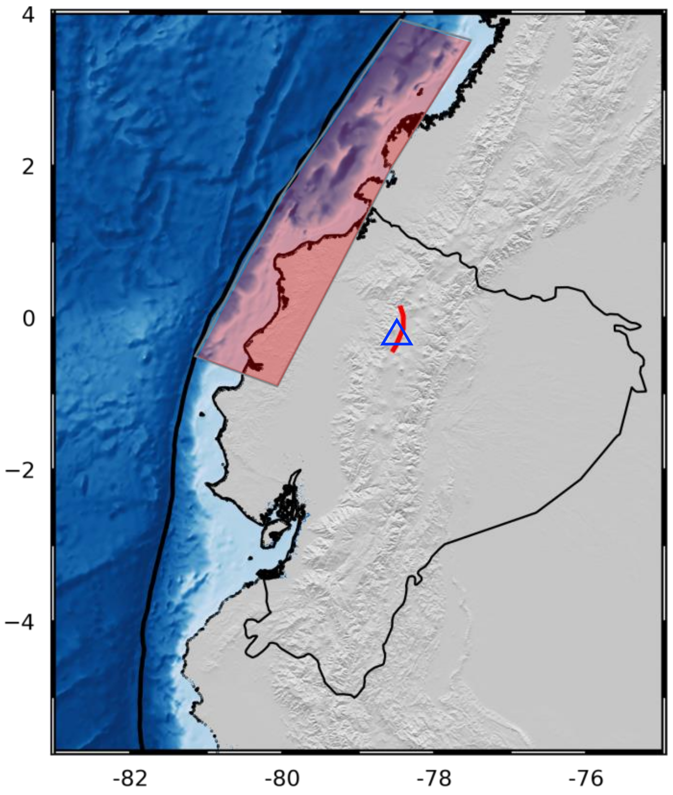

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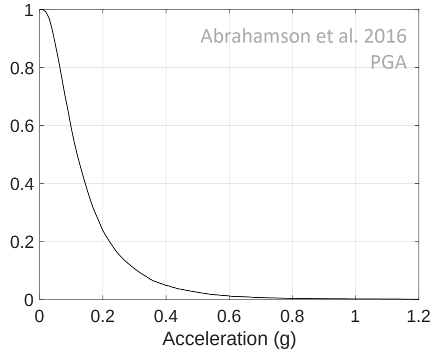

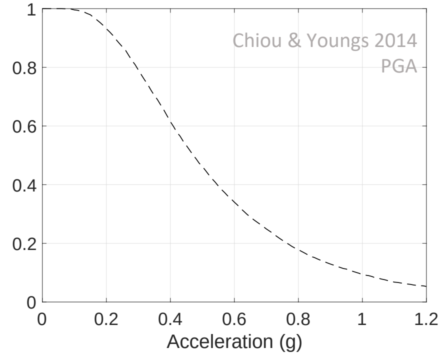

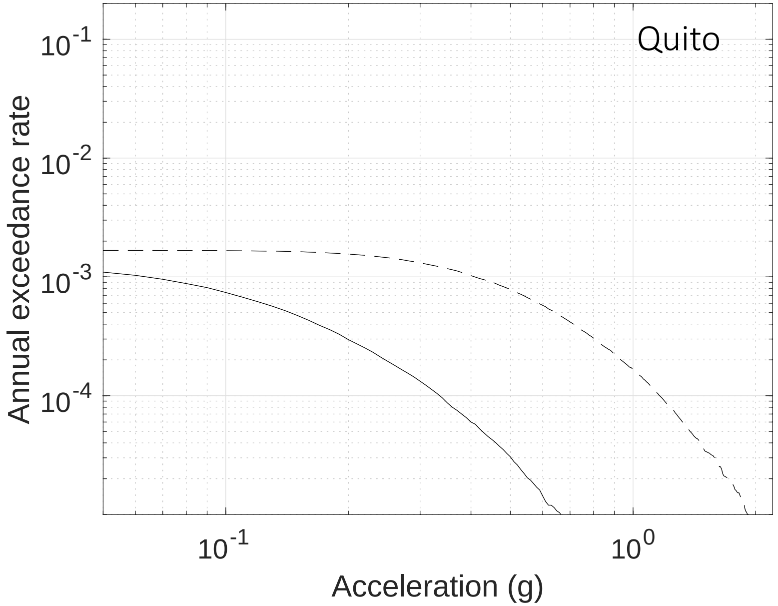

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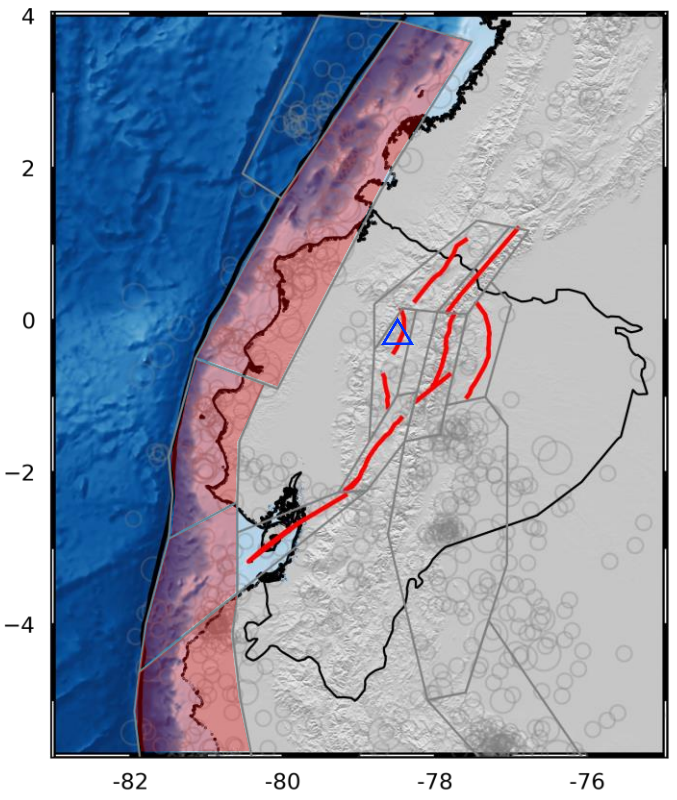

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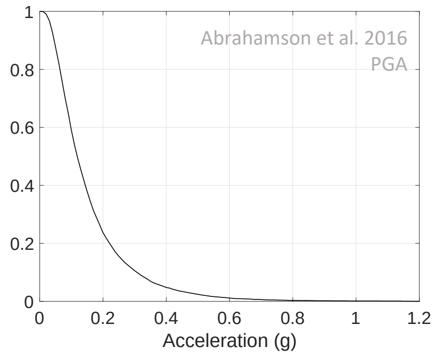
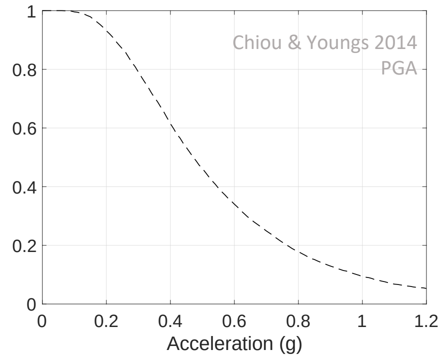
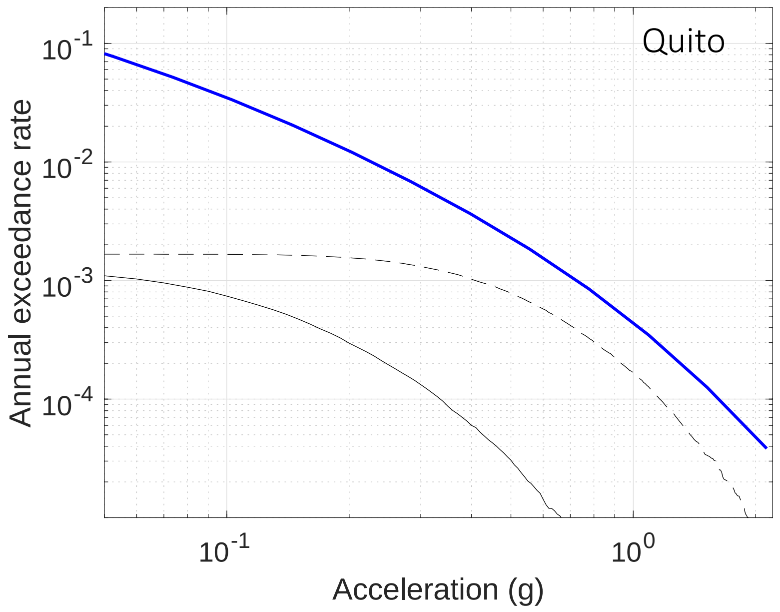




hazard curve



$$\sum_{all\ events} \lambda_{event}\ P(> A)$$

Contribution from ALL events

Earthquake catalogs: what happened in the past, primary information for assessing hazard

Earthquake catalogs

To extend the observation time window at maximum : merging heterogeneous datasets

~several millennia BC

~1500 Ecuador
~1000 France
~2000 Lebanon

~1900

~1960

present

Instrumental period

Low magnitude of completeness
Precise earthquake parameters

Early instrumental

Rather high magnitude of completeness
significant uncertainties on earthquake parameters
Limited number of seismological stations before WWSSN

Historical

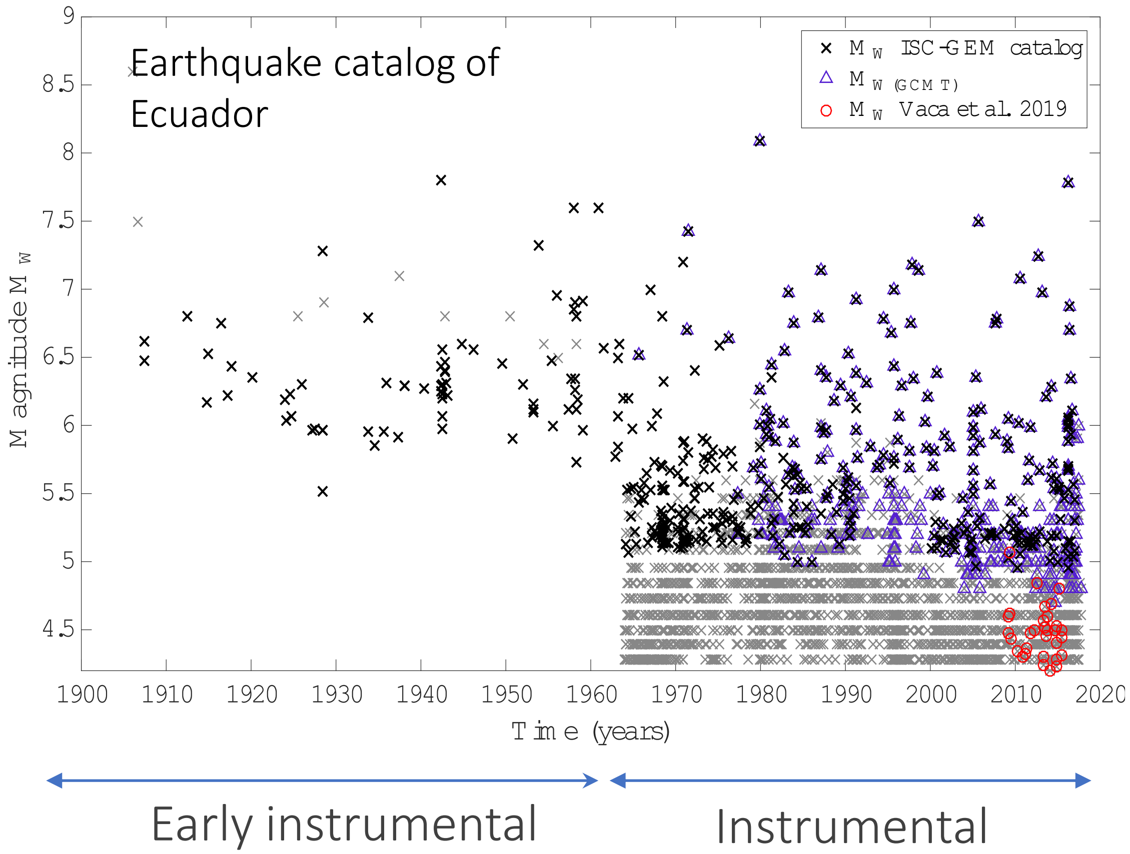
Mostly events that produced damages
large uncertainties on earthquake parameters, derived from macroseismic intensity data

Paleoseismic earthquakes

If available at some faults
uncertainties on the ages and on the magnitudes of the earthquakes

Earthquake catalogs: instrumental period

We aim at getting a homogeneous catalog, but it is never homogeneous



From 1900 to present time, the seismological networks have constantly and considerably evolved

The earthquakes are characterized by different magnitude types (e.g. M_D, M_L, m_b, M_S, M_W), that need to be converted into the same definition of magnitude, usually moment magnitude M_W.

Earthquake catalogs used in hazard assessment bear considerable uncertainties.

Marinière et al. (2021); Lopez Ordoñez et al. (2024)

Earthquake catalogs : historical period

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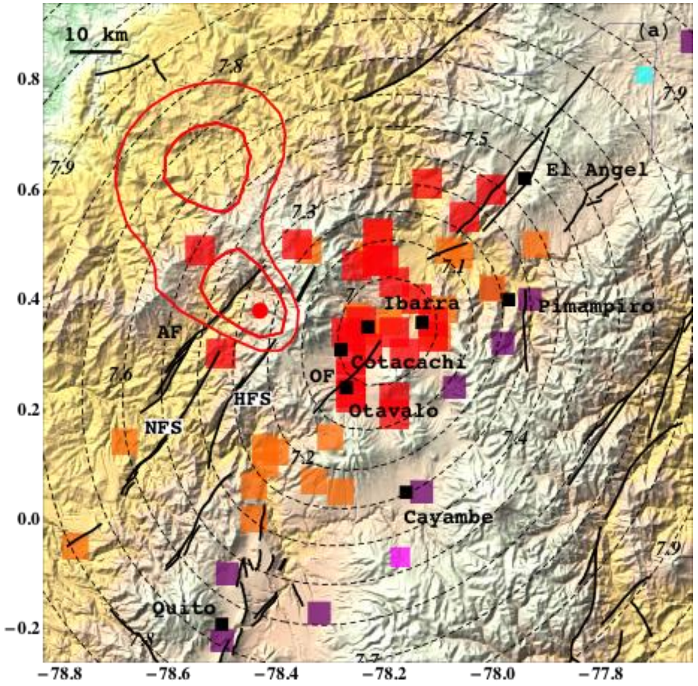
Estimation of magnitudes and locations of pre-instrumental earthquakes from macroseismic intensity data

Example historical event in Ecuador: Ibarra 1868 M_W 7.1-7.8

Pre-requisite : equation predicting intensities depending on the magnitude and the distance to the earthquake

Uncertainties on the location and on the equivalent M_W quantified



intensity center IC (minimum rms)

confidence contours for the intensity centre (deduced from boostrap) 50, 67 and 95% probability that the IC is inside this area (inner contour: 50%; outer contour: 95%)

----- iso-contour of magnitude (equivalent Mw)

Intensities (MSK) : squares, color and size depend on intensity

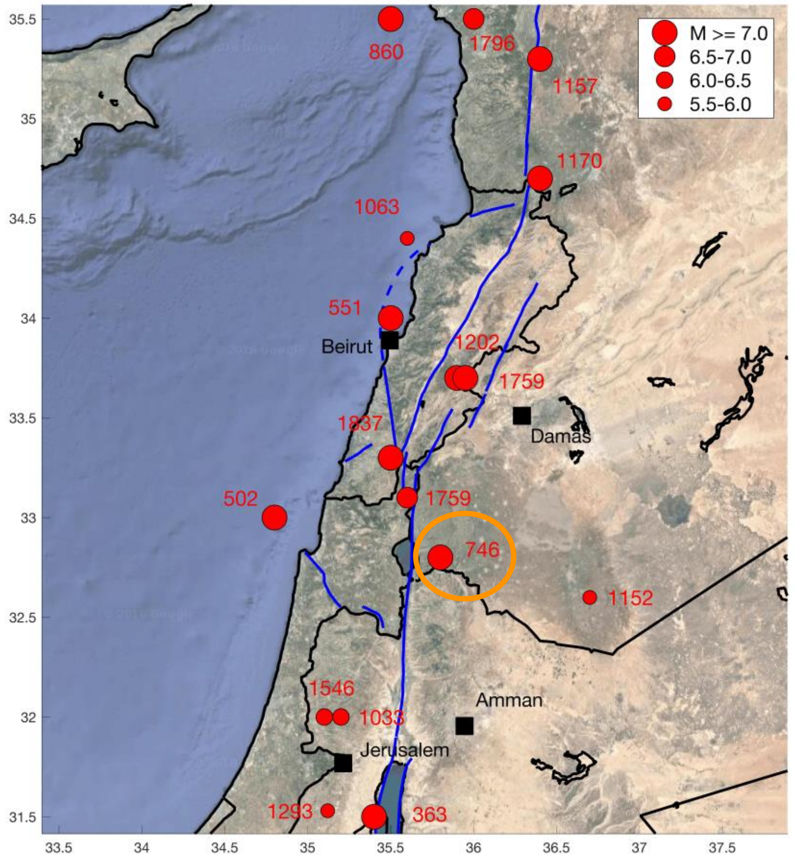
III IV V VI VII VIII IX X XI

Beauval, Yepes et al. (2010)

Earthquake catalogs: historical period

In the Eastern Mediterranean region, a longer history, a wealth of studies published on historical earthquakes

In this case, the work consists in analyzing all the studies available per earthquake and keep the most reliable(s).



Historical earthquake catalog for the Lebanese region

Brax, Albini et al. (2019)

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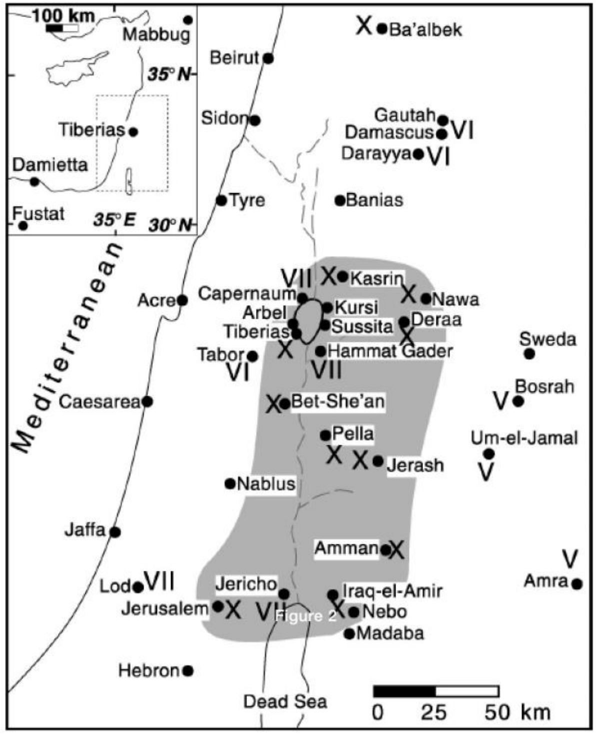
Example : 746 January event, described by many sources, but the interpretation of the archives available is still debated



Marco et al. (2003)

1 huge earthquake (destruction from Egyptian littoral to NE Syria) magnitude 7.3-8.0

Amiran (1950), Russell (1985), Ben Menahem 1991, Guidoboni et al. 1994, Marco et al. 2003

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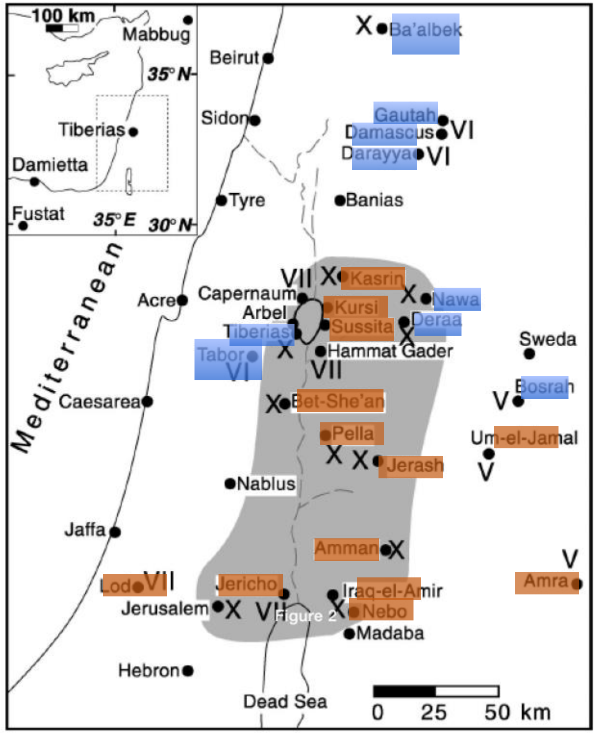
746 EQ

757 EQ



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At least 2 events, 11 years apart and hundreds km apart magnitude 7.0

Karcz 2004; Ambraseys 2005, 2006, 2009

- confusion created by the use of different dating systems in the ancient texts => all felt reports associated to the same earthquake
- contemporary sources and sources written centuries after are given the same level of reliability

Brax, Albini et al. (2019)

Earthquake catalogs

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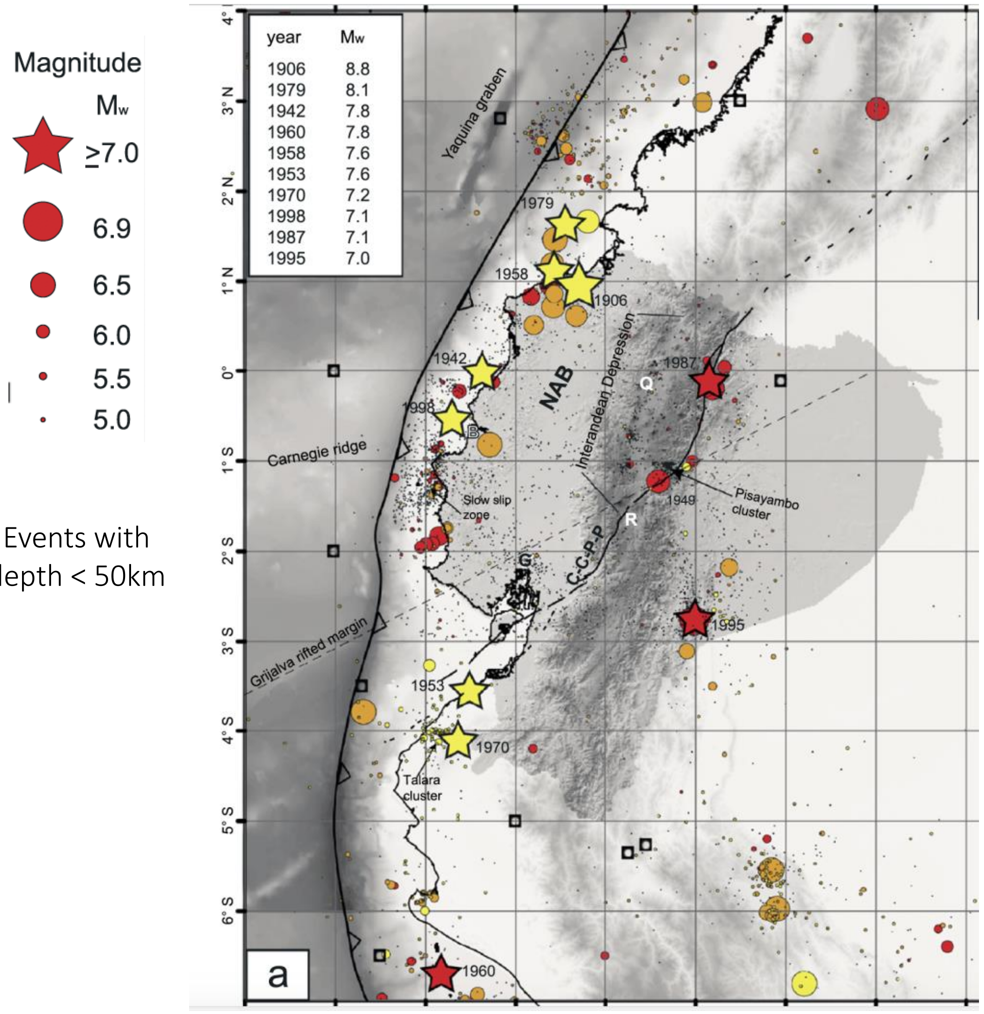
- Earthquake catalogs bear large uncertainties, but they are primary information for assessing hazard : past events for which we have a record

- Earthquakes may occur where they already occurred
- Earthquakes may occur in areas that have been quiet in the history

➡ this information needs to be combined with other data, other "measures" of the seismic potential of the area under study

Building a seismic hazard model based on the available knowledge: illustration in Ecuador

Seismic hazard assessment in Ecuador



Events with depth < 50km

Yepes, Audin et al. (2016)

High seismic activity with destructive earthquakes

- Nazca plate subducting beneath South American plate (~56 mm/yr)
- North Andean Sliver moving at ~9 mm/yr

Since 2007, collaboration with the Geophysical Institute in Quito, responsible for assessing seismic hazard in the country

Probabilistic Seismic Hazard Model
Team of seismologists, geologists and geodesists

Seismic hazard assessment in Ecuador : building the source model

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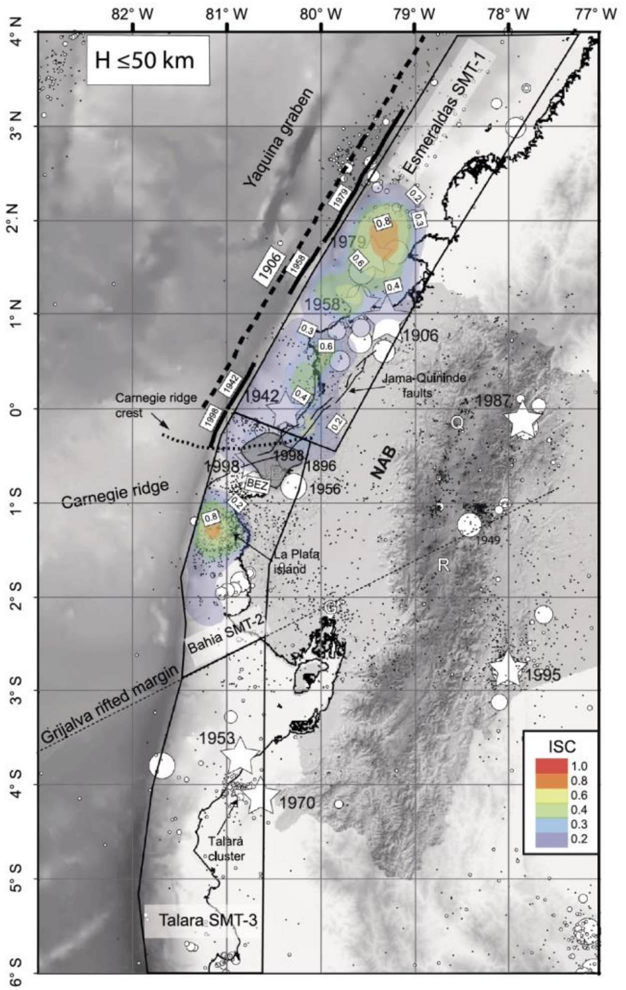
Source model : all earthquakes that may occur in the future, with their magnitudes and locations



- Subduction interface (0-40km) : segmentation proposed for the dipping planes

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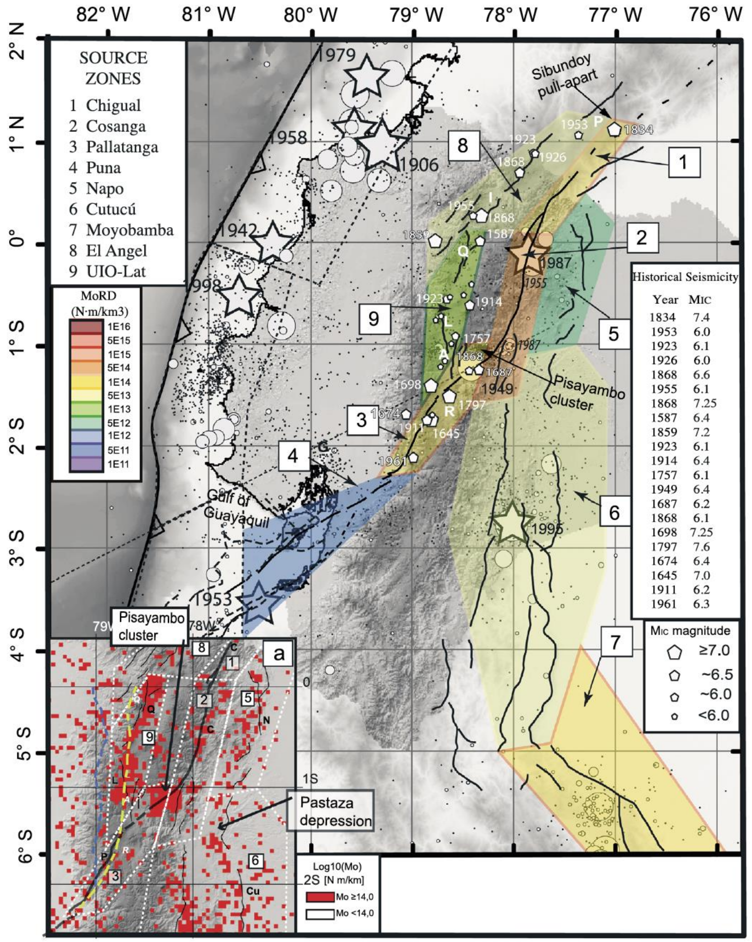

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- Subduction interface (0-40km) : segmentation proposed for the dipping planes
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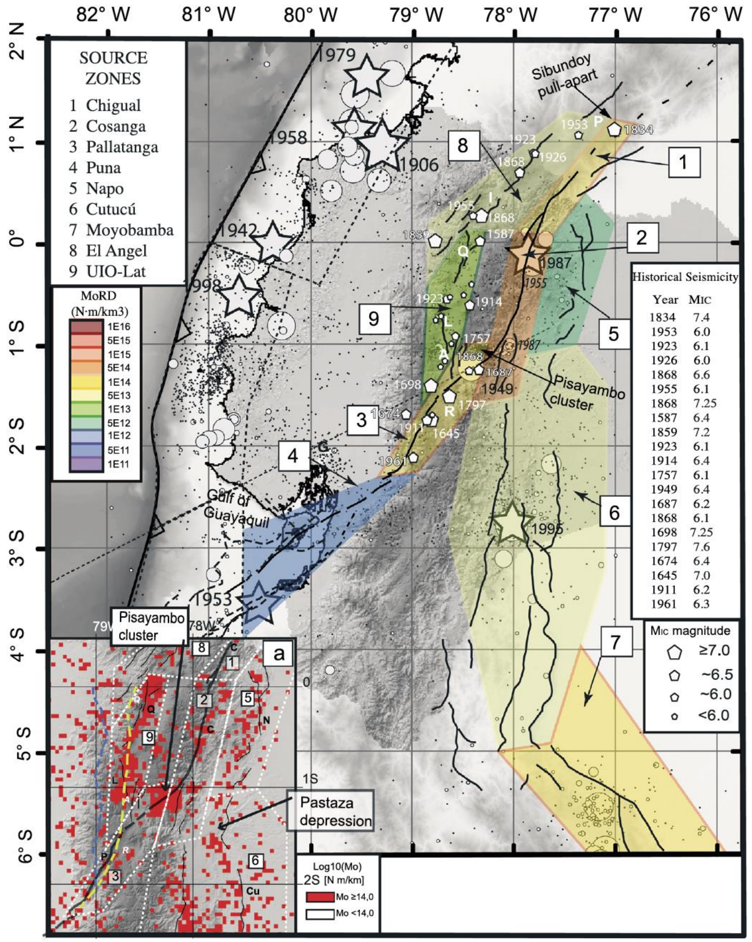

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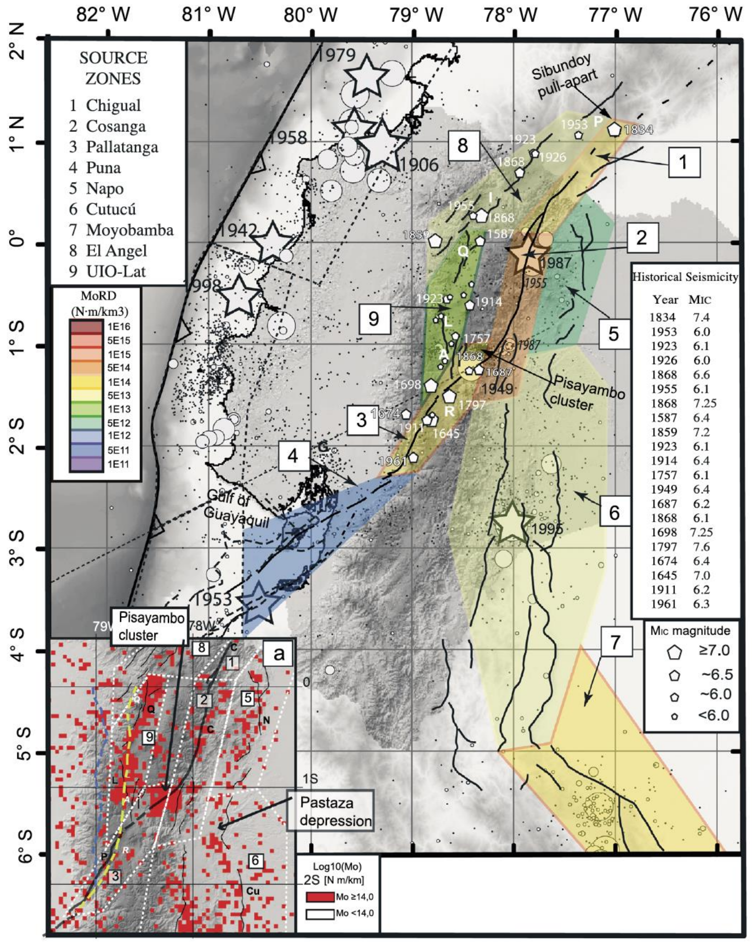

- Subduction interface (0-40km) : segmentation proposed for the dipping planes
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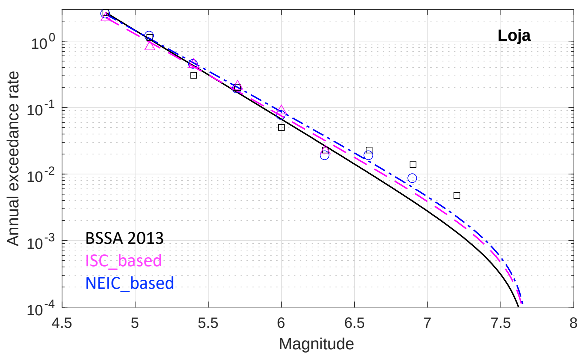
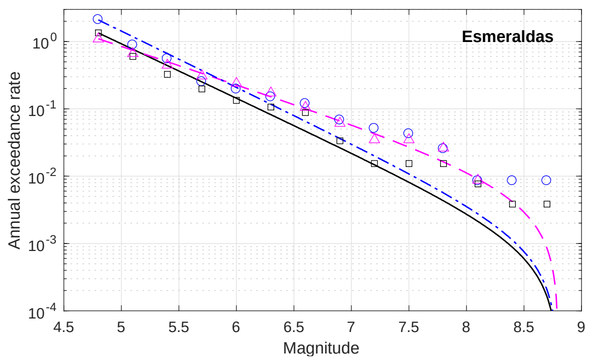
For each source zone:
establishment of an earthquake recurrence model (Gutenberg and Richter 1944), based on the earthquake catalog, bounded by an M_{max}





3 alternative earthquake catalogs ⇨ 3 alternative earthquake recurrence models

Seismic hazard assessment in Ecuador : ground-motion model

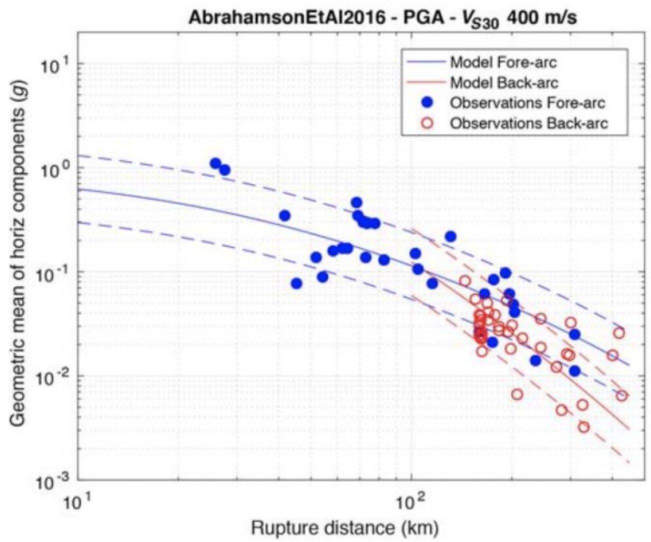
In the last ~ 15 years, a strong-motion network has been deployed with ~80 stations covering the country (RENSIG)
However, for now there isn't a ground-motion model developed specifically for Ecuador
Need to import reliable models that prove to behave well in different contexts

Subduction earthquakes

- Abrahamson et al. (2016) global database
- Montalva et al. (2016) Chilean database
- Zhao et al. (2006) Japanese database

Shallow crustal earthquakes

- Chiou & Youngs (2014) Western US & global database
- Akkar et al. (2014) Europe & Middle East database
- Zhao et al. (2006) Japanese database



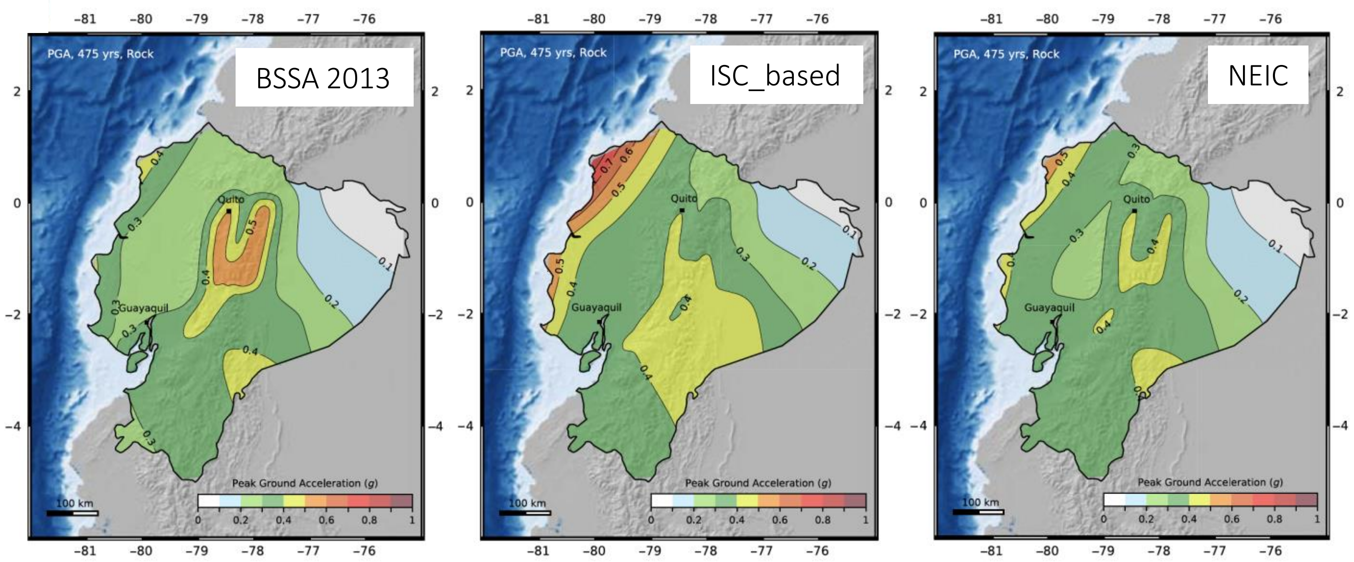
Observations: accelerations recorded during the 2016 M_W7.8 interface event
Model : Abrahamson et al. (2016)

Beauval, Marinière et al. (2017)

Seismic hazard assessment in Ecuador : source model uncertainties

The strategy applied to build the earthquake catalog impacts the hazard levels

PGA



PGA at 475 years return period: the acceleration mapped has a 10% probability of being exceeded at least once in the next 50 years (Poisson process)

Beauval et al. (2018) ; Marinière et al. (2021) ; Lopez Ordoñez et al. (2024)

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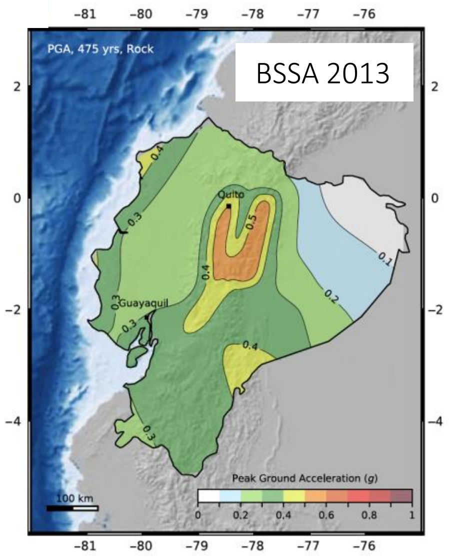

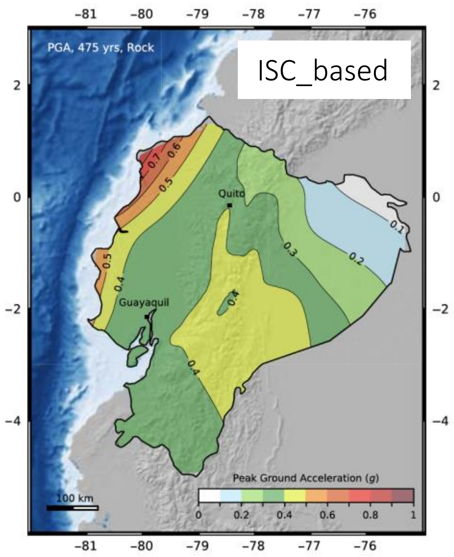

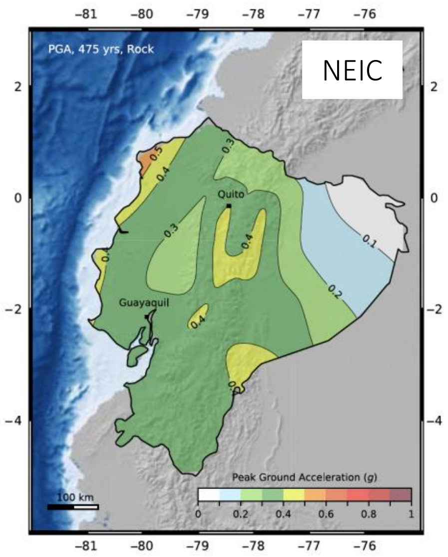

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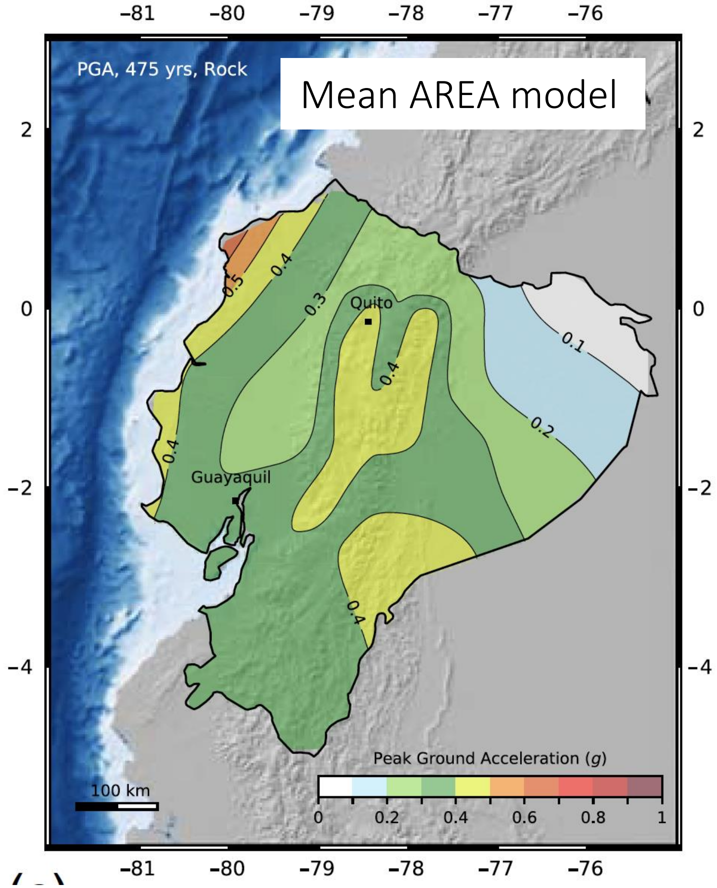
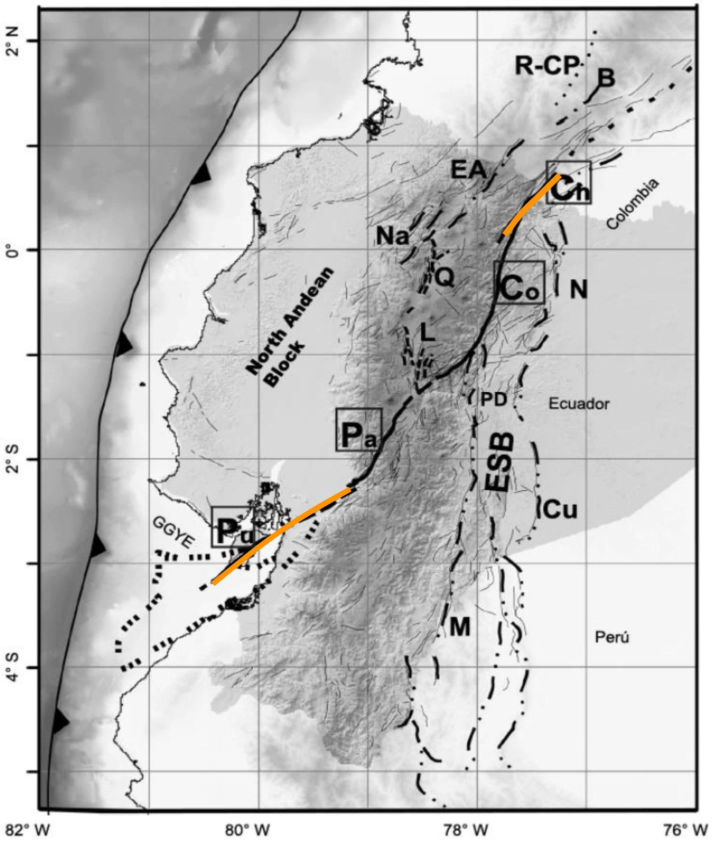


Beauval et al. (2018) ; Marinière et al. (2021) ; Lopez Ordoñez et al. (2024)

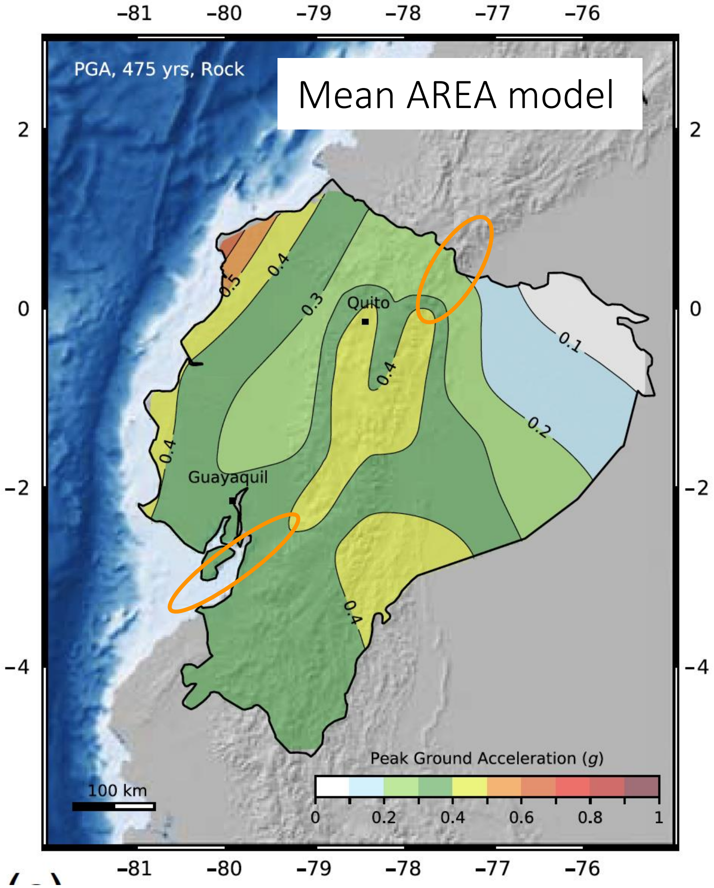
Seismic hazard assessment in Ecuador : issues with the area model

Chingual fault
9.8 mm/yr (geology)
8.1 mm/yr (geodetic)

Puna fault
6 mm/yr (geology)
7.1 mm/yr (geodetic)



Alvarado et al. 2016



Seismic hazard assessment in Ecuador : fault model

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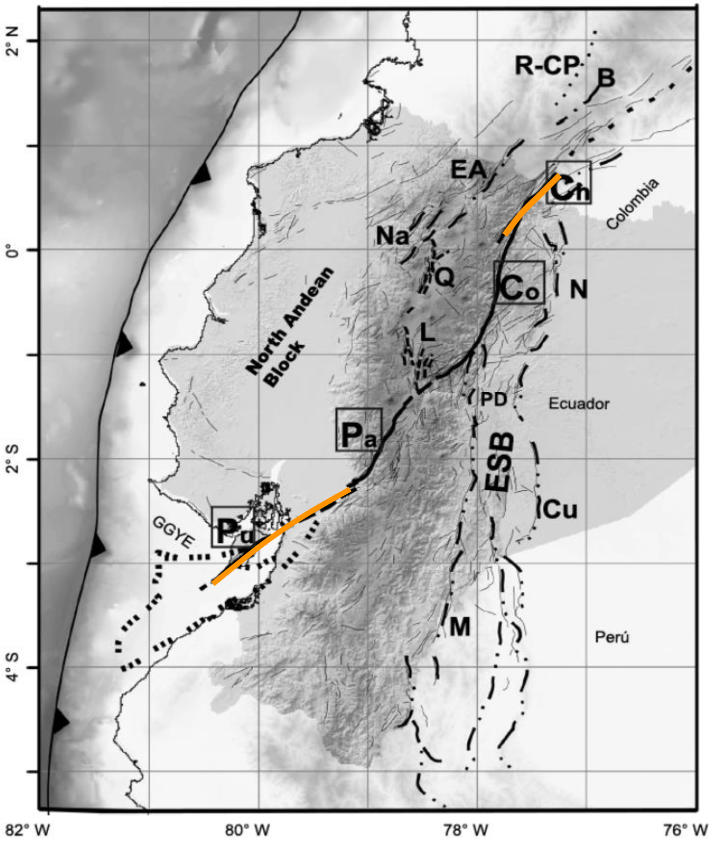

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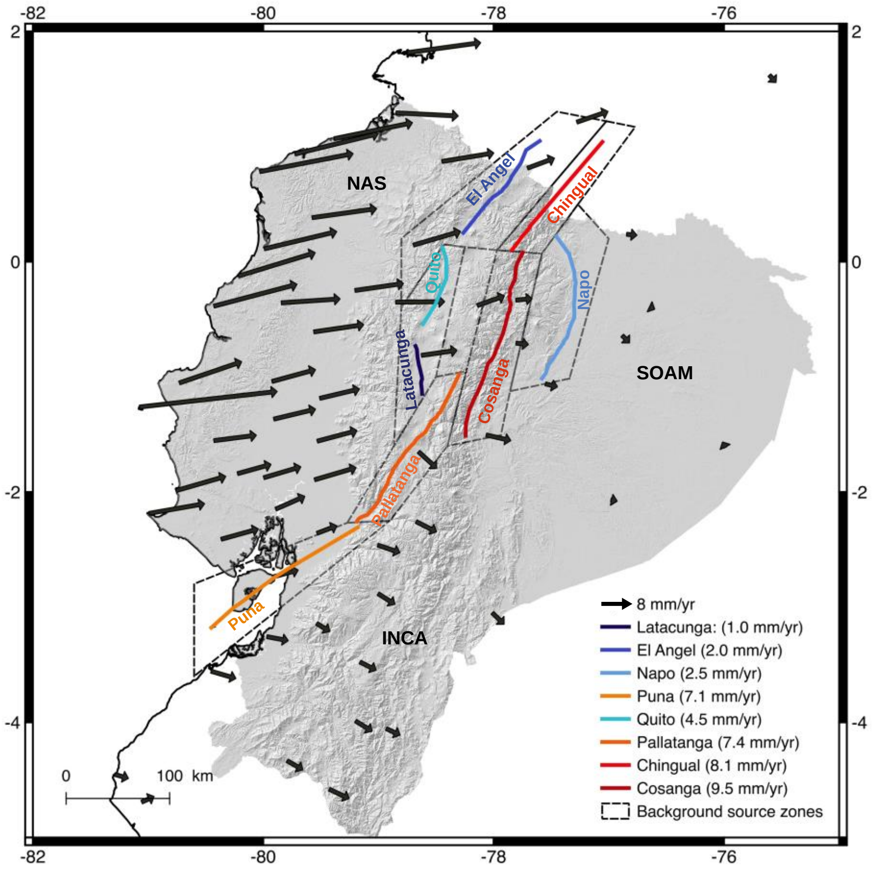


Assumption : most of the deformation is accommodated along these faults

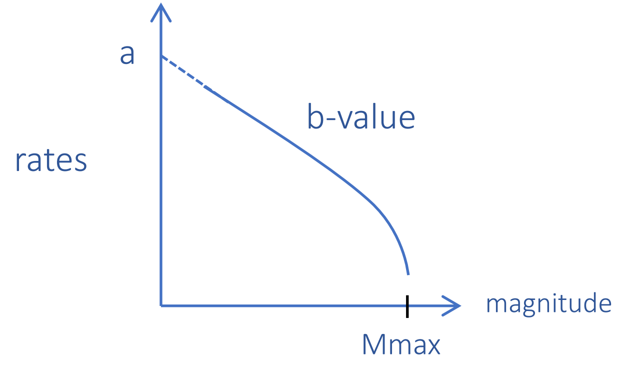
Seismic hazard assessment in Ecuador : fault model

Simplified set of faults, where average slip rates are available (geologic and/or geodetic)

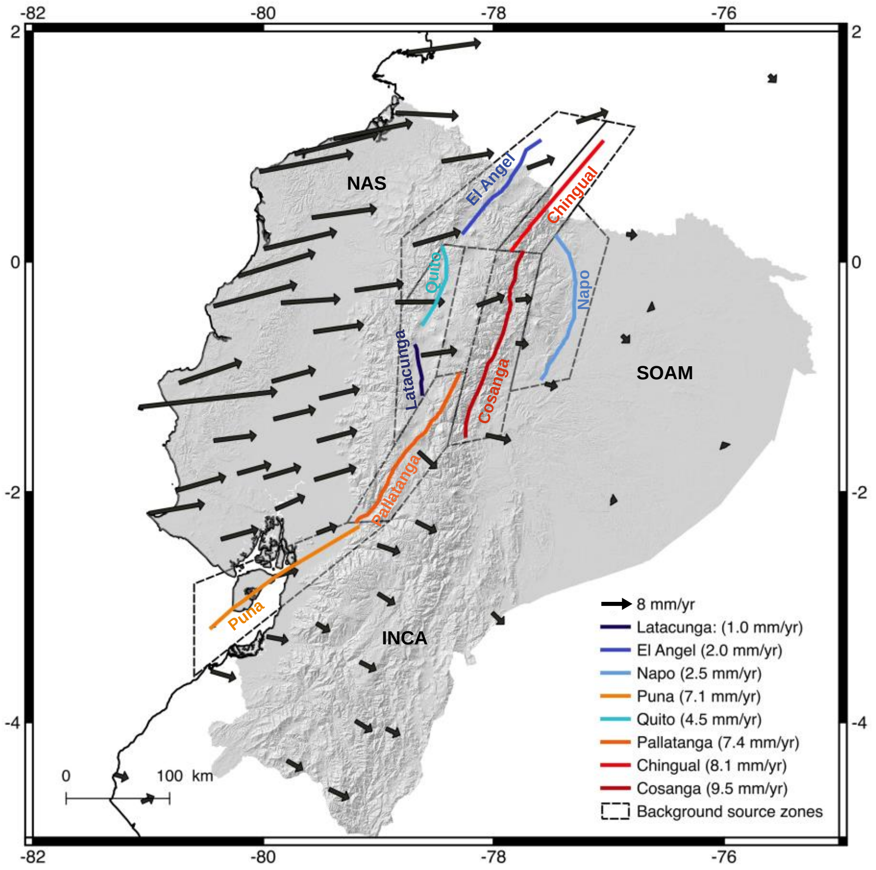
moment rate $\dot{M}_0 = \mu A S$

μ is the shear modulus
A surface of the fault plane
S is the slip rate

The productivity of the Gutenberg-Richter model can be obtained from the moment rate, assuming a b-value and an M_{max}



$$10^{a} = \dot{M}_0 \frac{c-b}{b} 10^{-d+(b-c)M_{max}}$$



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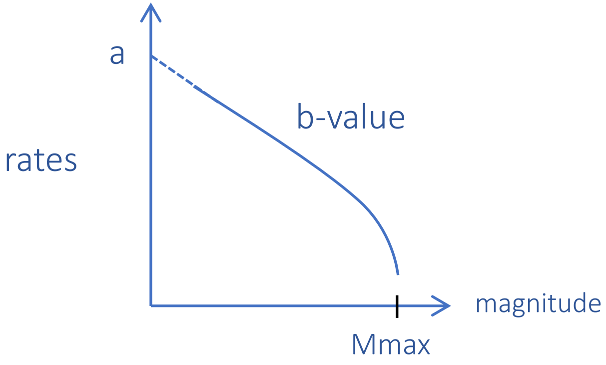

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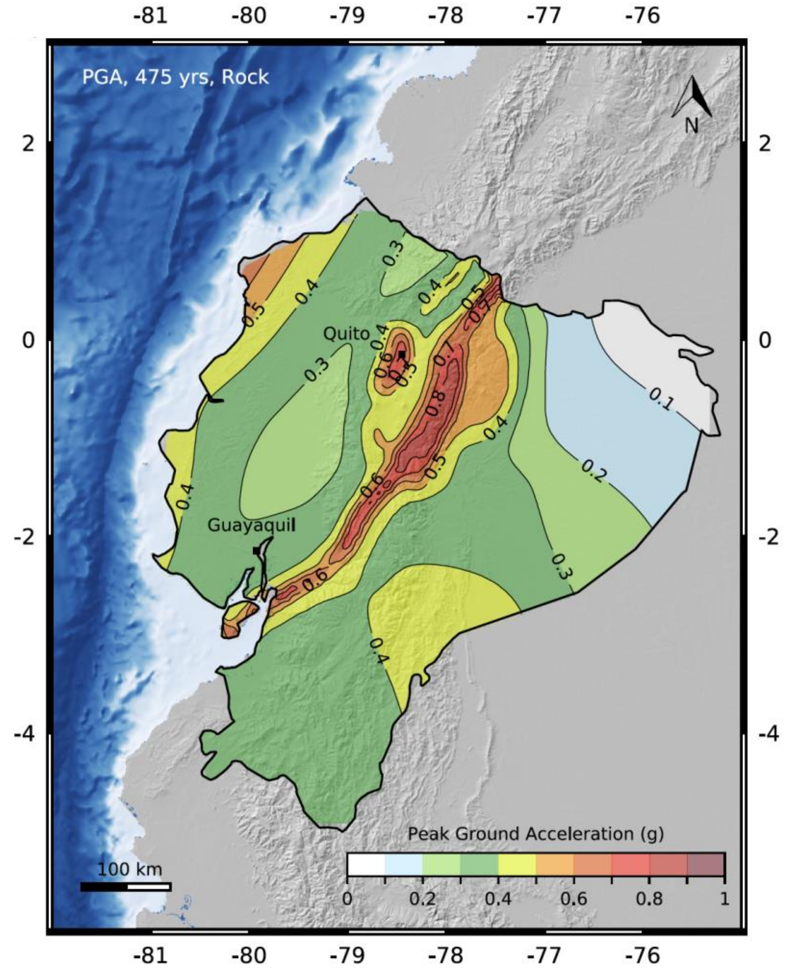
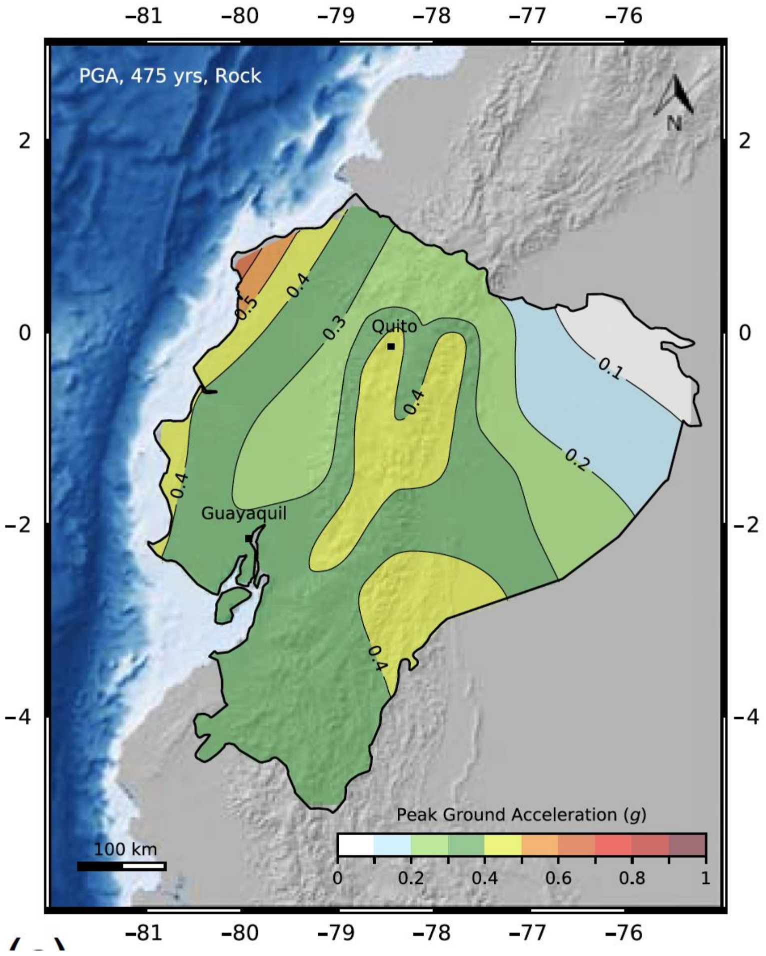
FAULT MODEL



Seismic hazard assessment in Ecuador : fault model

AREA MODEL



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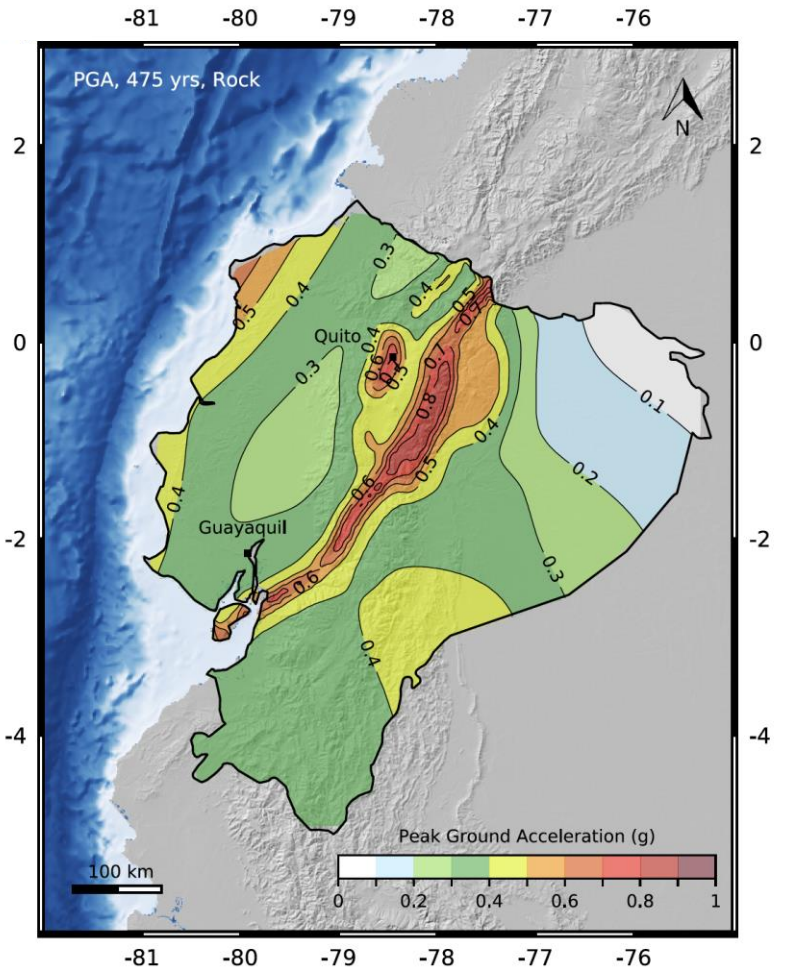


Beauval et al. (2018) ; Marinière et al. (2021)

Seismic hazard assessment in Ecuador, representative of our knowledge

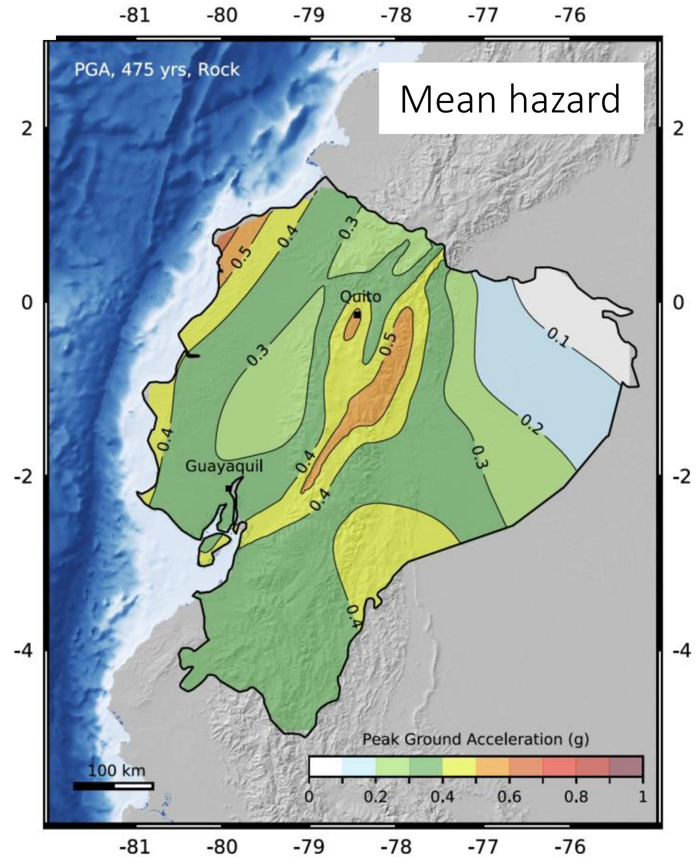
Source model logic tree

- AREA MODEL
  - BSSA 2013 earthquake catalog
  - ISC_based
  - NEIC_based
- FAULT MODEL
  - Geodetic slip rate 0% aseismic deformation
  - Geodetic slip rate 50% aseismic deformation
  - Geologic slip rates

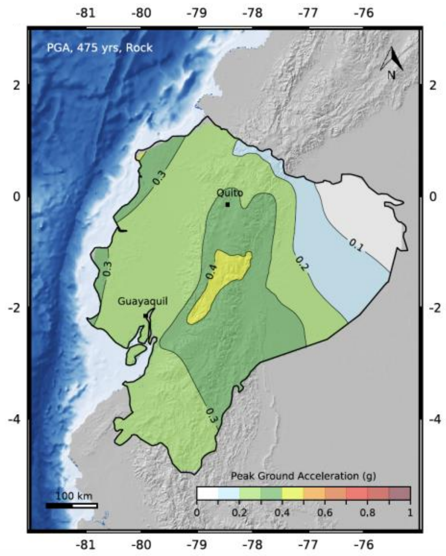
combined with the **ground-motion logic tree**

Seismic hazard assessment in Ecuador, representative of our knowledge

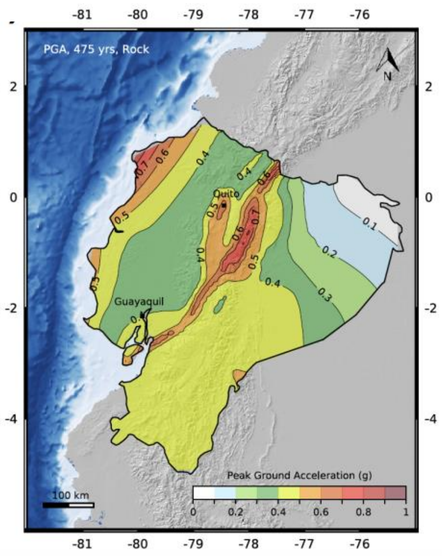
A distribution of seismic hazard maps



16th percentile



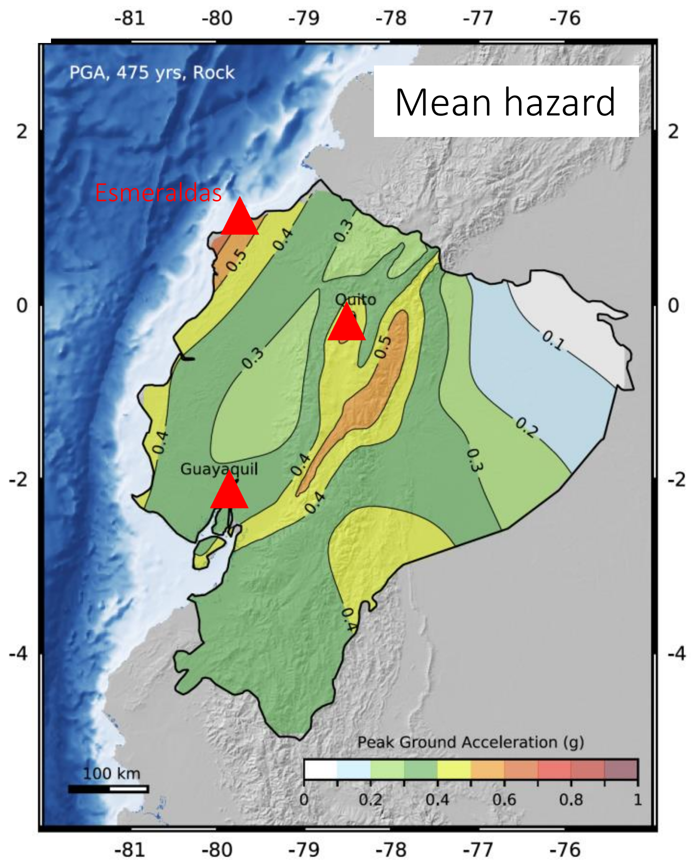
84th percentile



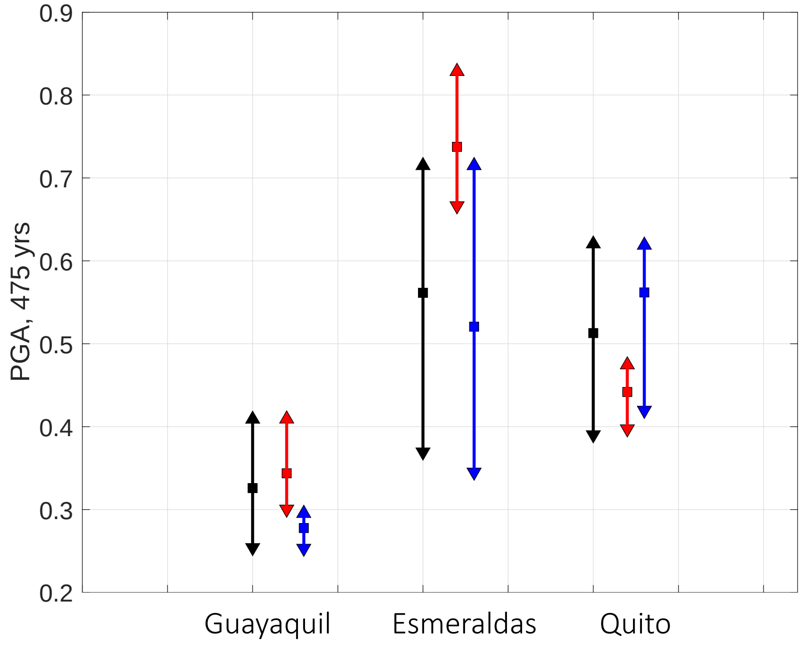
Beauval et al. (2018) ; Marinière et al. (2021)

Seismic hazard assessment in Ecuador, representative of our knowledge

A distribution of seismic hazard maps



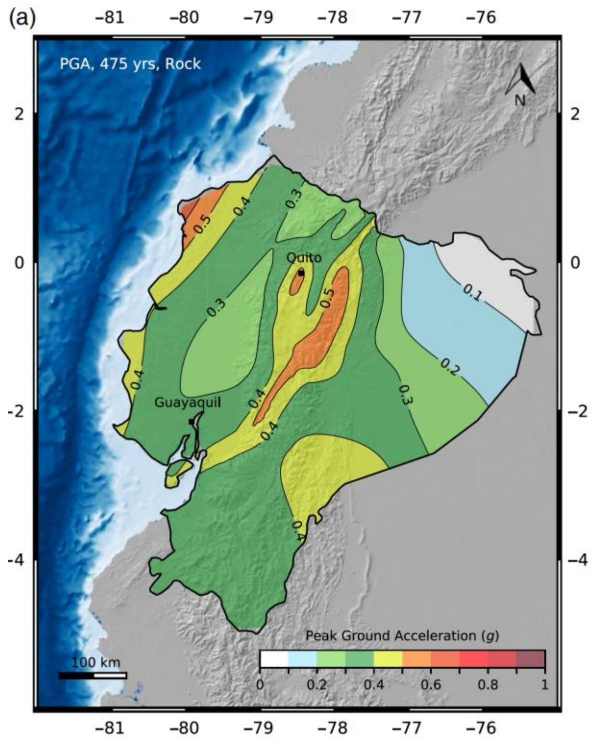
Total variability,
source model versus ground-motion model variability



Full logic tree
GMM logic tree (source model fixed)
SOURCE logic tree (GMM fixed)

From seismic hazard to seismic risk : contribution to public policy

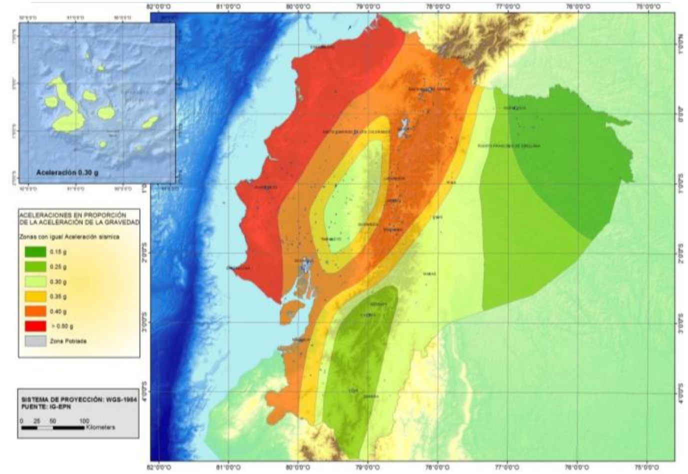
A set of seismic hazard maps, representative of the state of knowledge

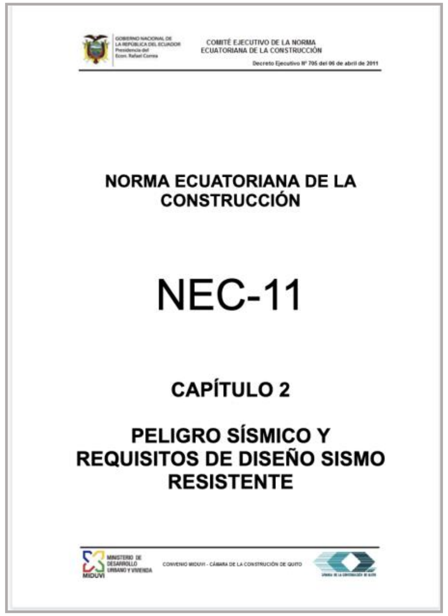


Comité Ecuatoriano de la Norma de la Construcción

Earthquake resistant building code

Mapa para diseño sísmico
Norma Ecuatoriana de la Construcción




NORMA ECUATORIANA DE LA CONSTRUCCIÓN

NEC-11

CAPÍTULO 2

PELIGRO SÍSMICO Y REQUISITOS DE DISEÑO SISMO RESISTENTE

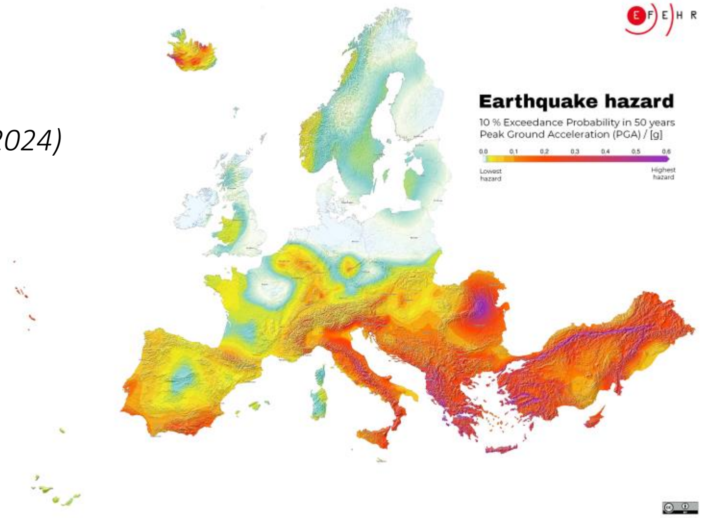
Regular updates of the building code (2011, 2015, 2023)

Status of hazard models in Europe and France

Status of hazard models for Europe and France

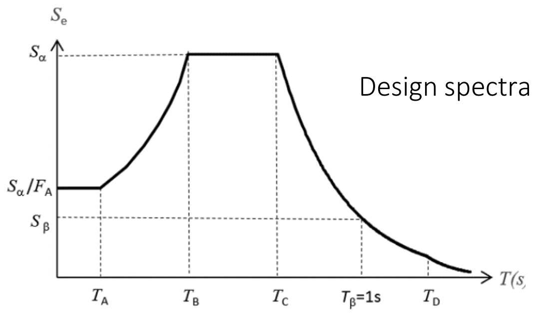
Europe: new seismic hazard model published last year

Danciu et al. (2024)
efehr.org



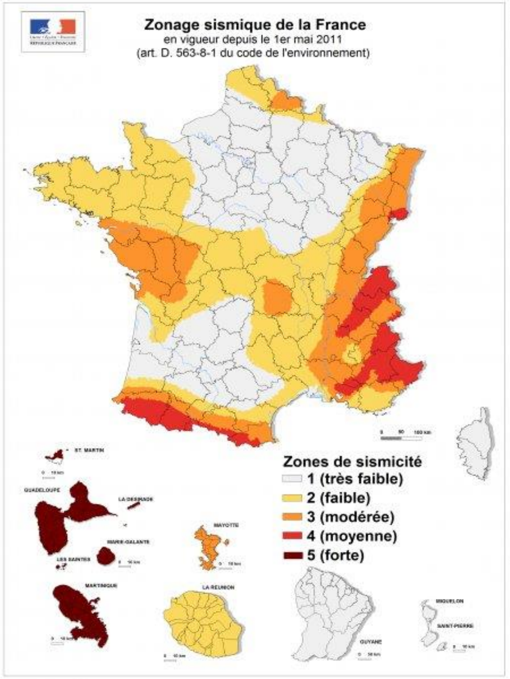
Annex of the Eurocode 8

Eurocode update in 2027



Design spectra

Metropolitan France and French West Indies
on-going ALCESTE and ATLAS projects
Results delivered end of 2026



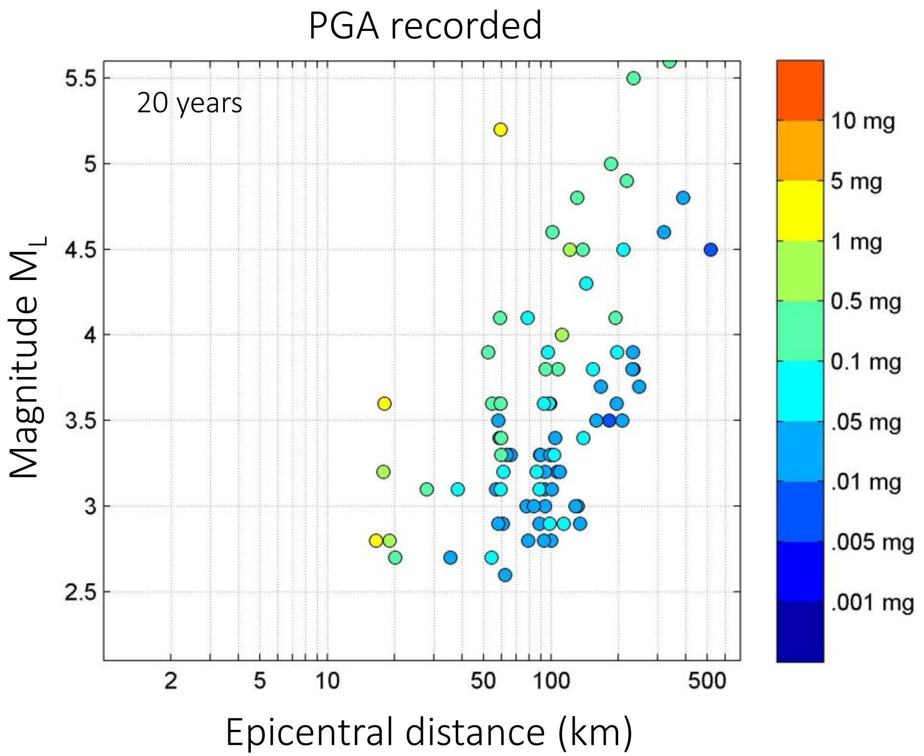
MINISTÈRES TERRITOIRES ÉCOLOGIE LOGEMENT

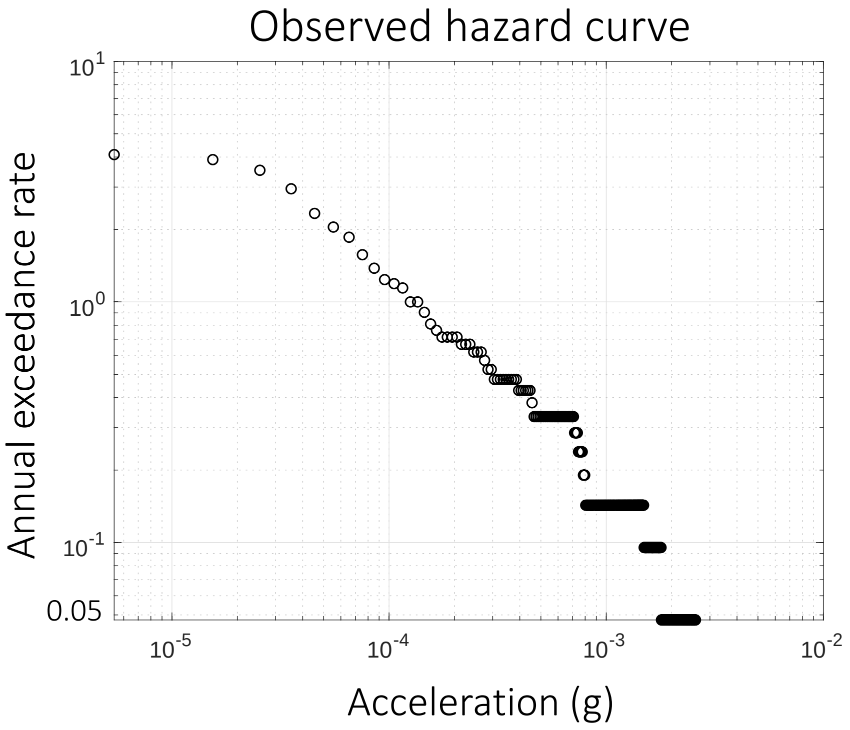
EPOS-FR

Seismic hazard models predict ground-motion occurrences, can these forecasts be tested against observations?

The most direct observation : the strong-motion recorded at an instrumented site

Example : Digne strong-motion station, France



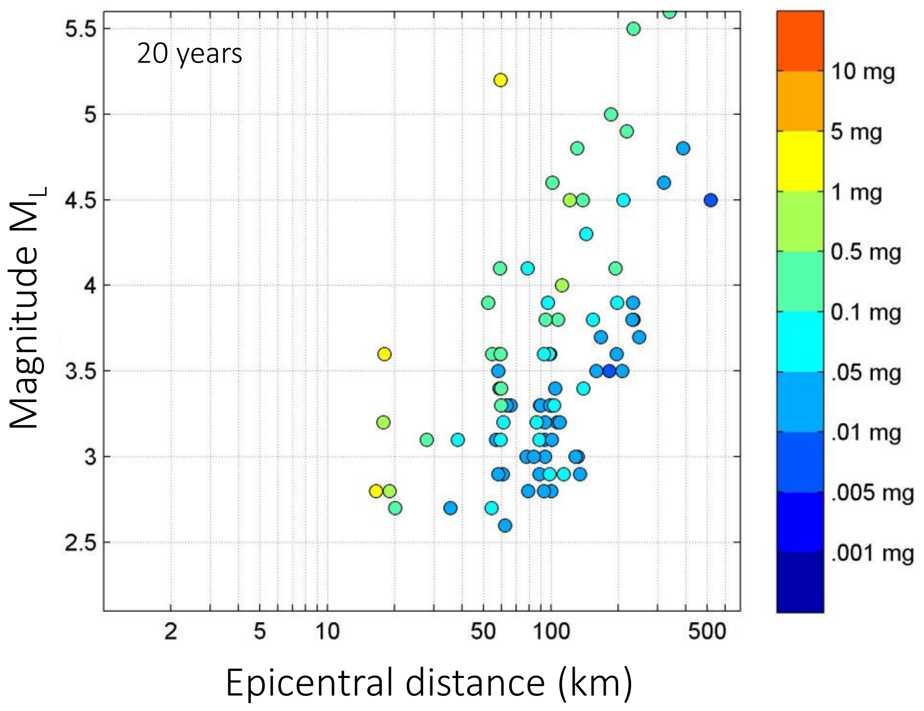


Database: Traversa, Maufroy et al. (2019)

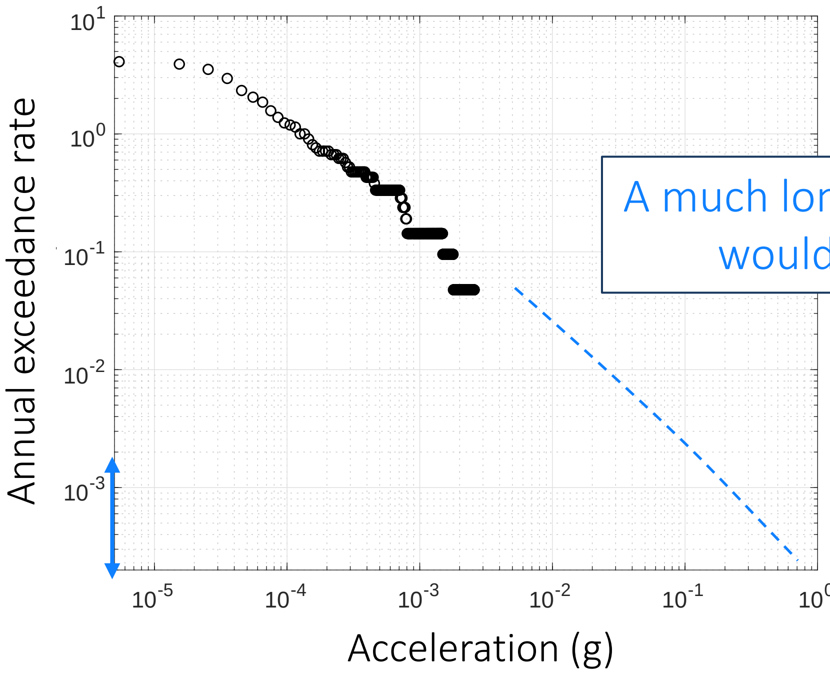
The most direct observation : the strong-motion recorded at an instrumented site

Example : Digne strong-motion station, France

PGA recorded



Observed hazard curve



A much longer time window would be required

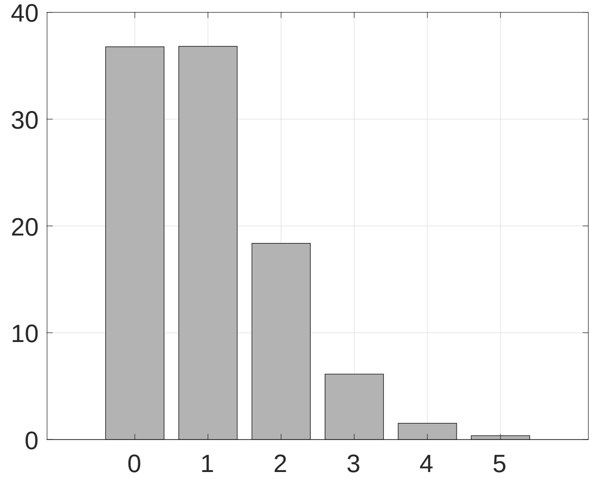
Database: Traversa, Maufroy et al. (2019)

Exceedance annual rates of interest for seismic design and building codes : ≤ 0.002 or return period > 475 years

What is a ground-motion with a mean 475 years return period?

a ground-motion that occurs on average once every 475 years, at the site

Accelerations at a site occur according to a Poisson process



Number of occurrences over a time window of 475 yrs

If we had 100 observation time windows of 475 years available at a site:
37 of these time windows with no occurrence
37 of these time windows with 1 occurrence

Ground-motions of reference in earthquake engineering are rather rare events.
True whatever the site, in low seismicity or active regions

Beauval, Bard, et al. (2008)

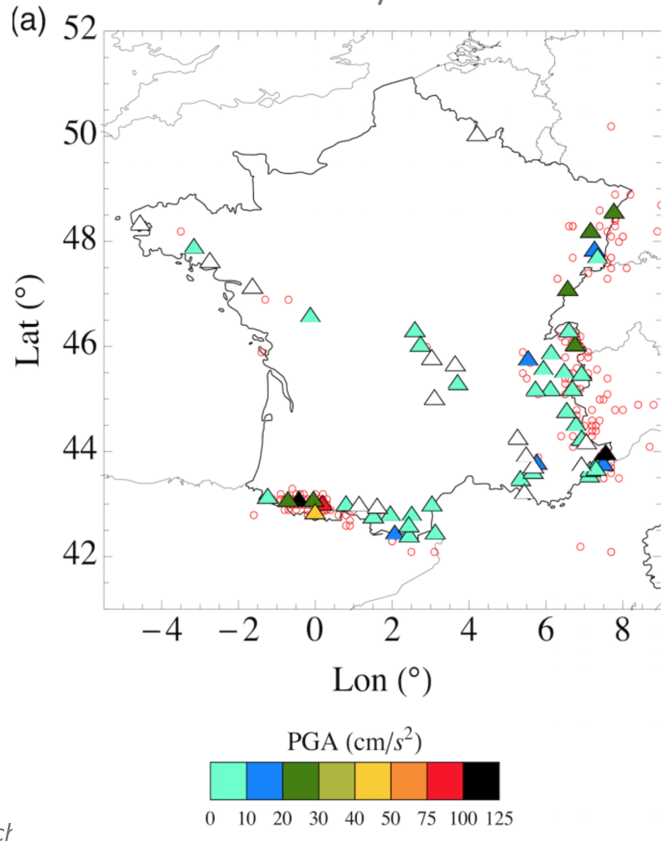
Comparing predictions and observations at the scale of a strong-motion network

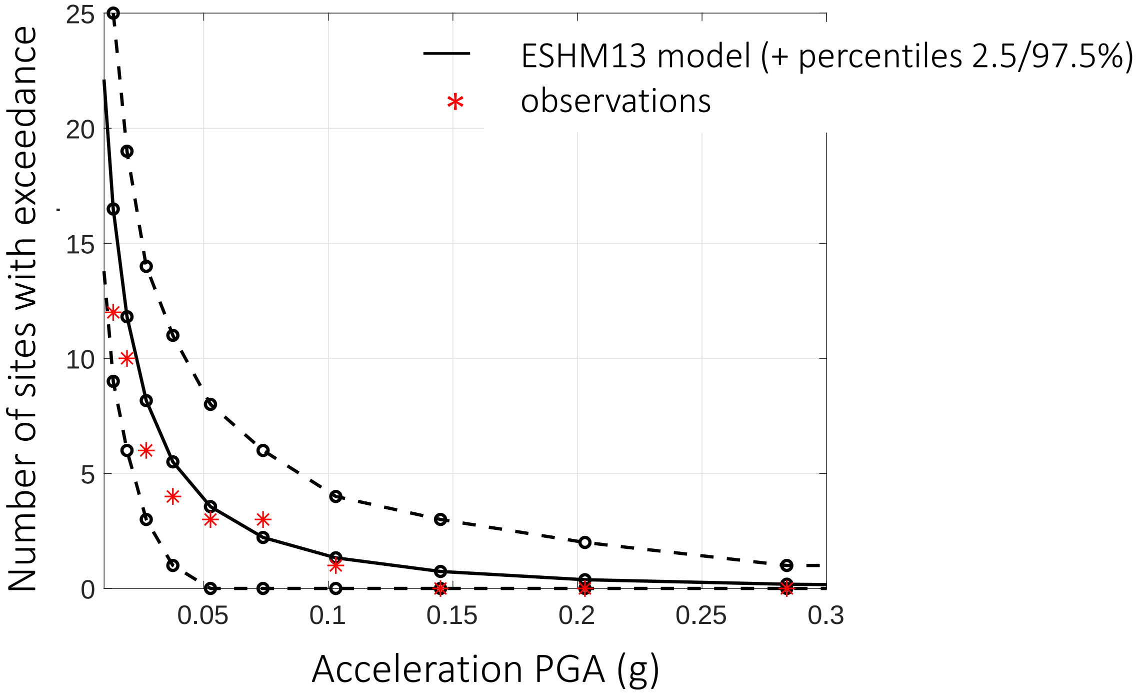
Sampling a large spatial zone to compensate for short observation time windows
➔ The model is tested as a whole at the scale of the seismic network

At each site: Assumption that accelerations occur according to a Poisson process

RAP: French ground-motion database

62 stations (~on rock)
449 yrs in total





Tasan et al. (2014)

Comparing predictions and observations at the scale of a strong-motion network

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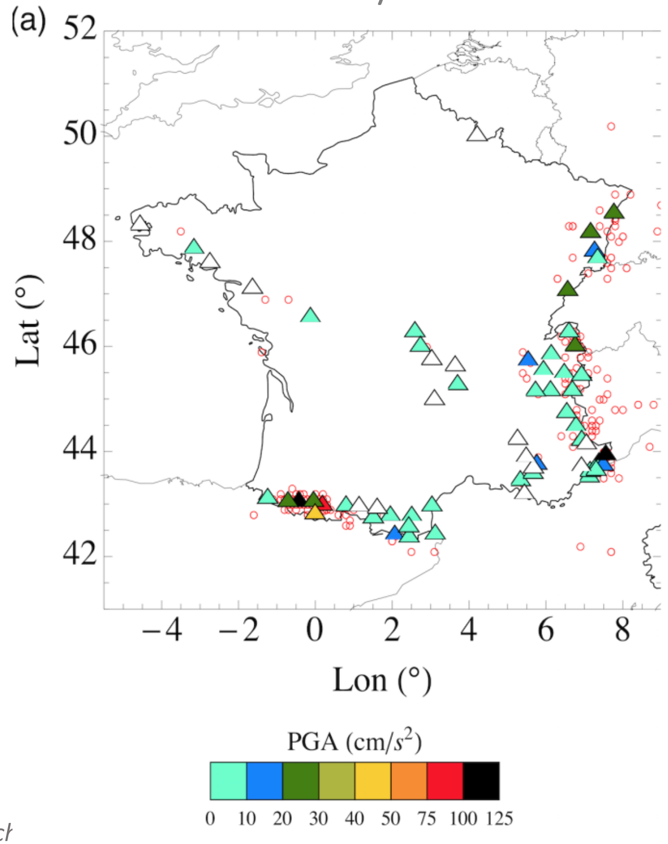
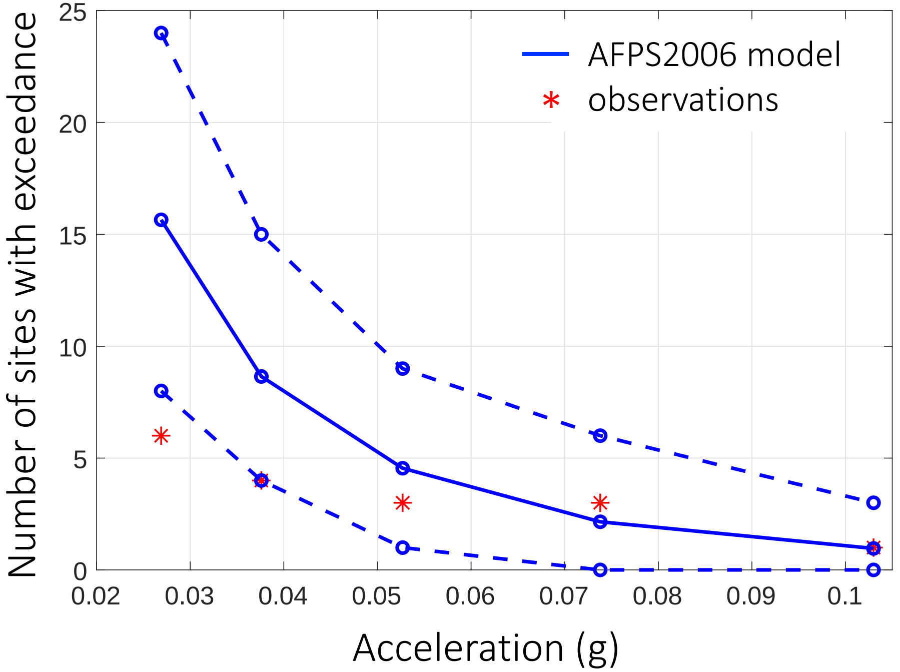


RAP: French ground-motion database



Tasan et al. (2014)

Comparing predictions and observations at the scale of a strong-motion network

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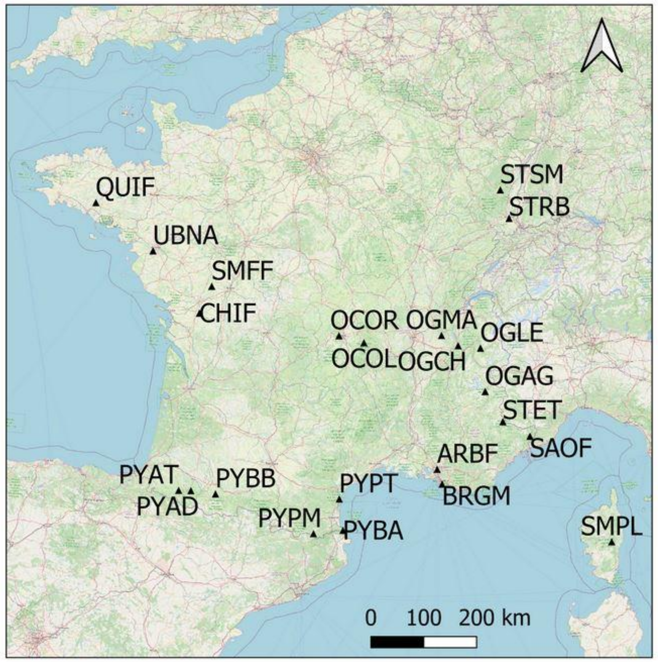
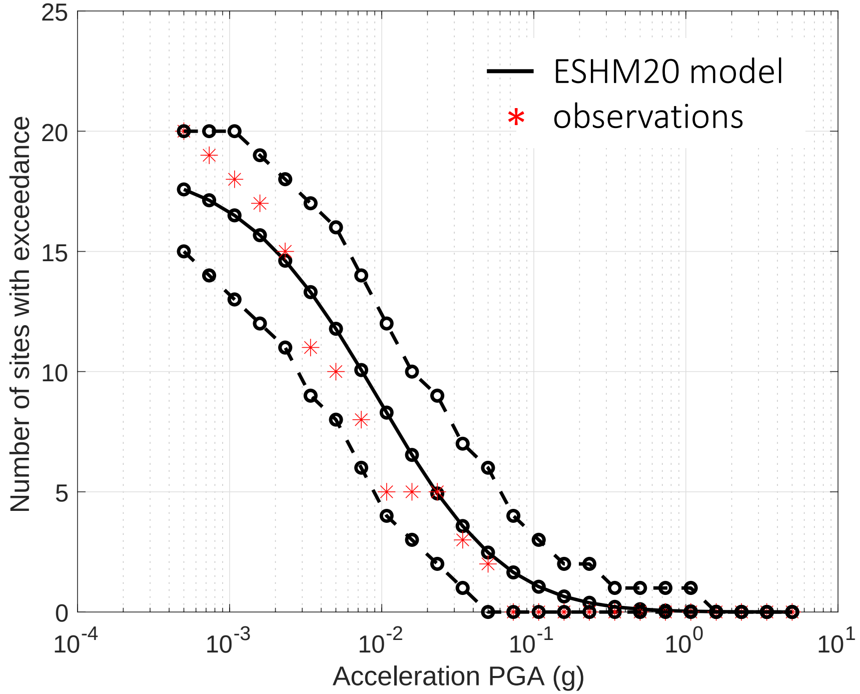




Beauval, Pellorce et al. (2022)

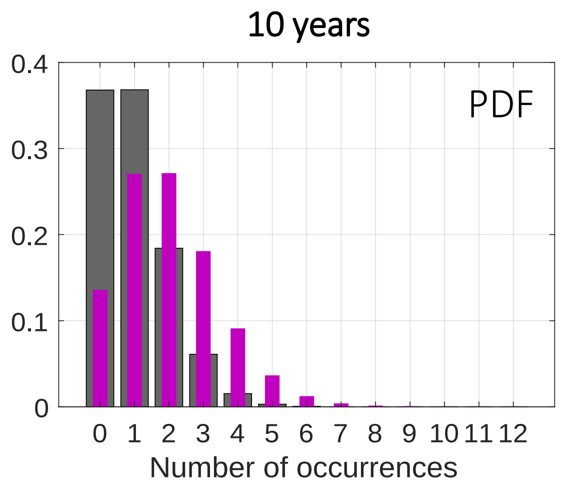
Short observation time windows : the data is unlikely to reveal inconsistencies

Simple simulations of a Poisson process

True rate = 0.2 / year

Modeled rate = 0.1 / year

Expected number of occurrences over a 10 years time window ?

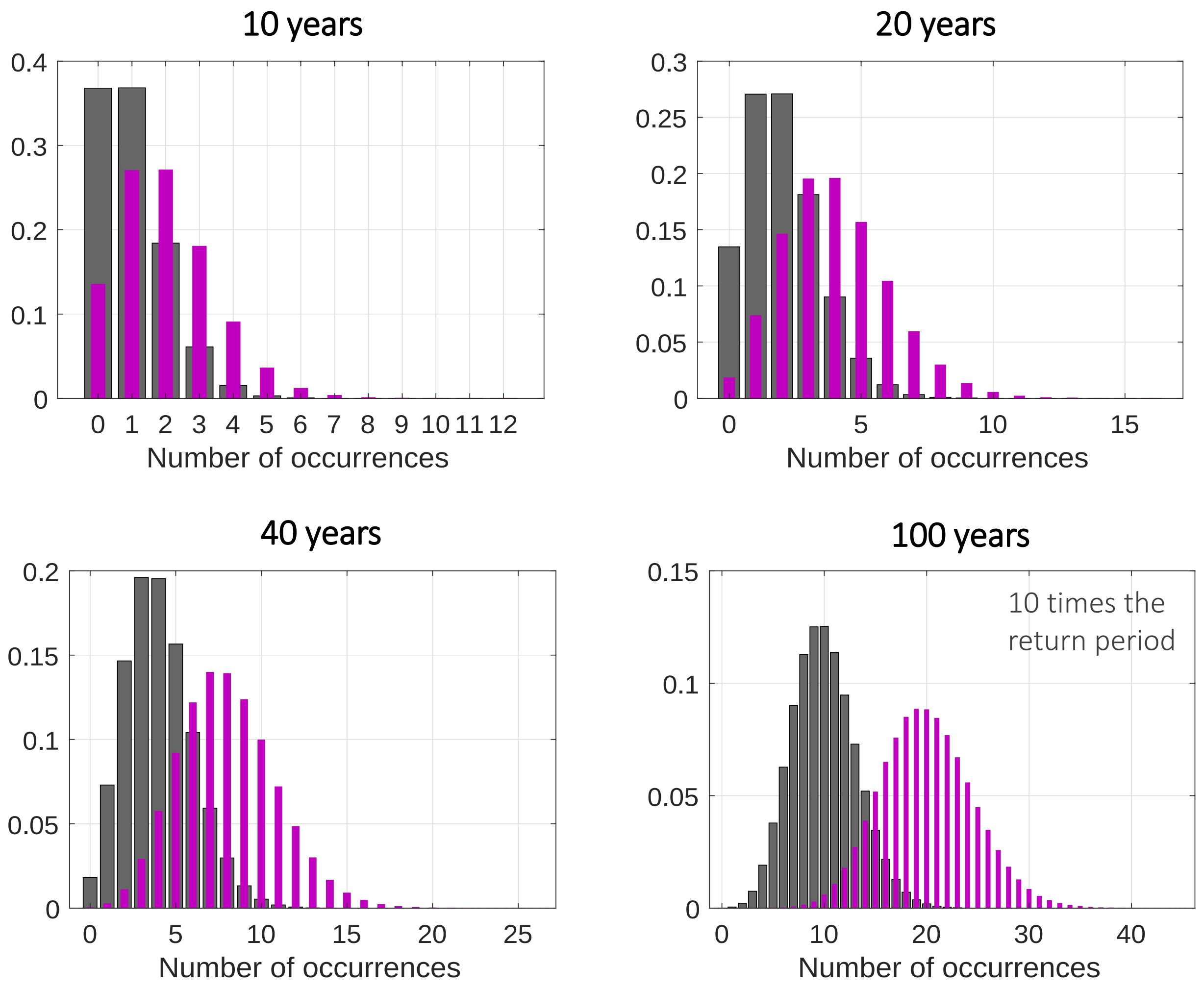


Short observation time windows : the data is unlikely to reveal inconsistencies

Simple simulations of a Poisson process

- True rate = 0.2 / year
- Modeled rate = 0.1 / year

Expected number of occurrences over increasing time window ?



Key points

- Building a hazard model for PSHA is a challenge both in low and high seismicity countries
  - Building a hazard model requires contributions from a large range of earth science fields (geology, seismology, geodesy, engineering seismology)
  - The source model is made to include all earthquakes that may occur in the future, uncertainties are huge, they must be tracked and propagated up to the hazard levels,
  - The final uncertainty range on the hazard levels is representative of the state of knowledge available at the time the model is developed
  - Researchers deliver hazard estimates with associated uncertainties, then the authorities take decisions and responsibility on which levels will go into the regulation

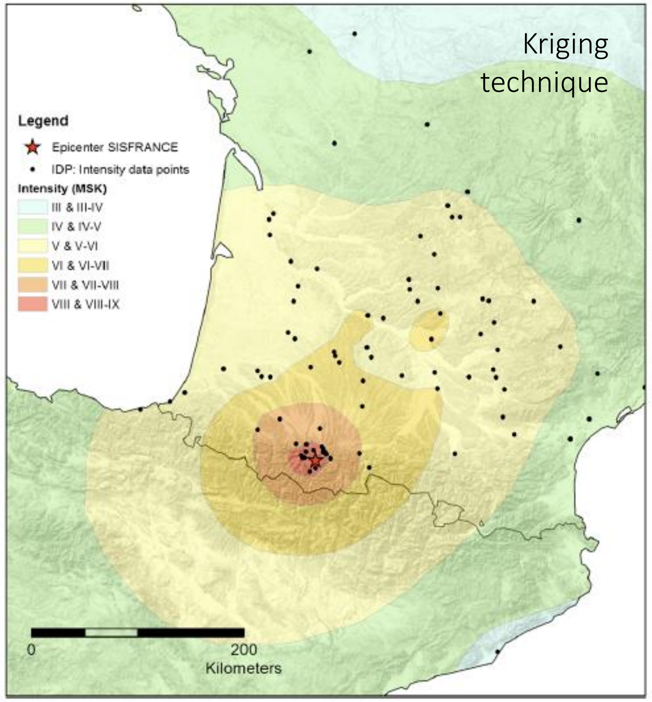
- Testing hazard forecasts against available observations is mandatory, but there are inherent strong limitations due to the length of observation time windows, we must also focus on testing the components (source model, ground-motion model)

Thank you for your attention

To lengthen the observation time windows: comparison with historical macroseismic observations

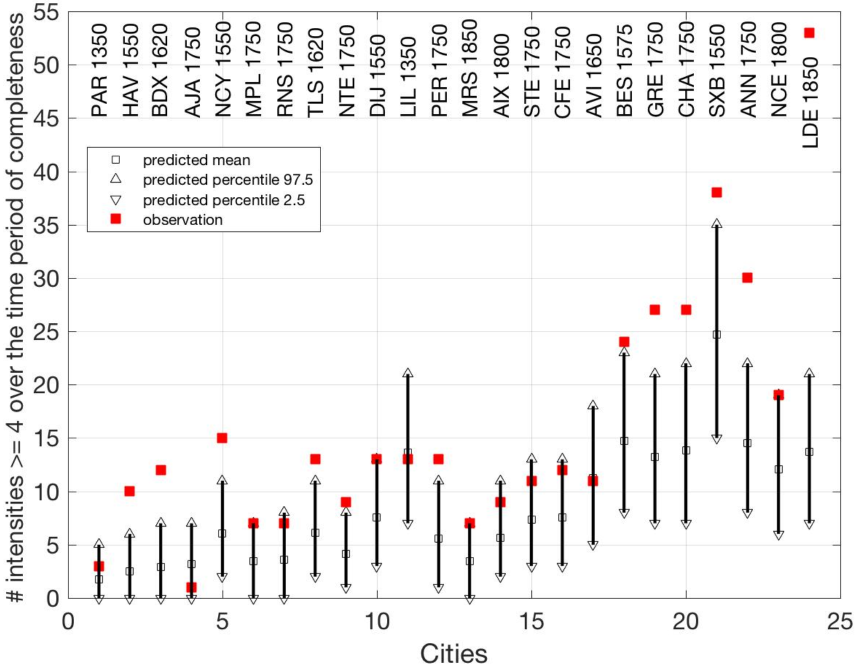
Testing predictions against macroseismic intensities : example with SisFrance

Interpolated database: example for the Bigorre 1660 event (M_W ~6.5 in the FCAT catalogue)



Rey, Beauval, Douglas (2018)

Number of intensities ≥ IV predicted (ESHM13) & observed



IV ⇔ 0.011 PGA
Caprio et al. 2015

Large uncertainty relying on the selection of a ground-motion to intensity conversion equation (GMICE)