

# ESTUDIOS SOBRE EL PELIGRO SÍSMICO EN EL ECUADOR

## Nueva base para el mapa de Zonificación Sísmica de la NEC

### *El Peligro Sísmico en el Ecuador y en Quito*

Grupo de estudios  
en riesgo y Habitat  
GIRHA

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Quito, 11 de abril de 2016

GIRHA

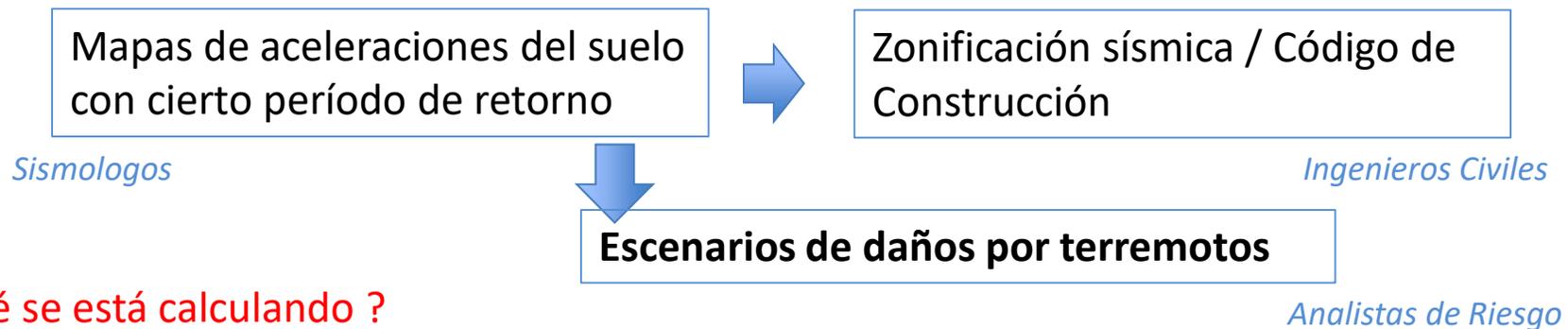
# ***El Peligro Sísmico***

## **CONTENIDO**

- El cálculo probabilista del peligro sísmico PSHA
- Desarrollo de los mapas de peligro a partir del 2007 y la zonificación sísmica adoptada
- Los actuales mapas de peligro sísmico dentro de un proceso de inclusión de las incertidumbres
- El peligro sísmico en Quito a la luz de terremotos en ambientes tectónicos similares

# Estimación de la amenaza sísmica probabilística al nivel del país

## Cálculo para la zonificación sísmica del Ecuador



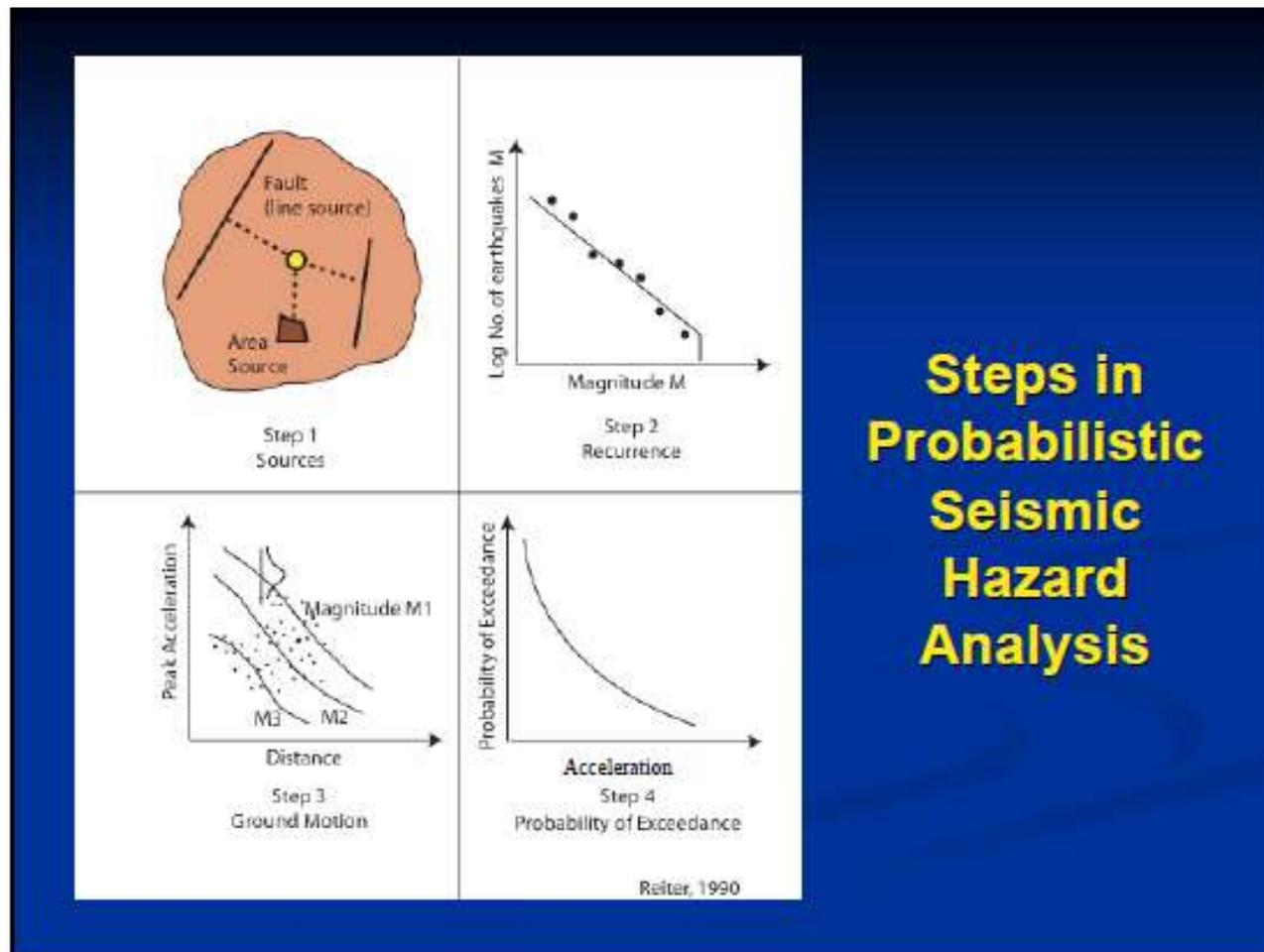
## Qué se está calculando ?

Probabilidad que ocurra cierta intensidad de movimiento fuerte del suelo durante ventanas de tiempo futuras (aceleraciones, Velocidades, desplazamientos, Intensidad)

## Qué tenemos que estudiar?



# El cálculo probabilista



# Cálculo de la amenaza sísmica de manera probabilística



# 12 Años de Investigación

Establecer modelos de  
recurrencia de sismos en  
esas fuentes

Identificar las  
fuentes sísmicas  
potenciales

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Geophysical Journal International

Geophys. J. Int. (2010)

doi: 10.1111/j.1365-246X.2010.04569.x

## An Earthquake Catalog for Seismic Hazard Assessment in Ecuador

by Céline Beauval, Hugo Yepes, Pablo Palacios, Monica Segovia, Alexandra Alvarado, Yvonne Font, Jorge Aguilar, Liliana Troncoso, and Sandro Vaca

## Locations and magnitudes of historical earthquakes in the Sierra of Ecuador (1587–1996)

Céline Beauval,<sup>1</sup> Hugo Yepes,<sup>2</sup> William H. Bakun,<sup>3</sup> José Egred,<sup>2</sup> Alexandra Alvarado<sup>2</sup> and Juan-Carlos Singaicho<sup>2</sup>

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**Abstract** Building a unified and homogeneous earthquake catalog is a preliminary step for estimating probabilistic seismic hazard in a country. Ecuador, a territory of ~600 km × 500 km, is characterized by an active seismicity, both in the shallow crust and in the subduction zone. Several international and local earthquake catalogs are available, covering different time and spatial windows, characterized by different magnitude types and uncertainties. After a careful analysis of each catalog, in particular for completeness and uncertainty levels, we propose a priority scheme for merging the instrumental catalogs. Moreover, several historical earthquakes are analyzed to estimate epicentral location and magnitude, completing the solutions obtained in a previous publication. Once the historical earthquakes are appended to the instrumental catalog, the resulting catalog covers five centuries in the Cordillera region. Next, homogenization of magnitudes and removal of aftershocks is performed; different options are studied and the impact on the recurrence curve is evaluated. For the Cordillera region within  $-2.5^{\circ}$  and  $1^{\circ}$  latitude, the average occurrence of an earthquake with  $M_w \geq 6.0$  is 10–20 years based on the historical catalog.

### SUMMARY

The whole territory of Ecuador is exposed to seismic hazard. Great earthquakes can occur in the subduction zone (e.g. Esmeraldas, 1906,  $M_w$  8.8), whereas lower magnitude but shallower and potentially more destructive earthquakes can occur in the highlands. This study focuses on the historical crustal earthquakes of the Andean Cordillera. Several large cities are located in the Interandean Valley, among them Quito, the capital (~2.5 millions inhabitants). A total population of ~6 millions inhabitants currently live in the highlands, raising the seismic risk. At present, precise instrumental data for the Ecuadorian territory is not available for periods earlier than 1990 (beginning date of the revised instrumental Ecuadorian seismic catalogue); therefore historical data are of utmost importance for assessing seismic hazard. In this study, the Bakun & Wentworth method is applied in order to determine magnitudes, locations, and associated uncertainties for historical earthquakes of the Sierra over the period 1587–1996. An intensity-magnitude equation is derived from the four most reliable instrumental earthquakes ( $M_w$  between 5.3 and 7.1). Intensity data available per historical earthquake vary between 10 (Quito, 1587, Intensity  $\geq VI$ ) and 117 (Riobamba, 1797, Intensity  $\geq III$ ). The bootstrap resampling technique is coupled to the B&W method for deriving geographical confidence contours for the intensity centre depending on the data set of each earthquake, as well as confidence intervals for the magnitude. The extension of the area delineating the intensity centre location at the 67 per cent confidence level ( $\pm 1\sigma$ ) depends on the amount of intensity data, on their internal coherence, on the number of intensity degrees available, and on their spatial distribution. Special attention is dedicated to the few earthquakes described by intensities reaching IX, X and XI degrees. Twenty-five events are studied, and nineteen new epicentral locations are obtained, yielding equivalent moment magnitudes between 5.0 and 7.6. Large earthquakes seem to be related to strike slip faults between the North Andean Block and stable South America to the east, while moderate earthquakes ( $M_w \leq 6$ ) seem to be associated with thrust faults located on the western internal slopes of the Interandean Valley.

**Key words:** Seismicity and tectonics; Seismic attenuation; South America.

# 11 Años de Investigación

Identificar las fuentes sísmicas potenciales

Determinar las aceleraciones producidas por esos futuros sismos



## Motion of continental slivers and creeping subduction in the northern Andes

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Along the western margin of South America, plate convergence is accommodated by slip on the subduction interface and deformation of the overriding continent<sup>1-6</sup>. In Chile<sup>1,4</sup>, Bolivia<sup>4</sup>, Ecuador and Colombia<sup>5,7</sup>, continental deformation occurs mostly through the motion of discrete domains, hundreds to thousands of kilometres in scale. These continental slivers are wedged between the Nazca and stable South American plates. Here we use geodetic data to identify another large continental sliver in Peru that is about 300–400 km wide and 1,500 km long, which we call the Inca Sliver. We show that movement of the slivers parallel to the subduction trench is controlled by the obliquity of plate convergence and is linked to prominent features of the Andes Mountains. For example, the Altiplano is located at the boundary of converging slivers at the concave bend of the central Andes, and the extending Gulf of Guayaquil is located at the boundary of diverging slivers at the convex bend of the northern Andes. Motion of a few

displayed abnormally long source duration, slow rupture velocity, enhanced long-period source spectrum and both induced relatively large tsunamis<sup>11,12</sup>. Both events have been categorized as tsunami earthquakes, rupturing the shallow, weaker material of the accretionary prism. In the absence of direct measurements, several behaviours are plausible to explain the observed seismic gap: a first endmember view is that the subduction interface is freely slipping, with no potential to generate great earthquakes. In contrast, a second possible model is that this interface is significantly locked and great earthquakes may have recurrence time greater than 500 yr. If the latter hypothesis is true, a total length of 1,200 km and a convergence rate of  $\sim 60 \text{ mm yr}^{-1}$  would imply an overall seismic moment deficit equivalent to a  $M_w > 9$  earthquake, if released in a single event. Of course, intermediate scenarios are also possible, but even a single 300-km-long segment being significantly coupled would still leave the potential for a  $M_w > 8$  earthquake to occur in the future. Quantitatively assessing the seismic potential of this

## Comparison of Observed Ground-Motion Attenuation for the 16 April 2016 $M_w$ 7.8 Ecuador Megathrust Earthquake and Its Two Largest Aftershocks with Existing Ground-Motion Prediction Equations

by Céline Beauval, J. Marinière, A. Laurendeau, J.-C. Singaucht, C. Viracucha, M. Vallée, E. Maufroy, D. Mercerat, H. Yepes, M. Ruiz, and A. Alvarado

### ABSTRACT

A megathrust subduction earthquake ( $M_w$  7.8) struck the coast of Ecuador on 16 April 2016 at 23:58 UTC. This earthquake is one of the best-recorded megathrust events to date. Besides the mainshock, two large aftershocks have been recorded on 18 May 2016 at 7:57 ( $M_w$  6.7) and 16:46 ( $M_w$  6.9). These data make a significant contribution for understanding the attenuation of ground motions in Ecuador. Peak ground accelerations and spectral accelerations are compared with four ground-motion prediction equations (GMPEs) developed for interface earthquakes, the global Abrahamson *et al.* (2016) model, the Japanese equations by Zhao, Zhang, *et al.* (2006) and Ghofrani and Atkinson (2014), and one Chilean equation (Montalva *et al.*, 2017). The four tested GMPEs are providing rather close predictions for the mainshock at distances up to 200 km. However, our results show that high-frequency attenuation is greater for back-arc sites, thus Zhao, Zhang, *et al.* (2006) and Montalva *et al.* (2017), who are not taking into account this difference, are not considered further. Residual analyses show that Ghofrani and Atkinson (2014) and Abrahamson *et al.* (2016) are well predicting the attenuation of ground motions for the mainshock. Comparisons of aftershock observations with the predictions from Abrahamson *et al.* (2016) indicate that the GMPE provide reasonable fit to the attenu-

equal to 6.0. Important cities are located at short distances (20–30 km), and magnitudes down to 6.0 must be included in seismic-hazard studies. The next step will be to constitute a strong-motion interface database and test the GMPEs with more quantitative methods.

**Electronic Supplement:** Figures of  $V_{S30}$  values based on topography versus rupture distance and difference between reference  $V_{S30}$  and  $V_{S30}$  based on topography versus distance, residuals, event terms, and intraevent standard deviations.

### INTRODUCTION

The megathrust Pedernales earthquake ( $M_w$  7.8) struck the coast of Ecuador on 16 April 2016 at 23:58 UTC. Sixty-nine accelerometric stations recorded the earthquake at fault distances ranging from 26 to 427 km (Fig. 1). One month after the mainshock, two large aftershocks have been recorded on 18 May 2016 at 7:57 and 16:46 (Table 1;  $M_w$  6.7 and 6.9, respectively). The accelerometric network in Ecuador started in 2009 with nine stations installed in the framework of the French-Ecuadorian research project Andes du Nord (ADN). In 2010,

# 11 Años de Investigación

Identificar las fuentes sísmicas potenciales

Calcular la amenaza sísmica de manera probabilística (tomando en cuenta todas las posibilidades)



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Geomorphology

journal homepage: [www.elsevier.com/locate/geomorph](http://www.elsevier.com/locate/geomorph)



## Paleoseismology and tectonic geomorphology of the Pallatanga fault (Central Ecuador), a major structure of the South-American crust

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Fault slip rate  
Seismic hazard

### ABSTRACT

The Pallatanga fault (PF) is a prominent NNE-SSW strike-slip fault crossing Central Ecuador. This structure is suspected to have hosted large earthquakes, including the 1797 Riobamba event which caused severe destructions to buildings and a heavy death toll (more than 12,000 people), as well as widespread secondary effects like landsliding, liquefaction and surface cracking. The scope of this study is to evaluate the seismic history of the fault through a paleoseismological approach. This work also aims at improving the seismotectonic map of this part of the Andes through a new mapping campaign and, finally, aims at improving the seismic hazard assessment.

We show that the PF continues to the north of the previously mapped fault portion in the Western Cordillera (Rumipamba-Pallatanga portion) into the Inter-Andean Valley (Riobamba basin). Field evidences of faulting are numerous, ranging from a clear geomorphological signature to fault plane outcrops. Along the western side of the Riobamba basin, the strike-slip component seems predominant along several fault portions, with a typical landscape assemblage (dextral offsets of valleys, fluvial terrace risers and generation of linear pressure ridges). In the core of the inter-Andean valley, the main fault portion exhibits a vertical component along the c. 100 m-high cumulative scarp. The presence of such an active fault bounding the western suburbs of Riobamba drastically increases the seismic risk for this densely inhabited and vulnerable city. To the east (Peltepec Massif, Cordillera Real), the continuation of the Pallatanga fault is suspected, but not definitely proved yet. Based on the analysis of three trenches, we state that the Rumipamba-Pallatanga section of the PF experienced 4 (maybe 5) Holocene to Historical strong events ( $M_w > 7$ ). The coseismic behavior of the fault is deduced from the occurrence of several colluvial wedges and layers associated with the fault activity and interbedded within the

AGU PUBLICATIONS

## Tectonics

### RESEARCH ARTICLE

10.1002/2015TC003941

#### Key Points:

- A reviewed model of Ecuador's geodynamics is used to define seismic source zones
- Differences in rheology and changes in convergence obliquity explain observed seismicity
- Shallow and intermediate-depth seismicity show slab bending and block motion, respectively

#### Supporting Information:

- Supporting Information S1
- Movie S1

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#### Citation:

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## A new view for the geodynamics of Ecuador: Implication in seismogenic source definition and seismic hazard assessment

Hugo Yepes<sup>1,2</sup>, Laurence Audin<sup>2</sup>, Alexandra Alvarado<sup>1</sup>, Céline Beauval<sup>2</sup>, Jorge Aguilar<sup>1</sup>, Yvonne Font<sup>3</sup>, and Fabrice Cotton<sup>4</sup>

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**Abstract** A new view of Ecuador's complex geodynamics has been developed in the course of modeling seismic source zones for probabilistic seismic hazard analysis. This study focuses on two aspects of the plates' interaction at a continental scale: (a) age-related differences in rheology between Farallon and Nazca plates—marked by the Grijalva rifted margin and its inland projection—as they subduct underneath central Ecuador, and (b) the rapidly changing convergence obliquity resulting from the convex shape of the South American northwestern continental margin. Both conditions satisfactorily explain several characteristics of the observed seismicity and of the interseismic coupling. Intermediate-depth seismicity reveals a severe flexure in the Farallon slab as it dips and contorts at depth, originating the El Puyo seismic cluster. The two slabs position and geometry below continental Ecuador also correlate with surface expressions observable in the local and regional geology and tectonics. The interseismic coupling is weak and shallow south of the Grijalva rifted margin and increases northward, with a heterogeneous pattern locally associated to the Carnegie ridge subduction. High convergence obliquity is responsible for the North Andean Block northeastward movement along localized fault systems. The Cosanga and Pallatanga fault segments of the North Andean Block-South American boundary concentrate most of the seismic moment release in continental Ecuador. Other inner block faults located along the western border of the inter-Andean Depression also show a high rate of moderate-size earthquake production. Finally, a total of 19 seismic source zones were modeled in accordance with the proposed geodynamic and neotectonic scheme.

# 11 Años de Investigación

Identificar las fuentes sísmicas potenciales

Incorporar el el cálculo incertidumbres epistémicas incorporadas en cada paso del cálculo

Bulletin of the Seismological Society of America, 2014, 94(1), 1-12, doi: 10.1785/0120170259

AGU PUBLICATIONS

## Tectonics

### RESEARCH ARTICLE

10.1002/2012TC003224

#### Key Points:

- Neotectonics of Quito faults are studied by a multidisciplinary approach
- Our kinematic model defines a N-S fold system migrating eastward
- The GPS rate for QFS is 4 mm/yr, suggesting a deficit of crustal seismicity

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#### Citation:

Alvarado, A., L. Audin, J. M. Nocquet, S. Lagreulet, M. Segovia, Y. Font, G. Lamarque, H. Yepes, P. Mothes, F. Rolandone, P. Jarrin, and X. Quidelleur (2014), Active tectonics in Quito, Ecuador, assessed by geomorphological studies, GPS data, and crustal seismicity, *Tectonics*, 33, 67–83, doi:10.1002/2012TC003224.

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## Active tectonics in Quito, Ecuador, assessed by geomorphological studies, GPS data, and crustal seismicity

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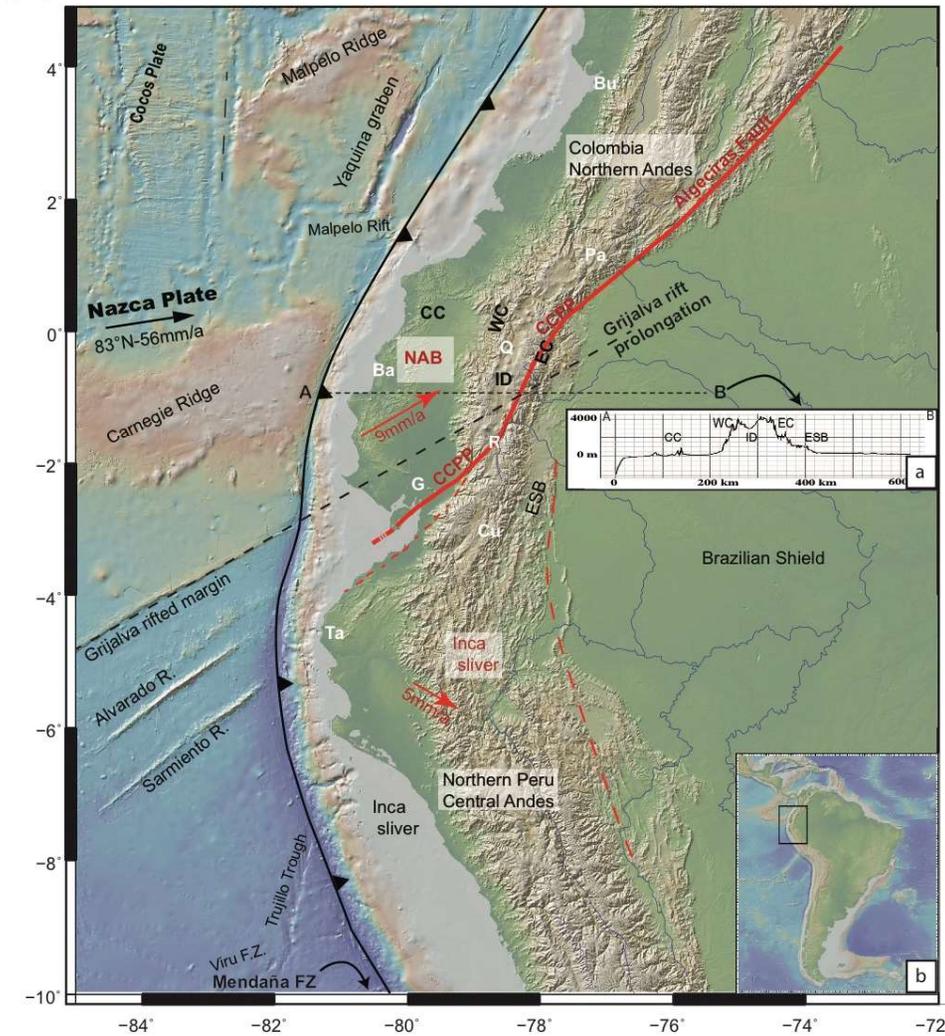
**Abstract** The Quito Fault System (QFS) extends over 60 km along the Interandean Depression in northern Ecuador. Multidisciplinary studies support an interpretation in which two major contemporaneous fault systems affect Quaternary volcanoclastic deposits. Hanging paleovalleys and disruption of drainage networks attest to ongoing crustal deformation and uplift in this region, further confirmed by 15 years of GPS measurements and seismicity. The resulting new kinematic model emphasizes the role of the N-S segmented, en echelon eastward migrating Quito Fault System (QFS). Northeast of this major tectonic feature, the strike-slip Guayllabamba Fault System (GFS) aids the eastward transfer of the regional strain toward Colombia. These two tectonic fault systems are active, and the local focal mechanisms are consistent with the direction of relative GPS velocities and the regional stress tensor. Among active features, inherited N-S direction sutures appear to play a role in confining the active deformation in the Interandean Depression. The most frontal of the Quito faults formed at the tip of a blind thrust, dipping 40°W, is most probably connected at depth to inactive suture to the west. A new GPS data set indicates active shortening rates for Quito blind thrust of up to 4 mm/yr, which decreases northward along the fold system as it connects to the strike-slip Guayllabamba Fault System. The proximity of these structures to the densely populated Quito region highlights the need for additional tectonic studies in these regions of Ecuador to generate further hazard assessments.

## A New Seismic Hazard Model for Ecuador

by C. Beauval, J. Marinière, H. Yepes, L. Audin, J.-M. Nocquet, A. Alvarado, S. Baize, J. Aguilar, J.-C. Singaicho, and H. Jomard

**Abstract** We present a comprehensive probabilistic seismic hazard study for Ecuador, a country exposed to a high seismic hazard from megathrust subduction earthquakes and moderate-to-large shallow crustal earthquakes. Building on knowledge gained during the last decade about historical and contemporary seismicity, active tectonics, geodynamics, and geodesy, several alternative earthquake recurrence models have been developed. We propose an areal seismic zonation for the seismogenic crustal, in-slab, and interface sources, modified from Yepes *et al.* (2016), to account for the information gained after the 2016  $M_w$  7.8 Pedernales megathrust earthquake. Three different earthquake catalogs are used to account for uncertainties in magnitude–frequency distribution modeling. This first approach results in low hazard estimates for some areas near active crustal fault systems with low instrumental seismicity, but where geology and/or geodesy document rapid slip rates and high seismic potential. Consequently, we develop an alternative fault and background model that includes faults with earthquake recurrence models inferred from geologic and/or geodetic slip-rate estimates. The geodetic slip rates for a set of simplified faults are estimated from a Global Positioning System (GPS) horizontal velocity field from Nocquet *et al.* (2014). Various scenarios are derived by varying the percentage of motion that takes place aseismically. Combining these alternative earthquake recurrence models in a logic tree, and using a set of selected ground-motion models adapted to Ecuador's different tectonic settings, mean hazard maps are obtained with their associated uncertainties. At the sites where uncertainties on hazard estimates are highest (difference between 84th and 16th percentiles > 0.4g), the overall uncertainty is controlled by the epistemic uncertainty on the source model.

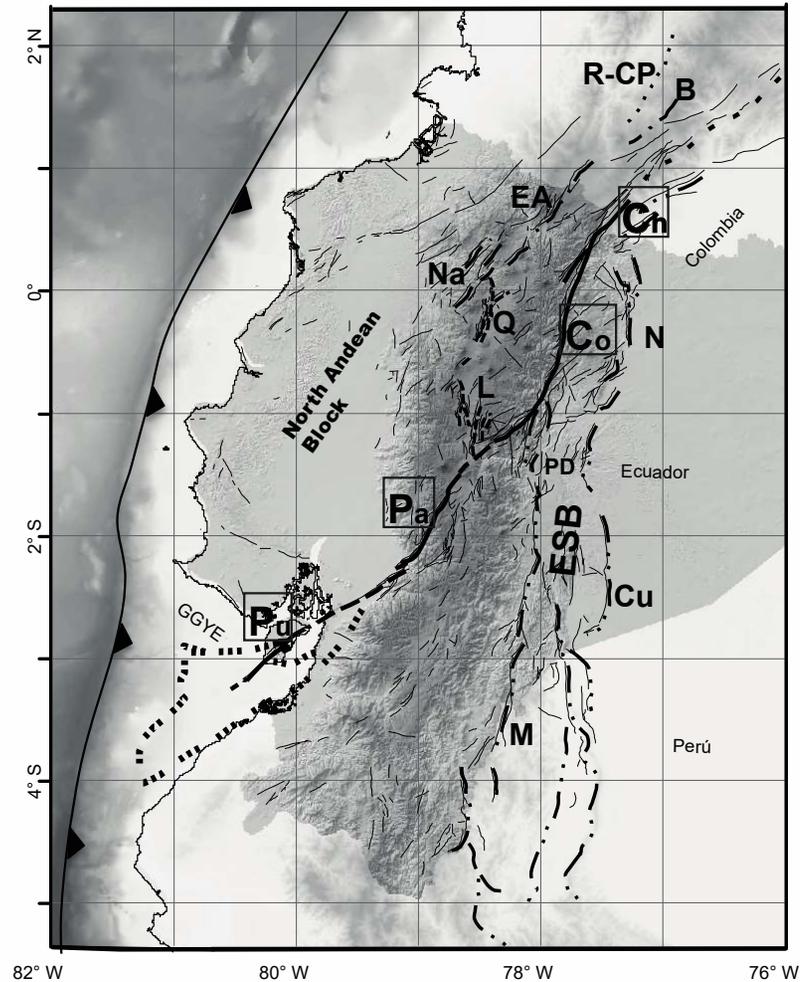
# La tectónica activa en el Ecuador y la generación de terremotos



Base Geodinámica para  
La modelación de las  
fuentes sismogénicas

# La tectónica activa en el Ecuador y la generación de terremotos

F6



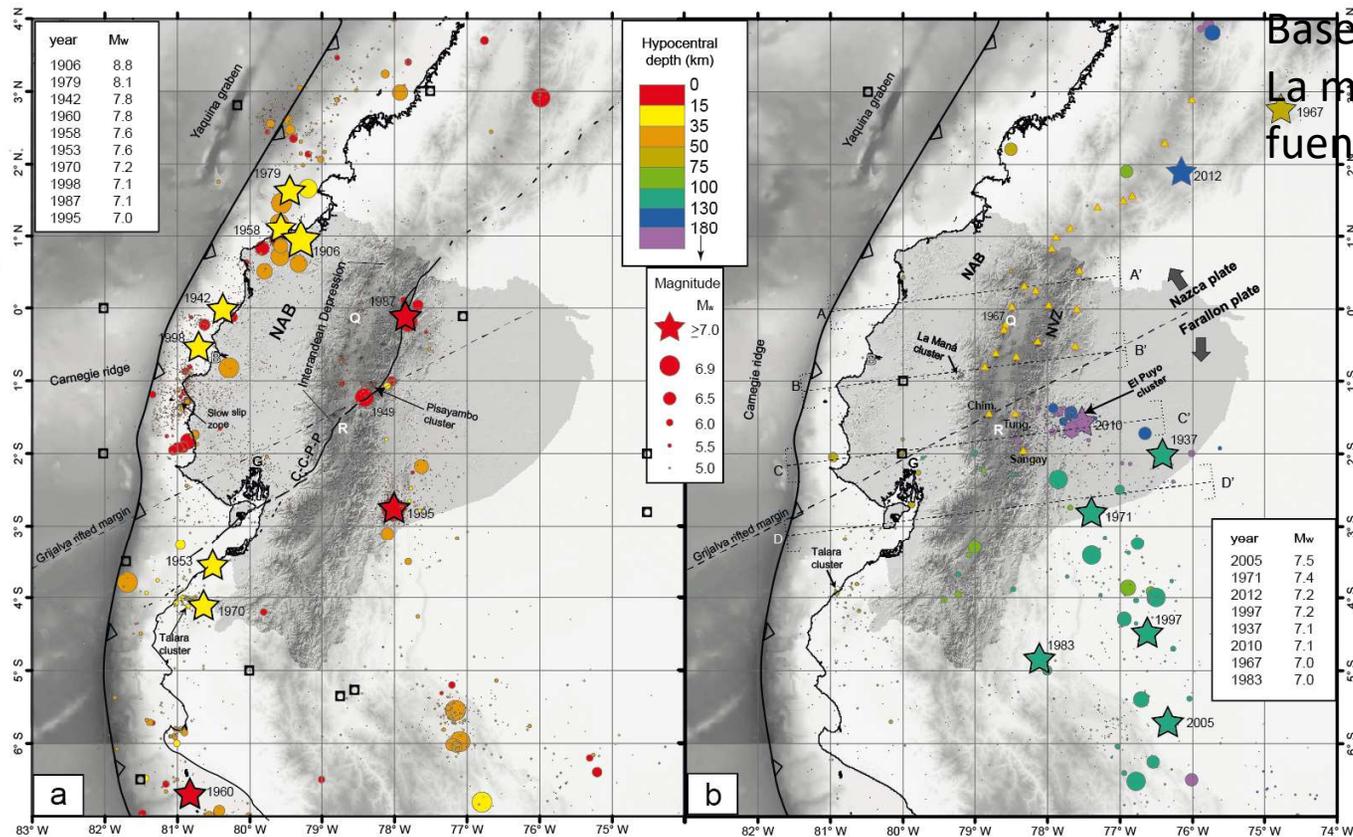
Base Geodinámica para  
La modelación de las  
fuentes sismogénicas

# La tectónica activa en el Ecuador y la generación de terremotos

F2

Z ≤ 50 Km.

Z > 50 Km.

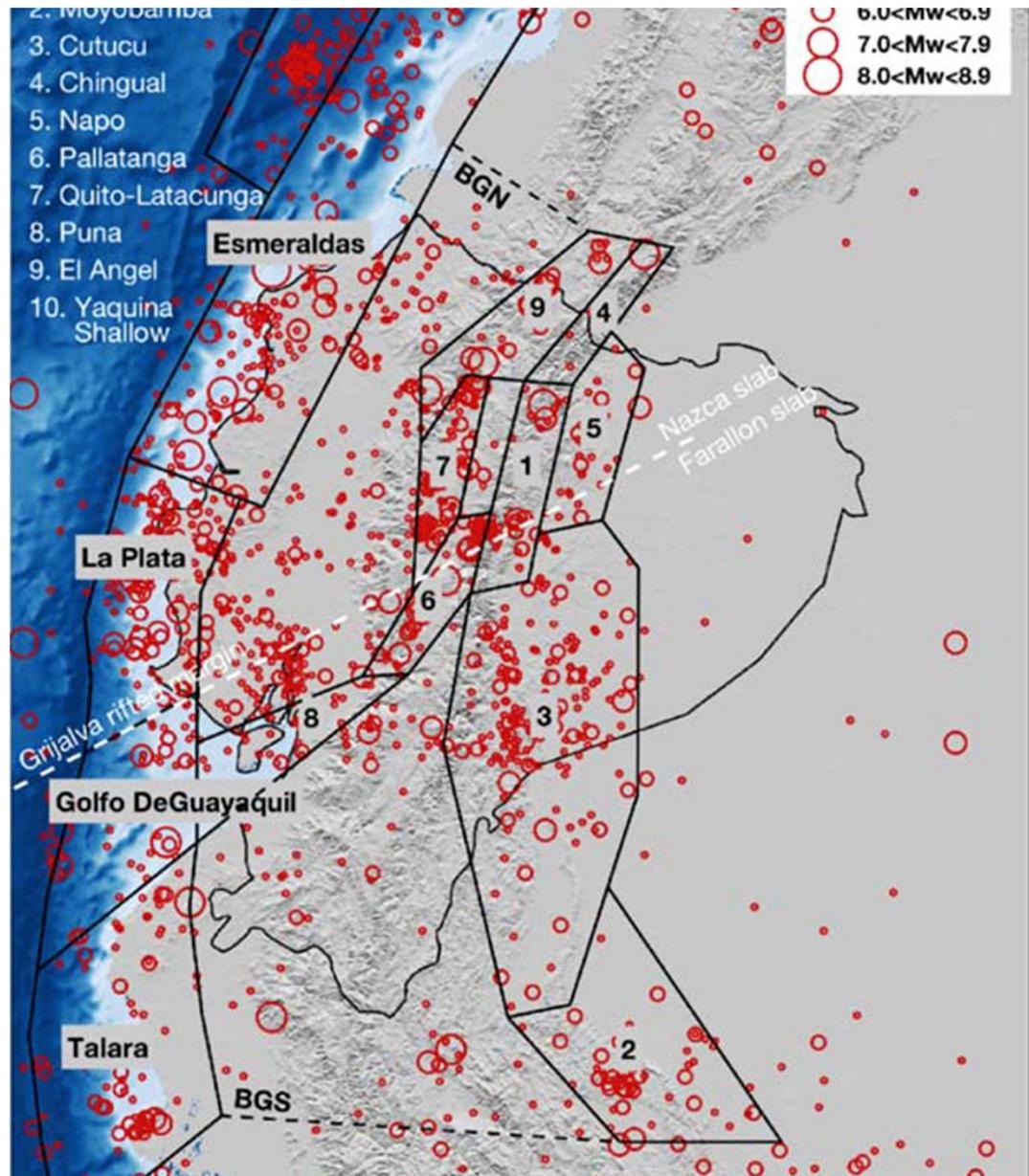


Base Geodinámica para  
La modelación de las  
fuentes sismogénicas

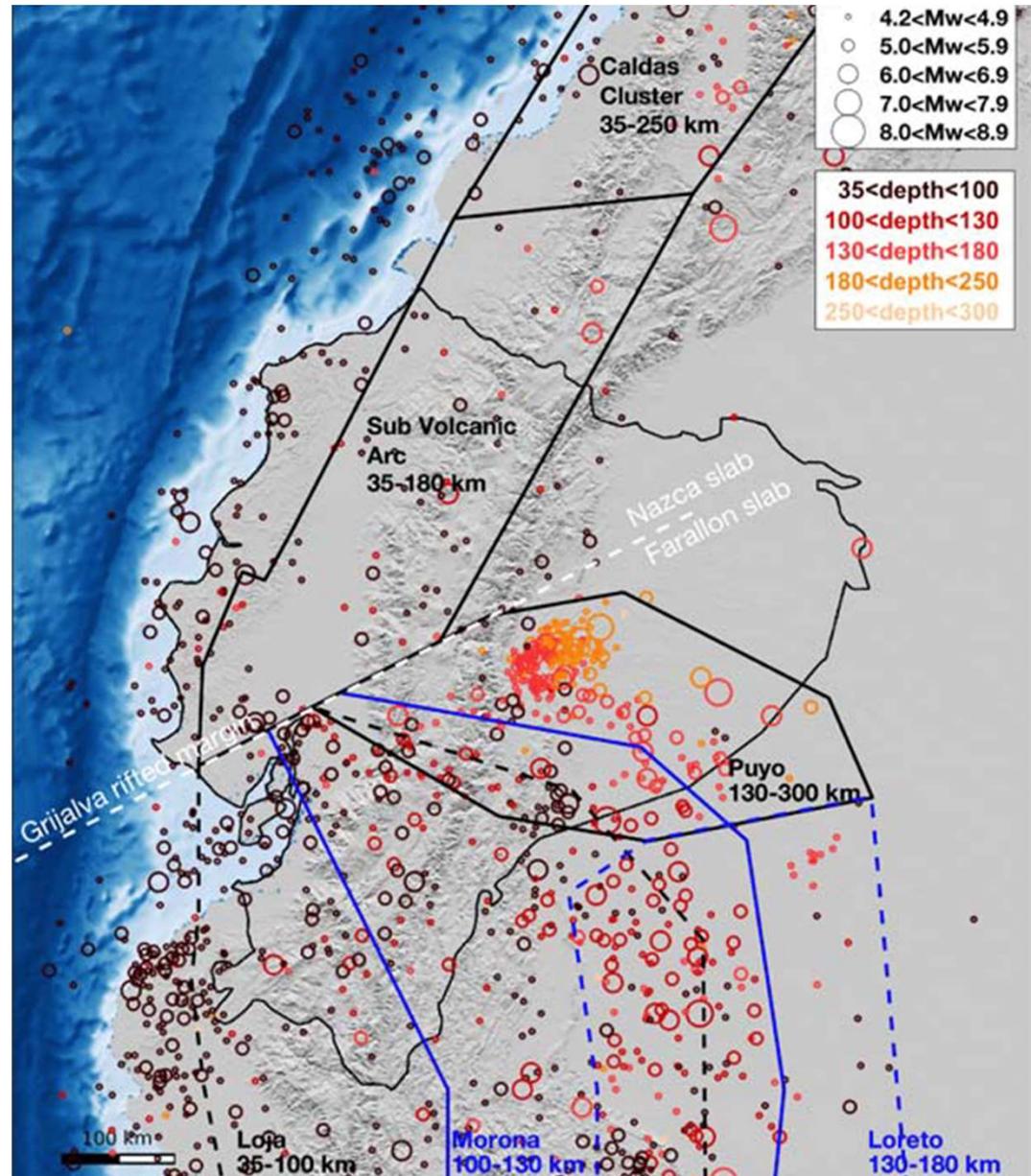
# Nuevo PSHA Ecuador 2018

- Innovación fundamental: **Inclusión de las incertidumbres en todas las etapas de cálculo**
  - Desarrollo de varios modelos alternativos de recurrencia de terremotos
    - Fuentes en base a zonas sísmicas
      - Tres catálogos diferentes → Incertidumbre de las G-R
    - Fuentes mixtas: fallas y zonas sísmicas de background
      - Escenarios en base a variación del acoplamiento en las fallas
    - Set de GMPEs (6)
    - Incertidumbres en el PSHA en base a la técnica de árbol lógico

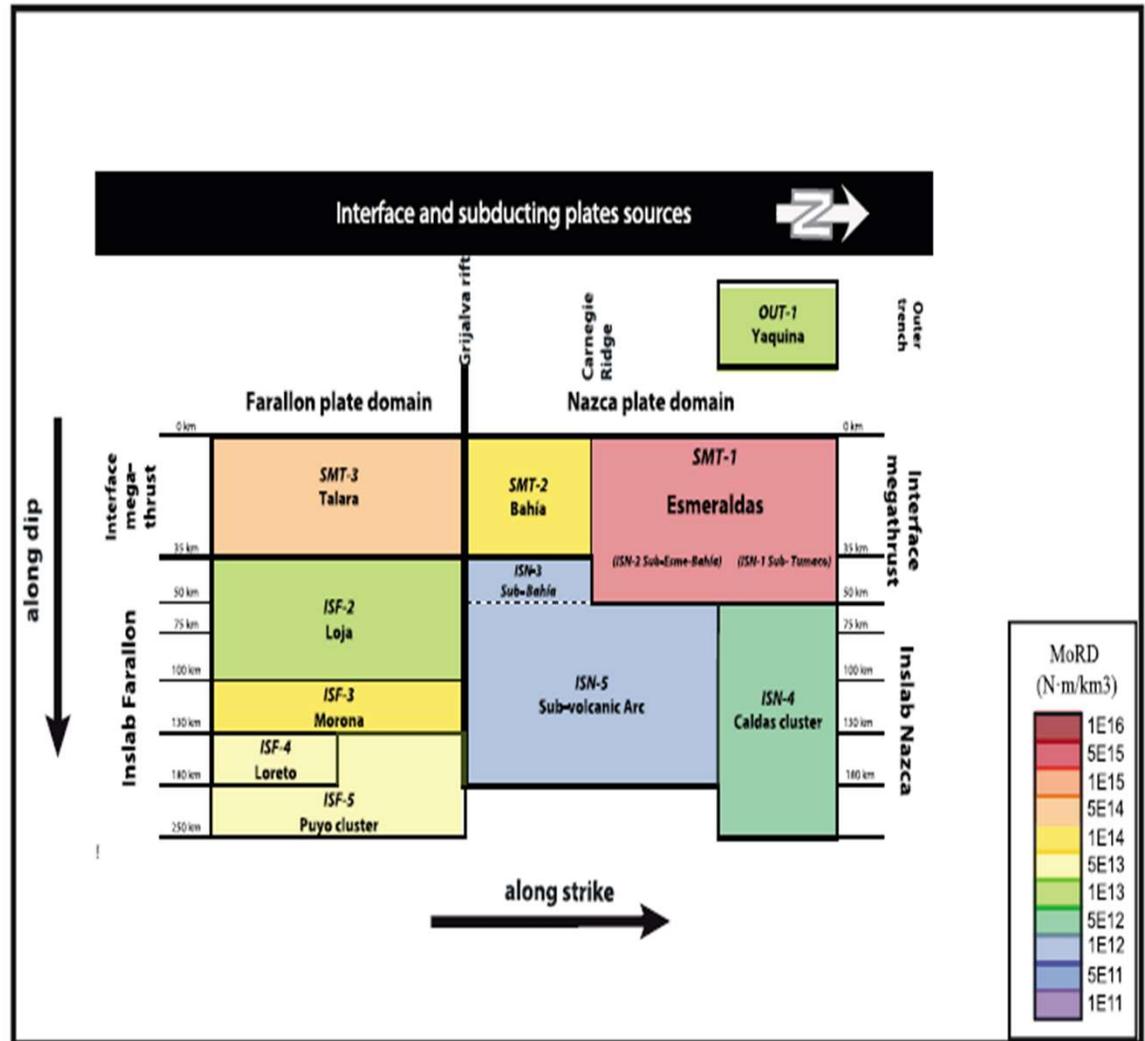
# Zonas sismogénicas corticales



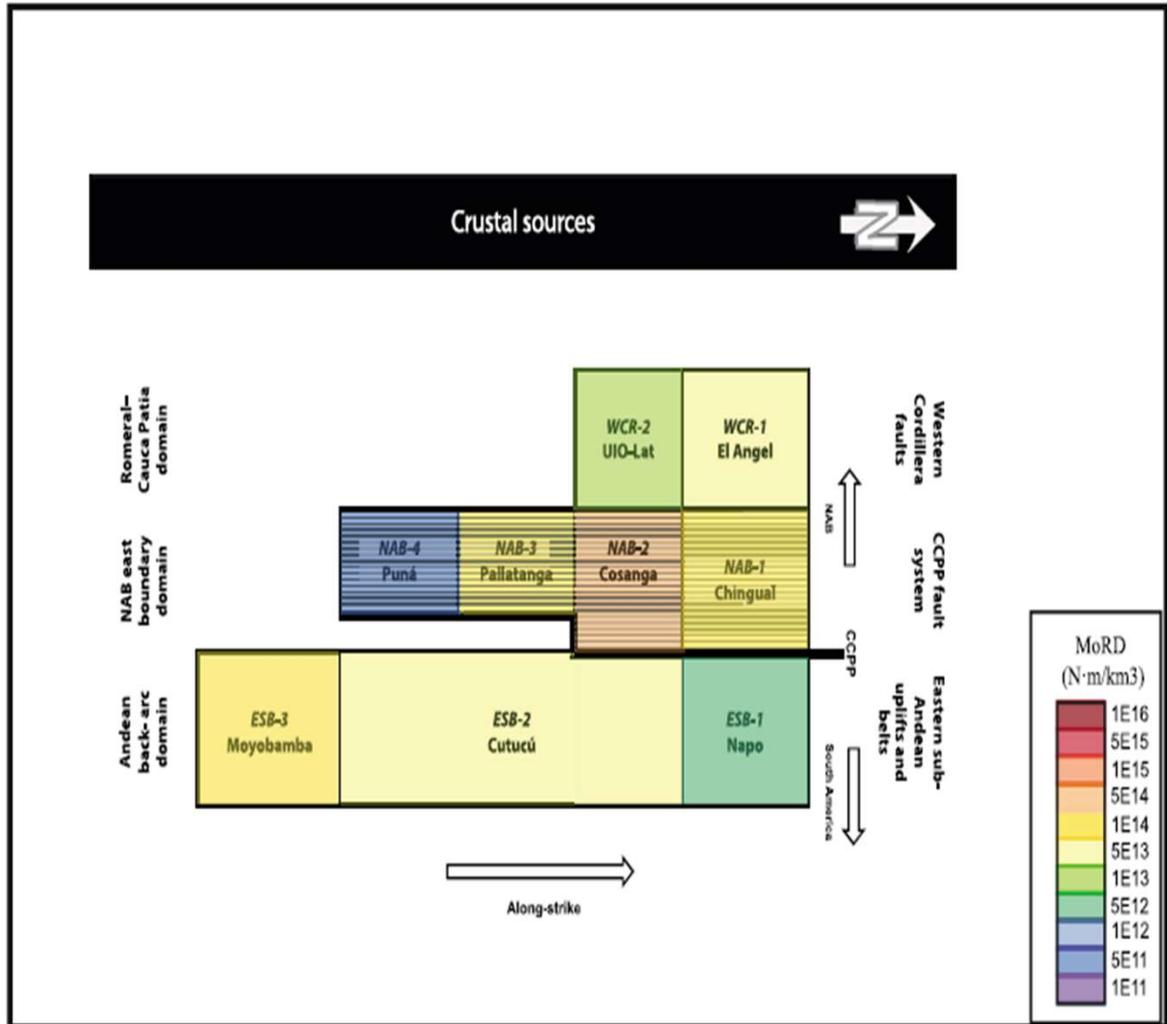
# Zonas sismogénicas profundas



# Esquema de relaciones de zonas sismogénicas de interfaz y profundas



# Esquema de relaciones de zonas sismogénicas corticales



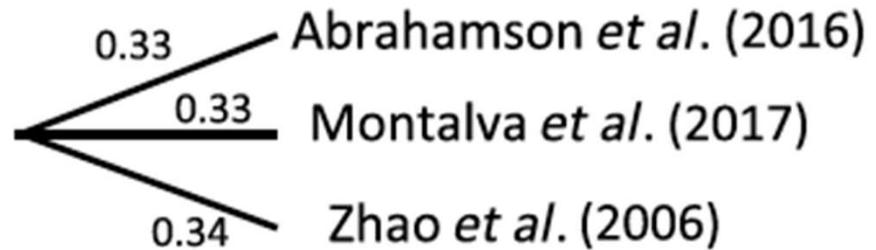
## **Cálculo probabilístico del movimiento del suelo**

- **Nuevos avances en el cálculo del peligro sísmico con árbol lógico de probabilidades:**
  - **Modelo de áreas fuente con la sismicidad distribuida**
  - **Contribución de todas las fuentes a nivel nacional**
  - **Modelo de falla fuente con la sismicidad  $M_W \geq 6$  concentrada en la Falla de Quito**
  - **Modelamiento de la recurrencia G-R en base a:**
    - » **Tasa de deslizamiento geológica**
    - » **Tasa de movimiento geodético**
    - » **tasa de acoplamiento de la Falla de UIO**
    - » **Diferentes catálogos sísmicos**
  - **Tres ecuaciones de predicción de movimiento fuerte GMPEs, una con factor de hanging wall**

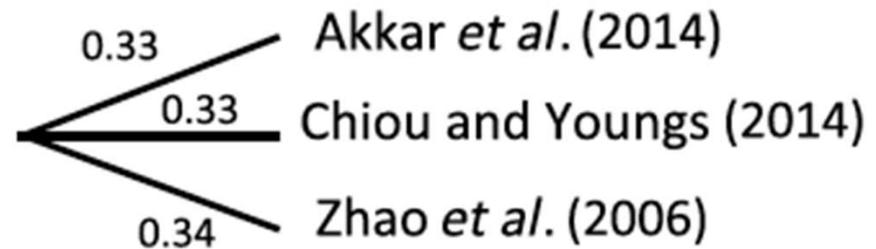
## Árbol lógico para el cálculo del movimiento del suelo

### Ground-motion model logic tree

#### Interface and inslab sources



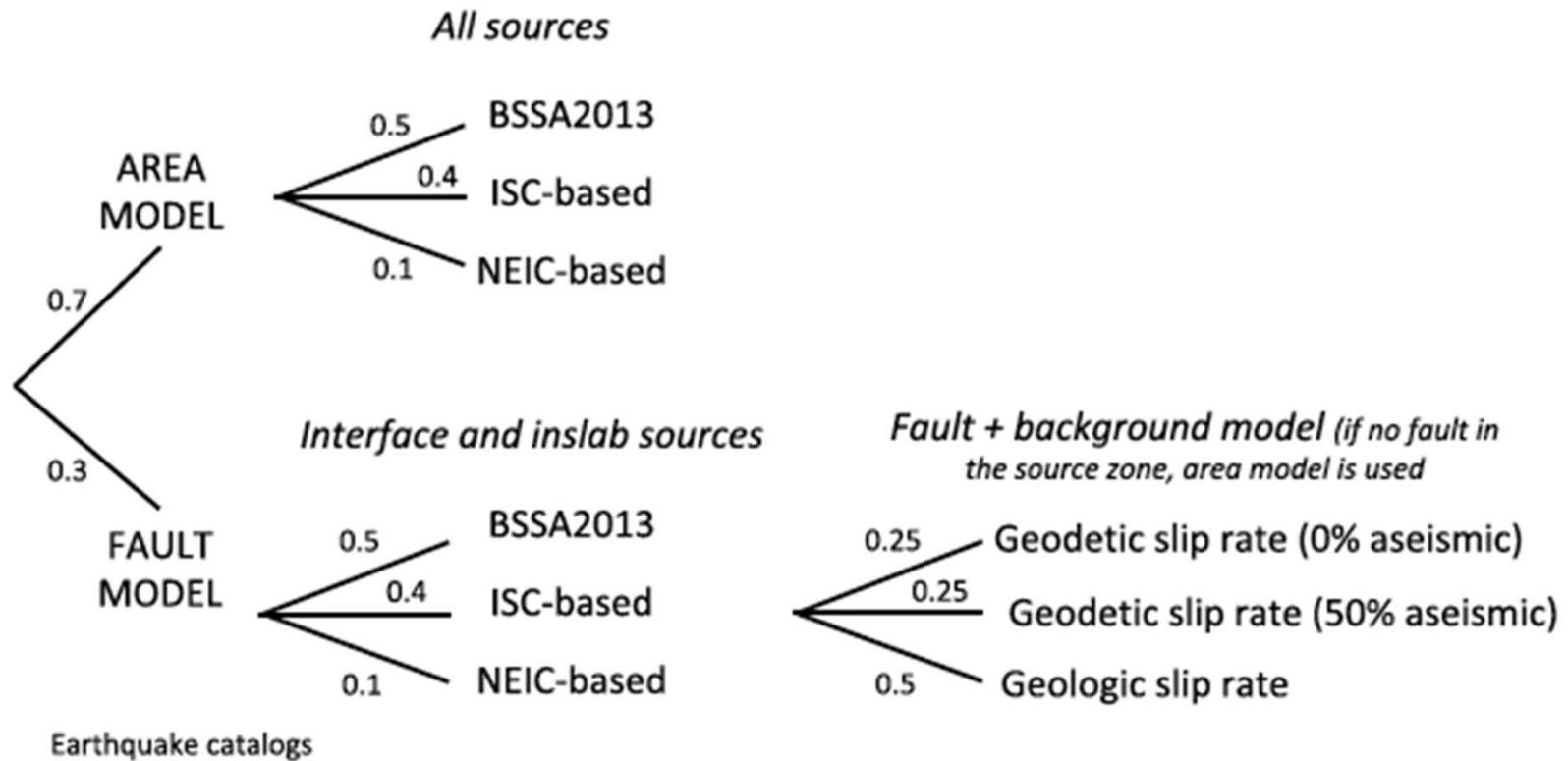
#### Crustal sources



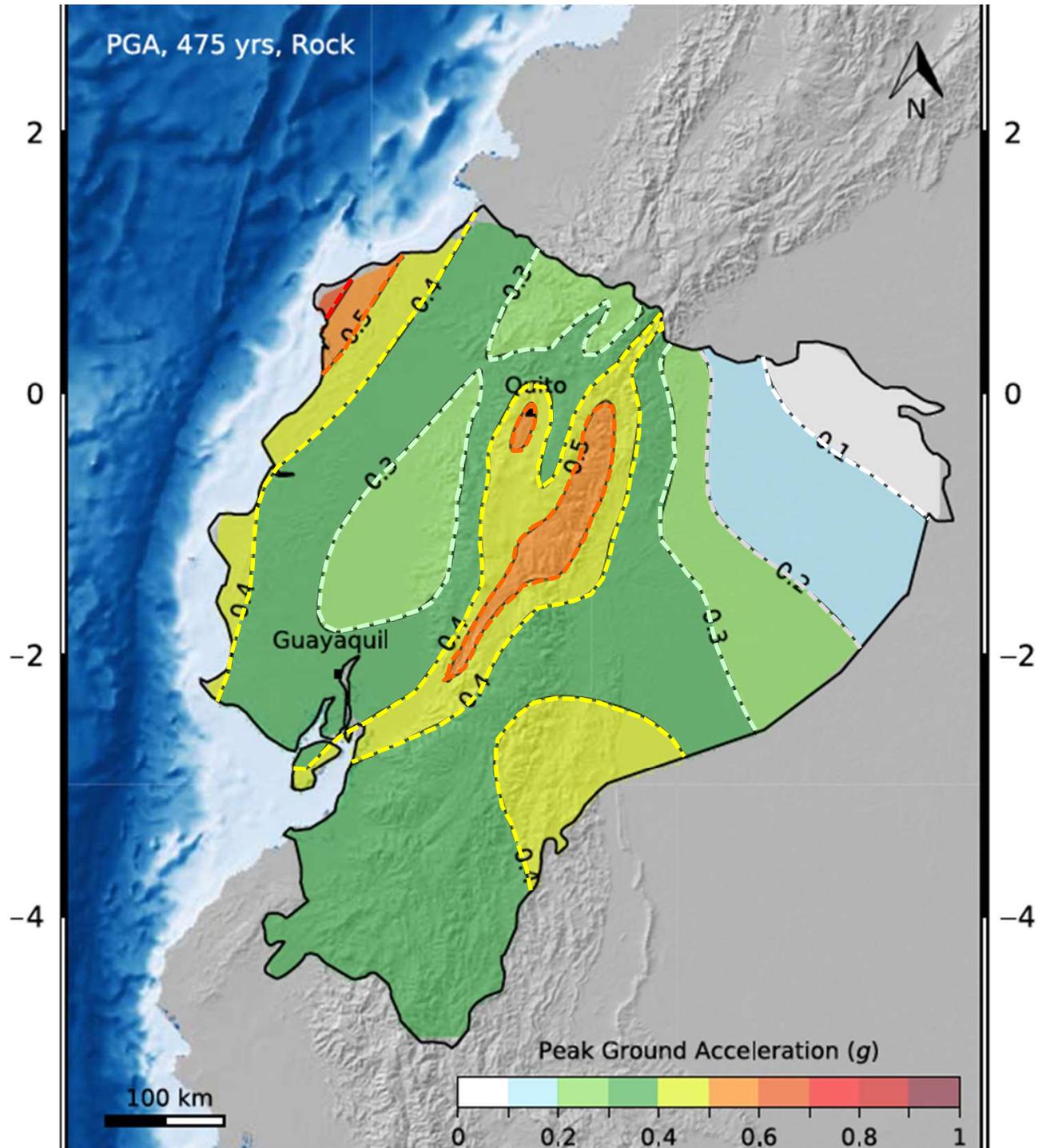
**Figure 6.** Ground-motion logic tree.

# Árbol lógico para el cálculo del movimiento del suelo

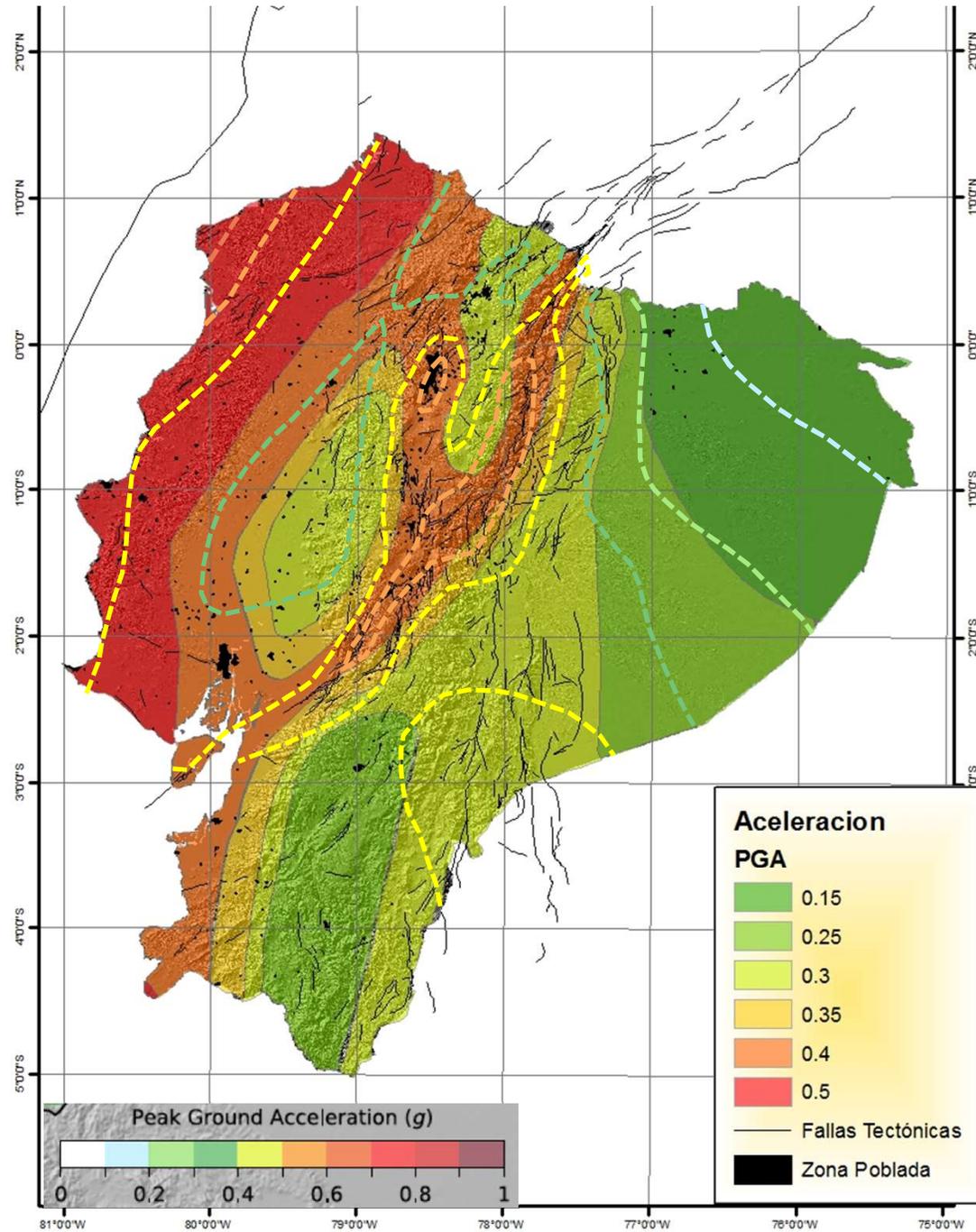
## Source model logic tree



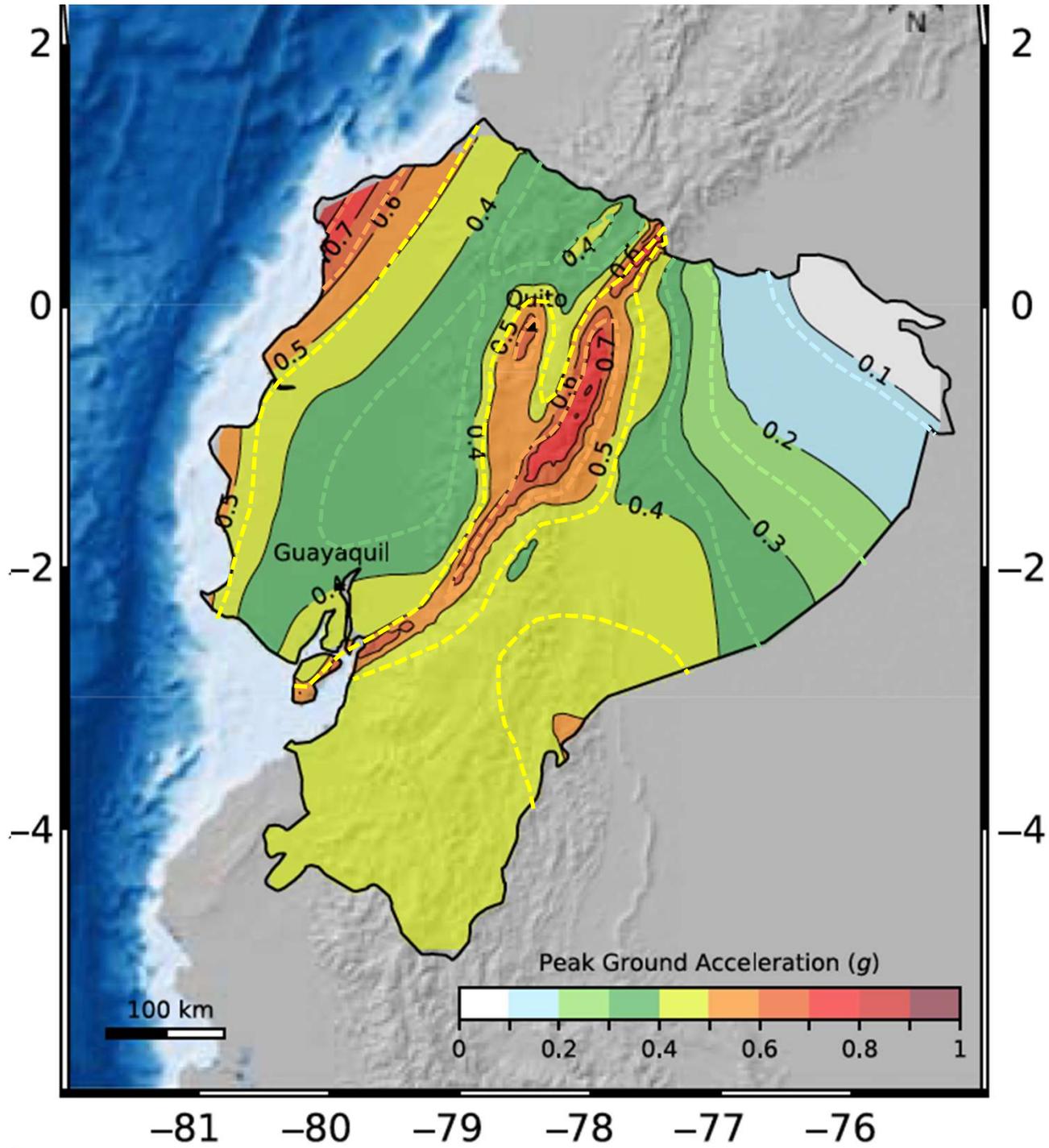
Valor medio  
de la  
amenaza con  
el árbol  
lógico  
completo



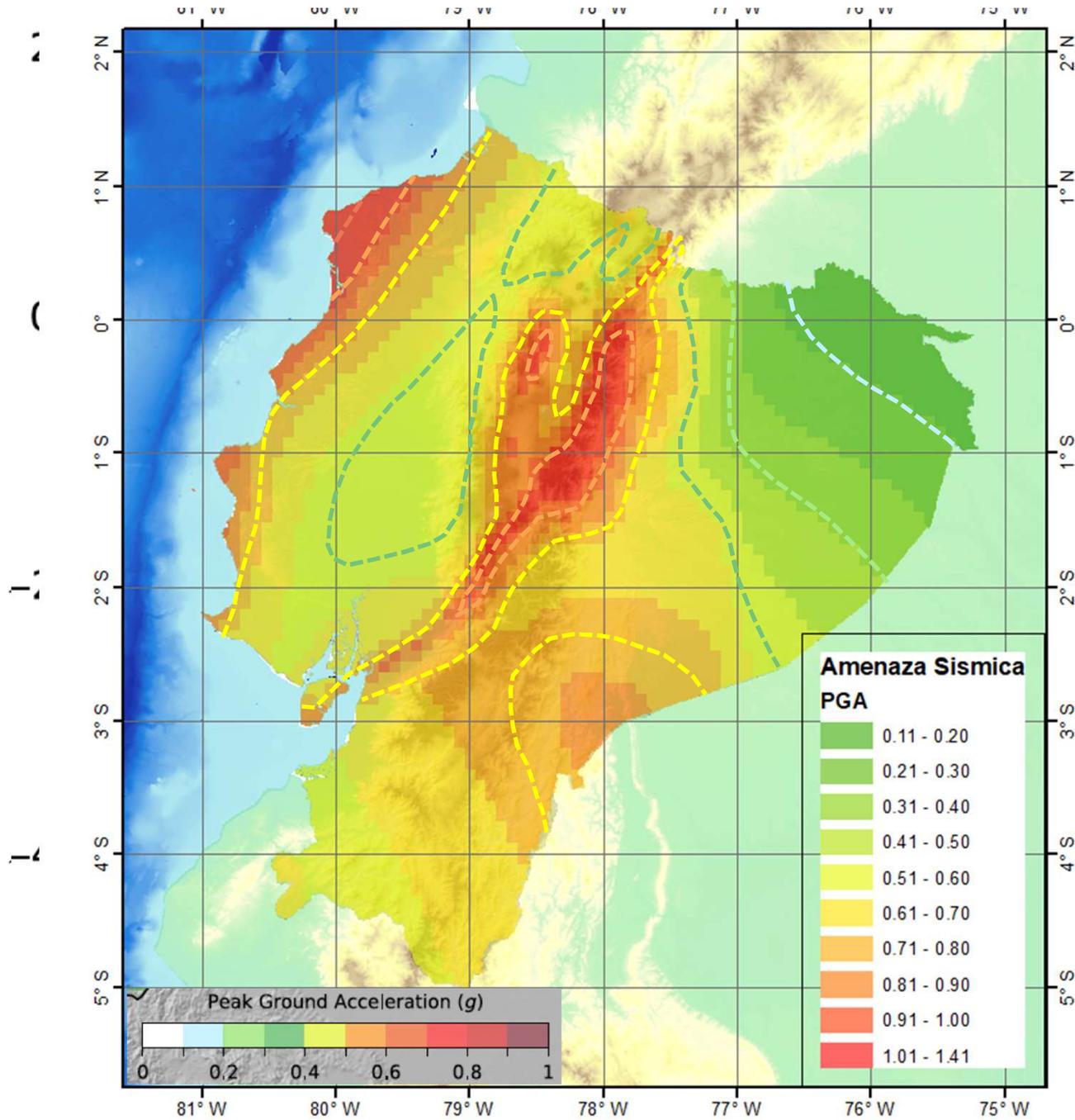
# Comparación entre el Valor medio de la amenaza y la zonificación de 2011

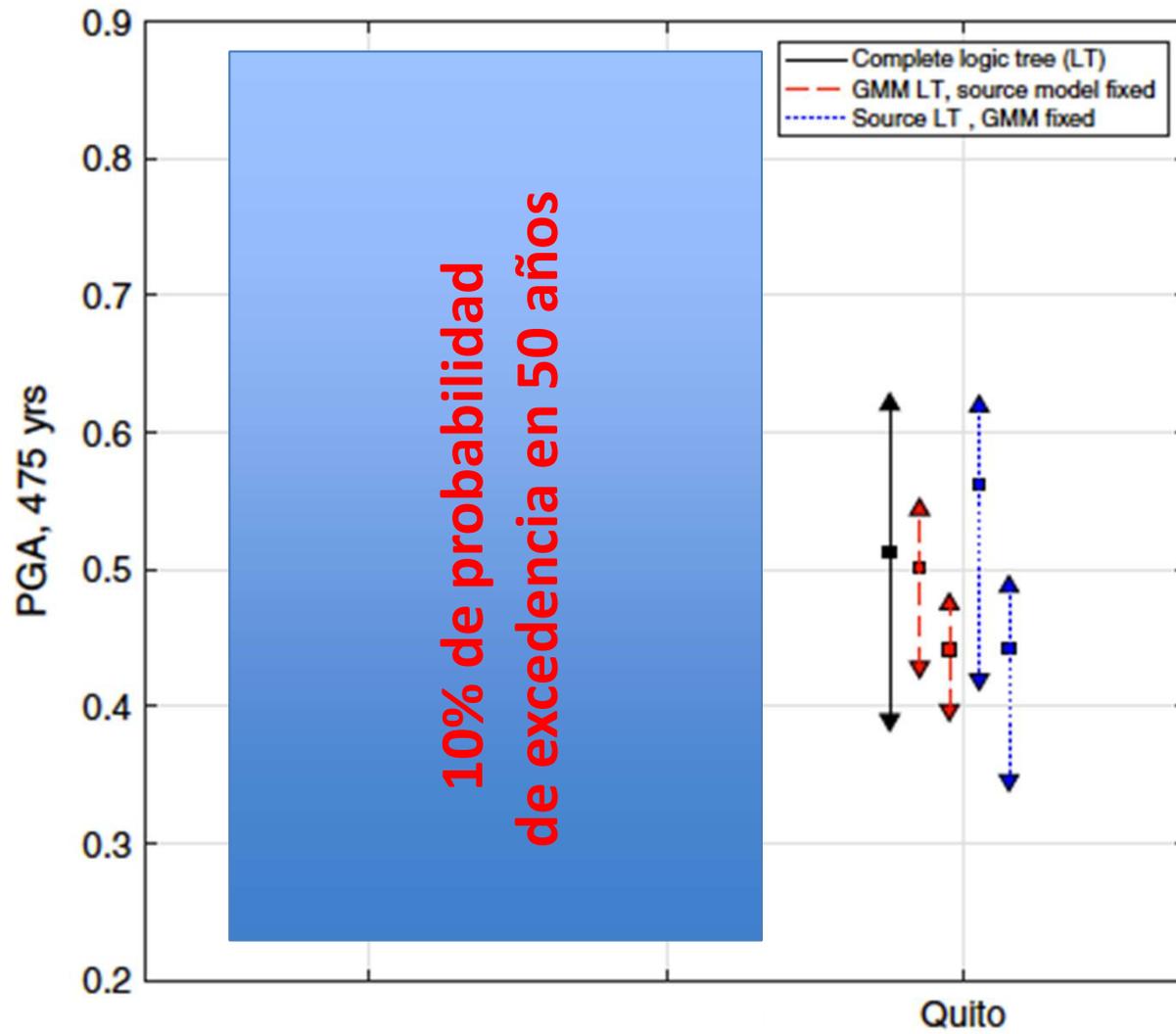


84 percentil



2475 a RT





# Definición Neotectónica de la falla activa de Quito

- Sistema Inverso
- ~60 km de largo
- Segmentos diferenciados
- Velocidad mayor que 1mm/yr
- Historia sísmica definida

*Bol. Geol. Ecuat., Vol. 2, N° 1, 1991, pp. 3-11*

## TECTONICA ACTIVA Y RIESGO SISMICO EN LOS ANDES ECUATORIANOS Y EL EXTREMO SUR DE COLOMBIA

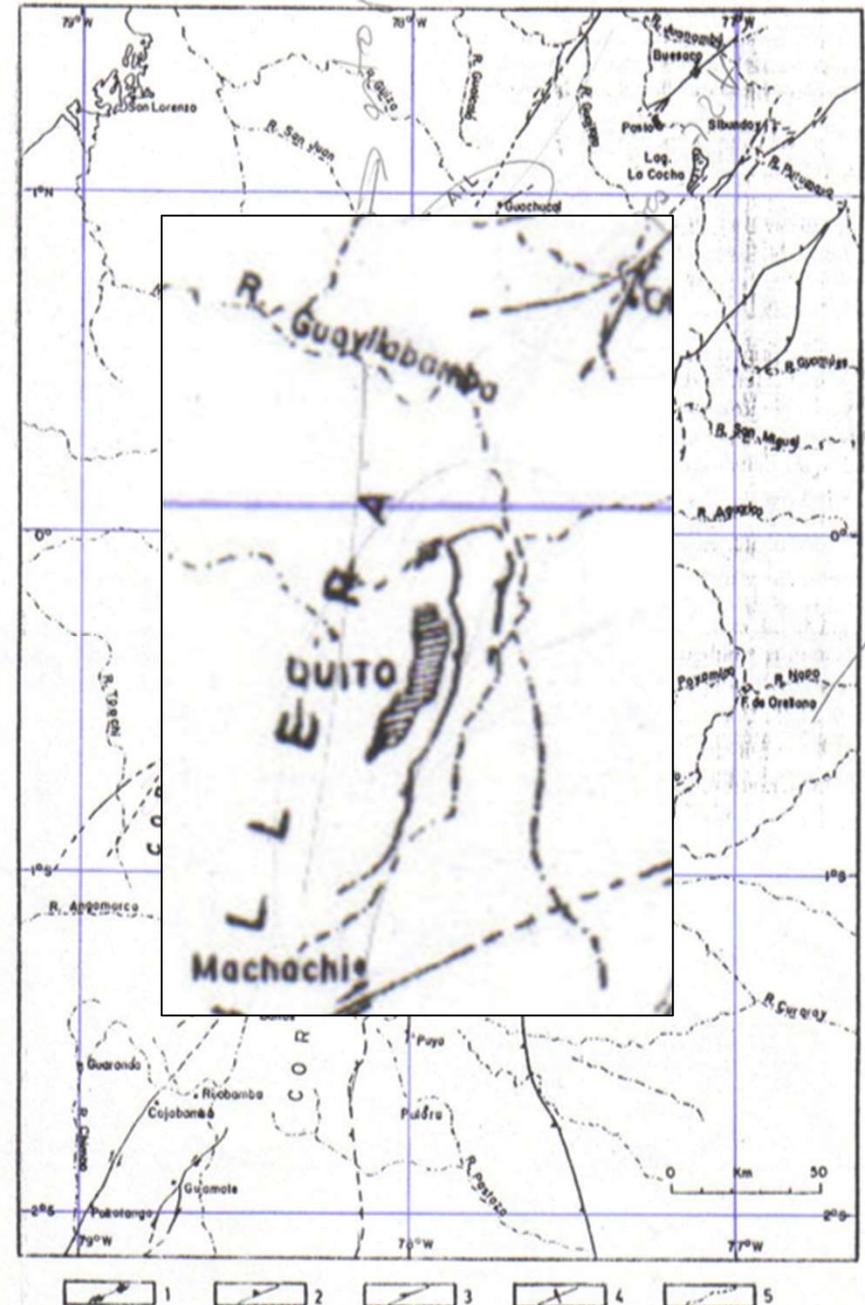
JEAN-PIERRE SOULAS (\*), ARTURO EGUEZ (\*\*), HUGO YEPES (\*\*), HUGO PEREZ (\*\*\*)

(\*) - Institut de Physique du Globe de Paris; y 18, Allée des Mésanges, Parc Pécire, 33120 Arcachon-France.

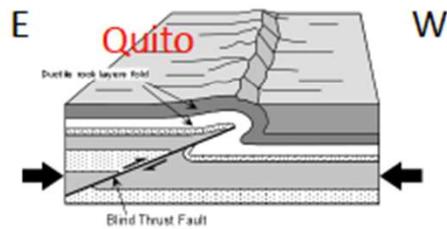
(\*\*) - Instituto Geofísico, Escuela Politécnica Nacional, Quito.

(\*\*\*) - Centro de Levantamientos Integrados de Recursos Naturales por Sensores Remotos, Quito.

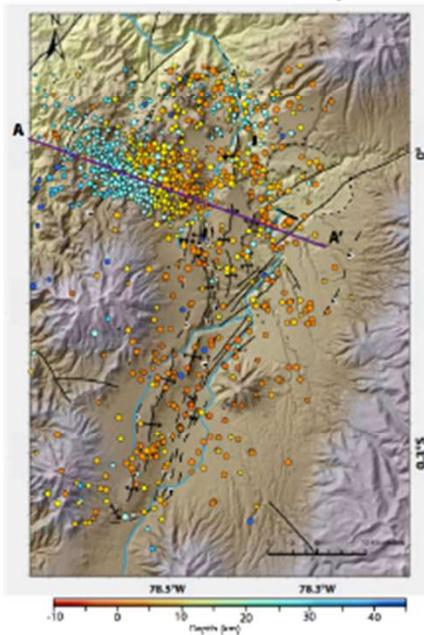
SOULAS ET AL.: TECTONICA ACTIVA Y RIESGO SISMICO EN LOS ANDES



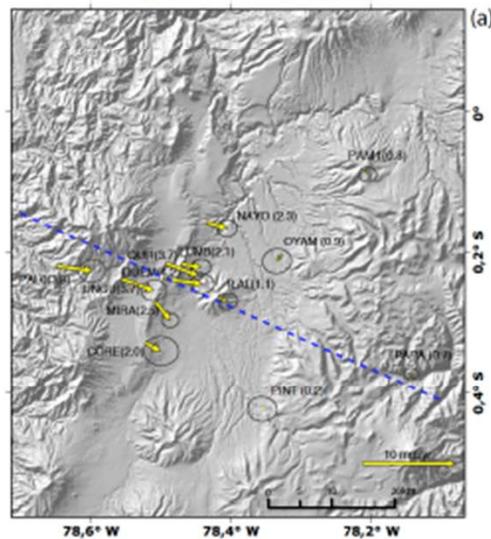
# Activity of the Quito thrust fault system



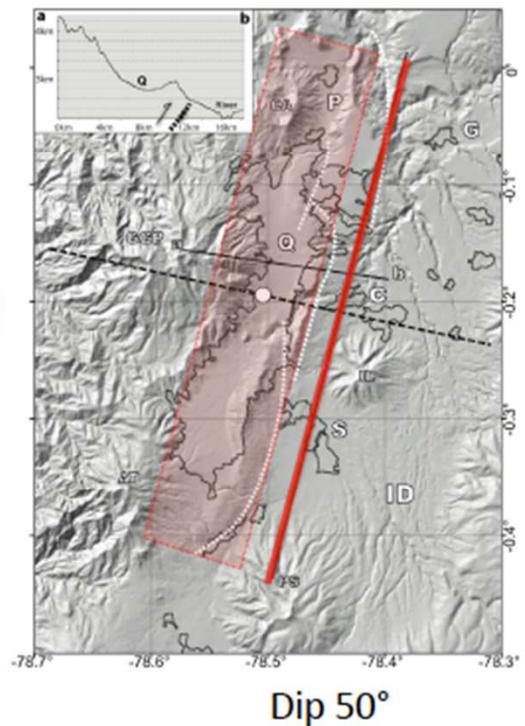
Microseismicity



GPS measurements  
(10 to 15yrs)

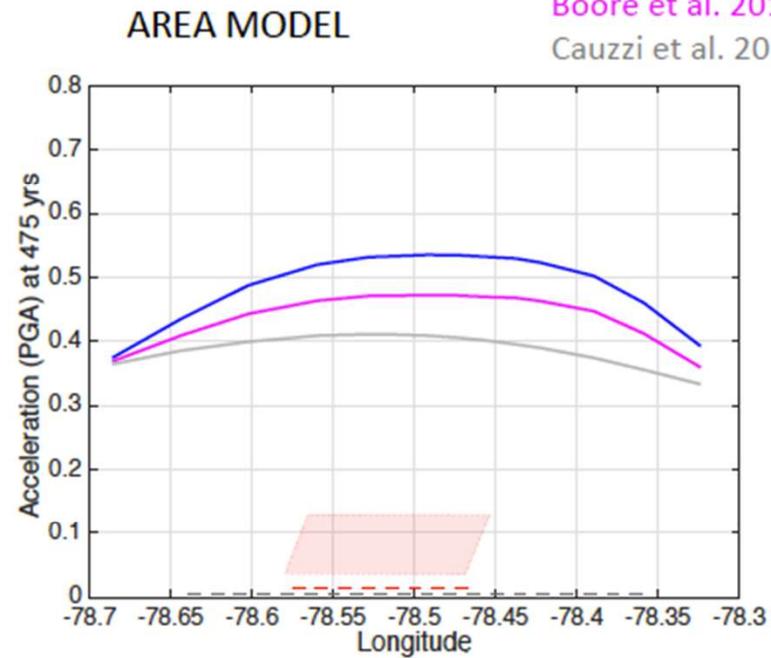
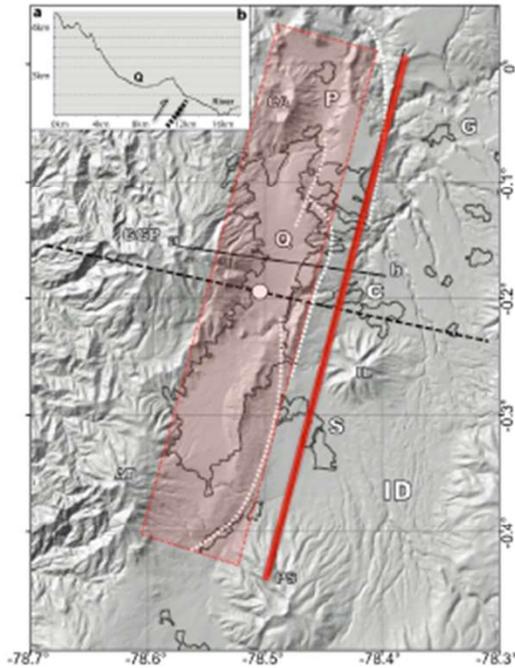


Simplified geometry of the  
blind fault



Alvarado et al. 2014

# PSHA in Quito – including the fault

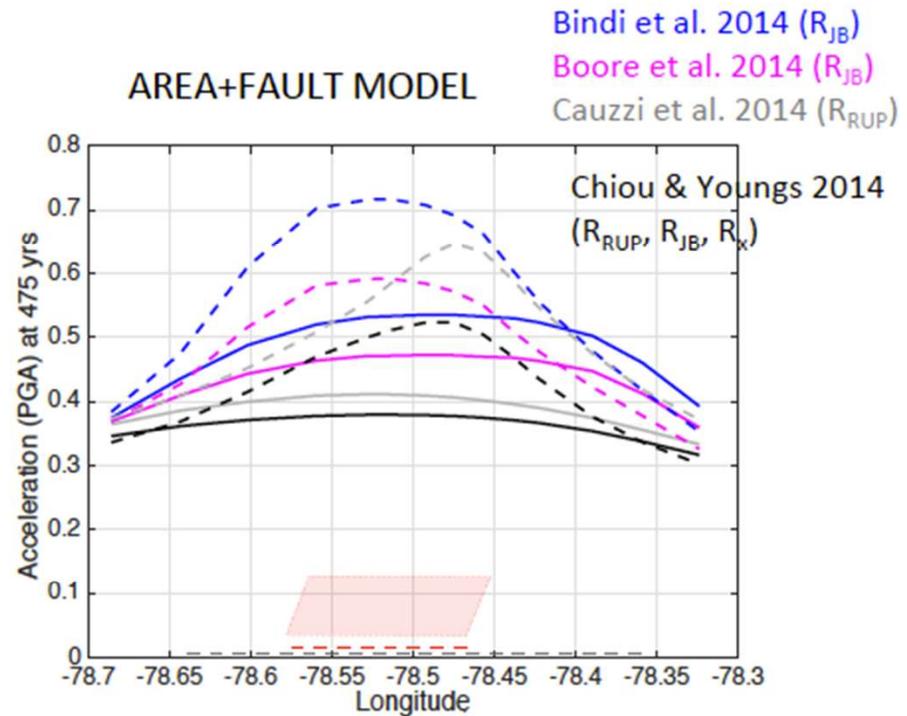
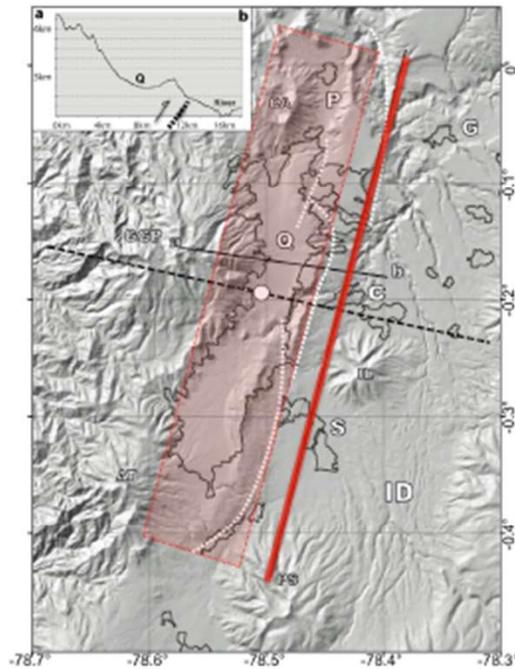


Bindi et al. 2014 ( $R_{JB}$ )  
Boore et al. 2014 ( $R_{JB}$ )  
Cauzzi et al. 2014 ( $R_{RUP}$ )

PSHA calculations with OpenQuake

# PSHA in Quito – including the fault

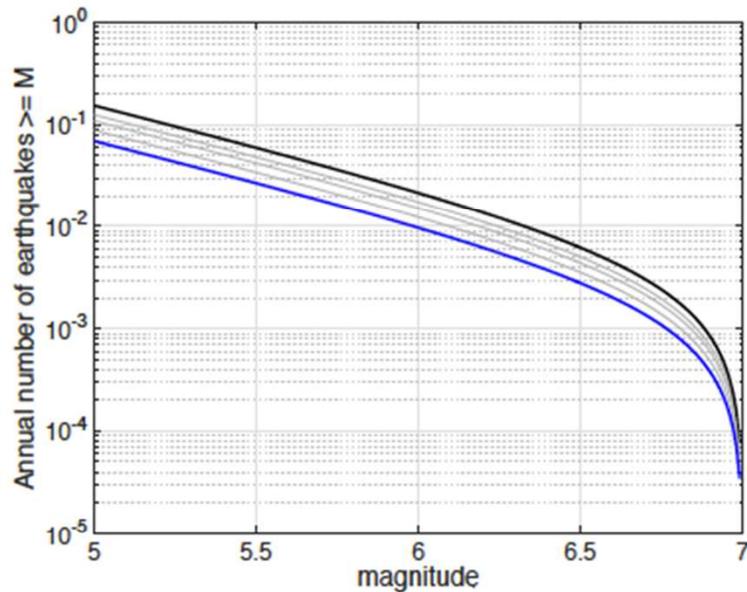
- Effect of restricting moderate-to-large EQs on the simplified fault plane



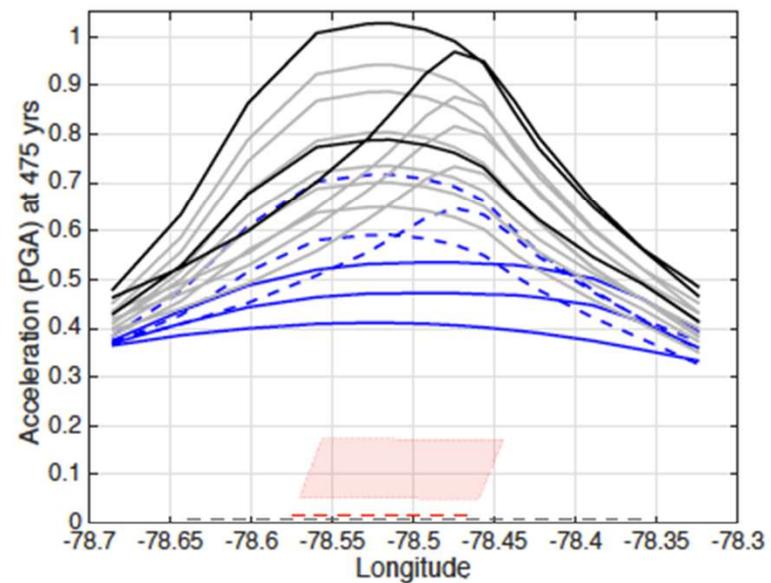
PSHA calculations with OpenQuake

# PSHA in Quito – recurrence based on the slip rate

The fault is locked (no aseismic slip)

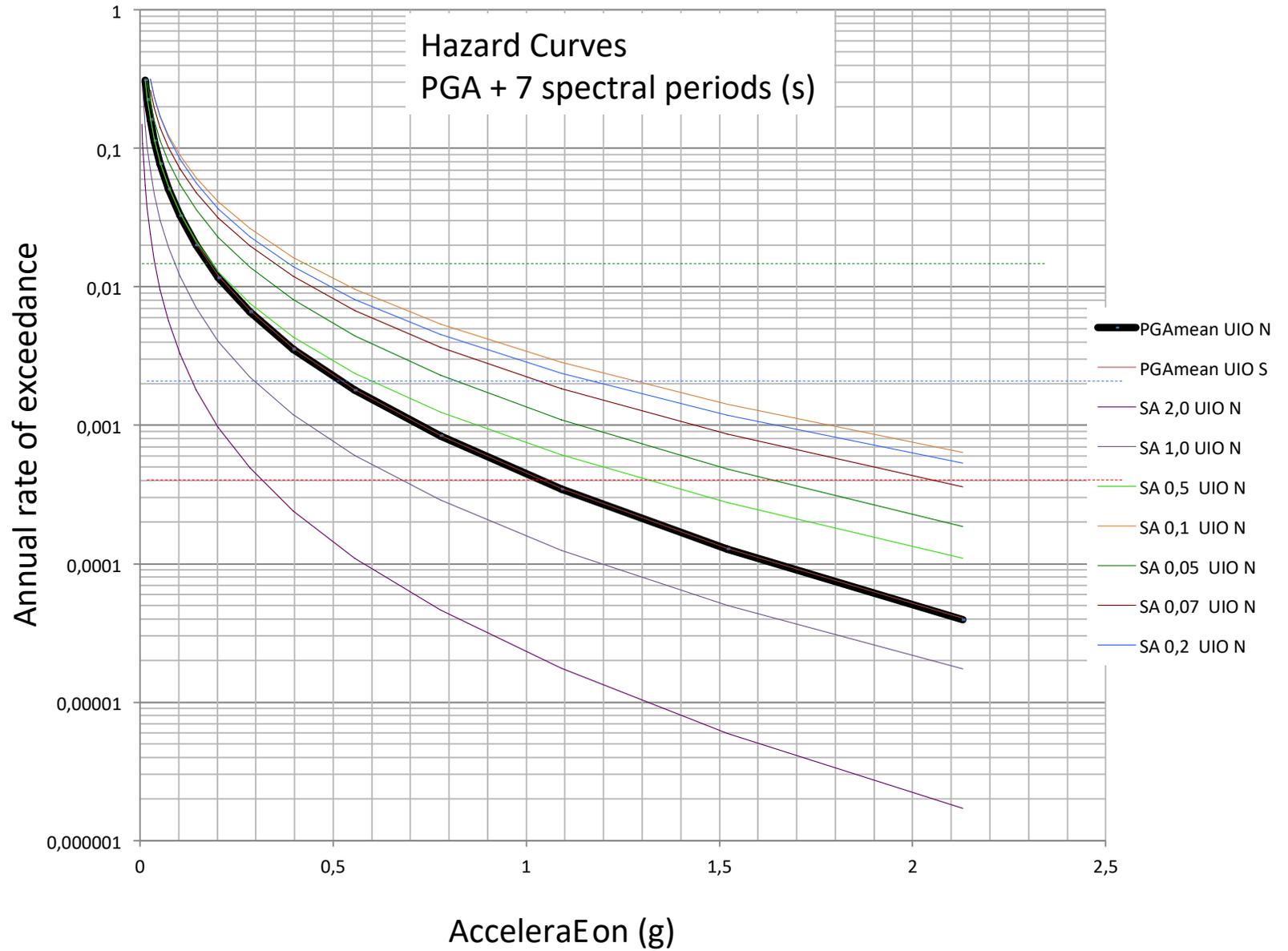


G-R based on the slip rate  
slip rate 5.3 mm/yr  
 $\alpha = 2e-5$

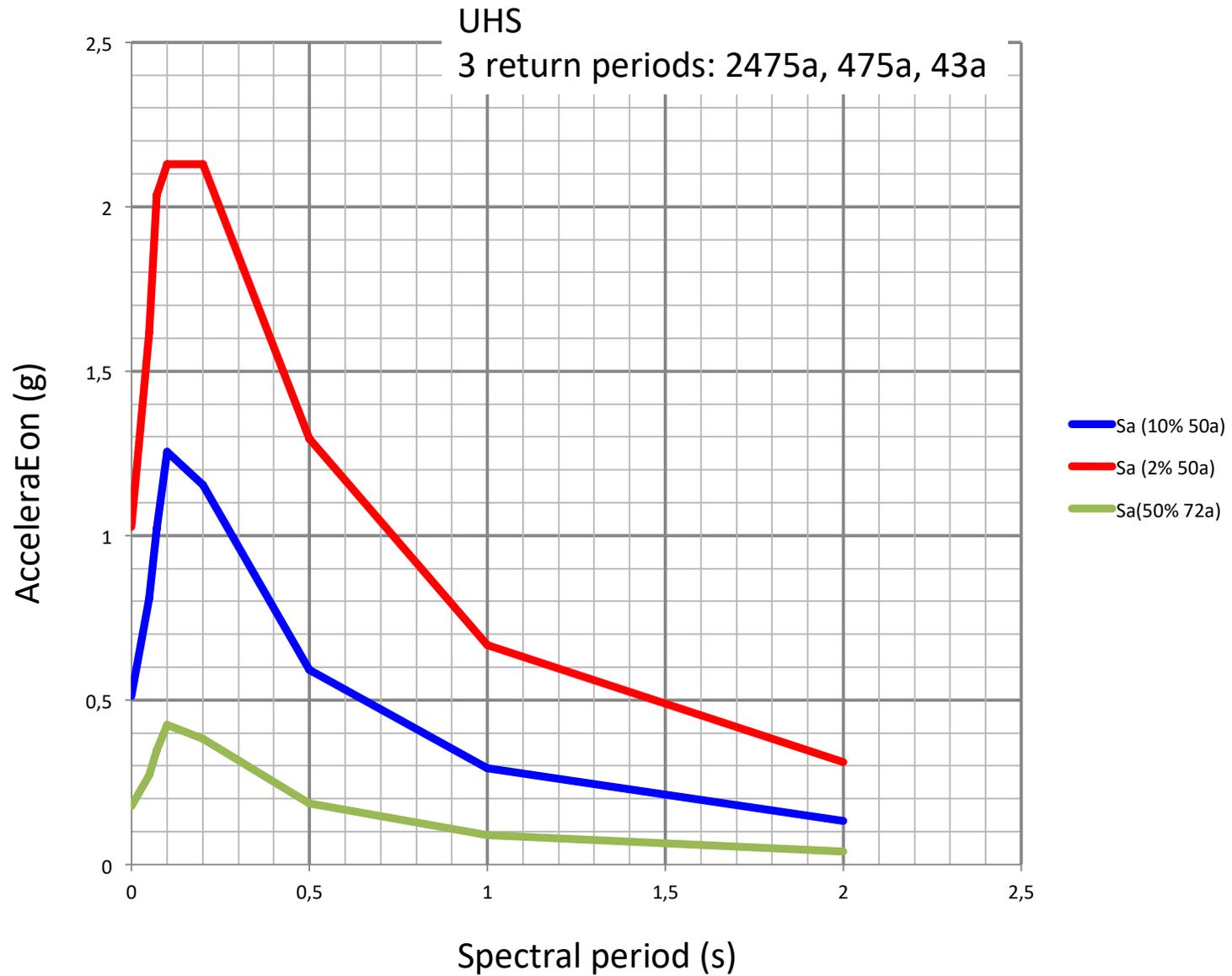


3 GMPEs: Bindi et al 2014, Boore et al. 2014, Cauzzi et al. 2014

# Curvas peligro en en roca para diferentes períodos estructurales en Quito



# Curvas de amenaza uniforme en roca para períodos específicos en Quito



# PSHA in Quito

Uncertainty on the hazard in Quito is large, ex for the PGA at 475 yrs

- Area model simple logic tree : 0.35-0.6g
- Area+Fault model, recurrence based on past EQs: 0.5-0.7g
- Area+Fault model, recurrence based on geodetic slip rate
  - 0% creep: 0.55-1.0 g
  - 50% creep (more probable) : 0.4-0.75g

Full exploration of uncertainties leads to a large range of possible values

How to improve the estimation of hazard:

- Improve the earthquake catalog
- Use more GPS measurements
- Perform trenches ?
- improve the selection of the GMPEs using more local data
- Single-station sigma + integration of site effects ?
- 3D ground-motion simulations: not yet possible (Quito basin not well-known)



Gracias