Topic 6

Selection of Ground Motion Prediction Equations (GMPEs) for Seismic Hazard in South America

Working Group for SARA's Topic 6| meeting Bogotá, Dec. 4-6, 2013

SUMMARY

Select, evaluate, and adjust Ground Motion Prediction Equations (GMPEs) for the three dominant tectonic contexts of South America: active crustal, subduction and intraplate regions.

Selection, evaluation and adjusment processes are based on comparison between local, regional or global GMPEs and **strong motion data recorded in South America**.

These tests require a standarized set of recorded response spectral amplitudes and associated metadata (information on the source and site) => compilation of a **South America's Strong Motion Database (SASMDB).**

WHAT IS A GMPE?

Ground-Motion Prediction Equation

- **Simple models** that predict response spectral amplitude (PGA, PGV, PSA) given source, site and path parameters. **Random variables**: distributions.
- Broad categories for different tectonic context: **Active Crustal Regions, Subduction Zones, Stable Continental Regions**
- Example Akkar & Bommer (2010) GMPE for active crustal regions:

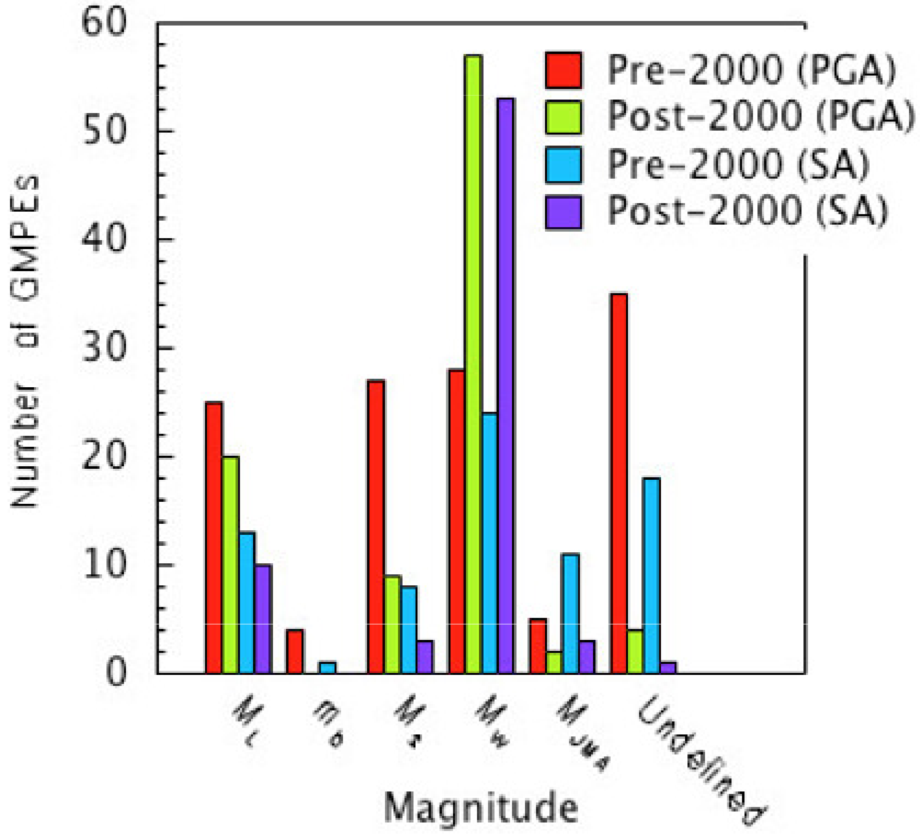
$$\log(PSA) = b_1 + b_2 M + b_3 M^2 + (b_4 + b_5 M)\log\sqrt{R_{jb}^2 + b_6^2} + b_7 S_S + b_8 S_A + b_9 F_N + b_{10} F_R + \sigma,$$

- Parameters: moment magnitude (M), Joyner-Boore distance (R_{jb}), site class (S_S, S_A), style-of-faulting (F_N, F_R)
- Coefficients b_1 to b_{10} determined by regression

MAGNITUDE SCALE

Various magnitude scales are used in GMPEs

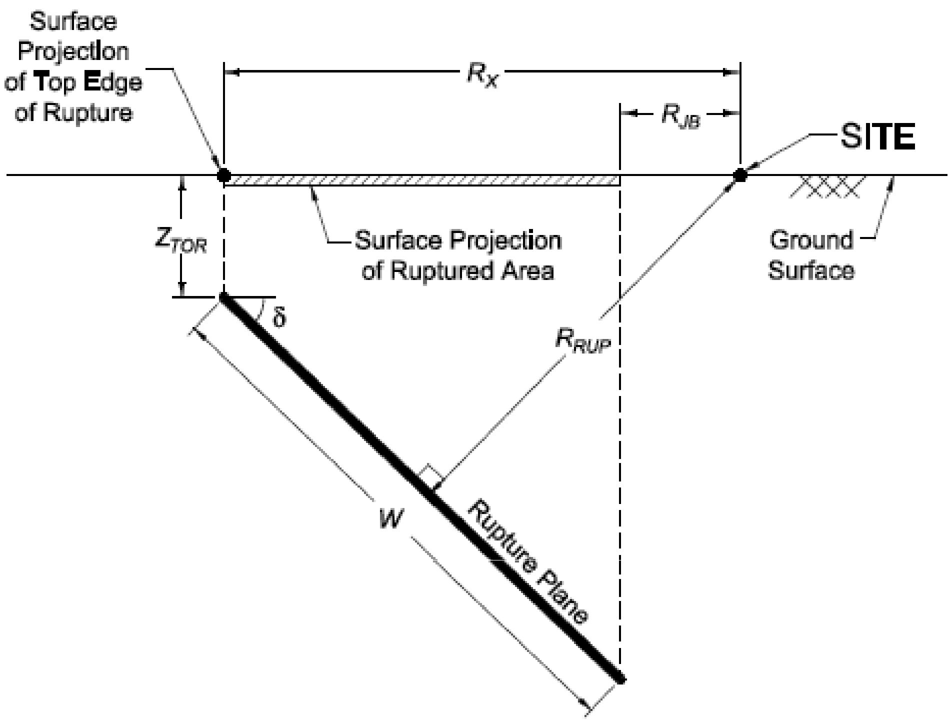
- The most recent GMPEs use moment magnitude
- In order to compare real data and GMPEs, the same magitude scale is needed
- If required use conversion relationships
- For each data, **all available magnitude measures** are needed
- **Link with Topic 4 earthquake catalogue**



TYPE OF DISTANCE

Different measures of distance are used in GMPEs

- Most PSHA code can handle the different types of distance
- For comparison with data, we **need all the distance measures for each recorded data**
- Conversions exist but lead to large uncertainties
- Need to know **fault extension** in order to compute the different measures
- **Link with Topic 4 Earthquake Catalogue**
- For small magnitudes (~<5), the fault extension is small compared to distance (R_{epi}~R_{jb}, R_{hypo}~R_{rup})



SITE PARAMETERS

Various site classifications exist

- Site classes: **Rock/Soil, NEHRP, EC8**. Discrete classification.
- Today's widely used parameter $\mathbf{v_{S30}}$ (average shear-wave velocity over the top 30 meters). Continuous classification.
- Warning: v_{S30} is only a **proxy for site effect**
- Other parameters, **frequency of amplification in H/V Fourier spectra**
- High-frequency attenuation parameter (**kappa**)
- **Need to collect all availbale information on the recording site**

Soil profile name	NEHRP class	EC8 class
Hard rock	A (v_{S30}> 1500 m/s)	
Rock	B (760<v_{S30}≤1500 m/s)	A (v_{S30}> 800 m/s)
Very dense soil & soft rock	C (360<v_{S30}≤760 m/s)	B (360<v_{S30}≤800 m/s)
Stiff soil	D (180<v_{S30}≤360 m/s)	C (180<v_{S30}≤360 m/s)
Soft soil	E (v_{S30}<180 m/s)	D (v_{S30}<180 m/s)

GEM

OTHER PARAMETERS

Many more Ztop, Z1.0, aftershock flag, hanging wall flag

- GMPEs from the NGA project introduced **more parameters**
- If possible these parameters should be included in the database
- If not some assumptions can be made (Kaklamanos et al., 2008)
- Horizontal component definition
- Style-of-faulting

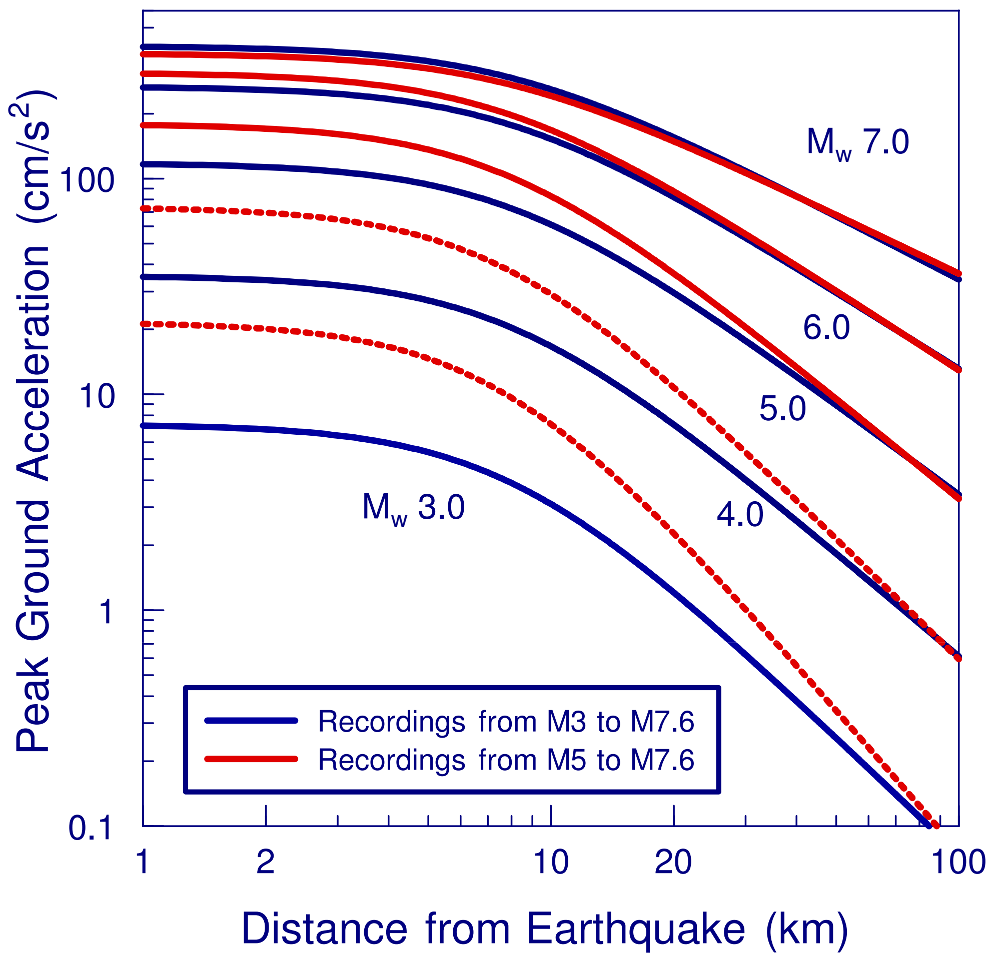
Table 1. Input parameters of the NGA models (modified from Kaklamanos and Baise, 2011)

Parameter	Model AS08	BA08	CB08	CY08	I08
Source parameters:					
Moment magnitude, M	•	•	•	•	•
Depth to top of rupture, Z_{TOR}	•		•	•	
Down-dip rupture width, W	•				
Fault dip, δ	•		•	•	
Style-of-faulting flag (function of rake angle, λ)	•	•	•	•	•
Aftershock flag (for models applicable to aftershocks)	•			•	
Path parameters:					
Closest distance to the rupture plane (rupture distance), R_{RUP}	•		•	•	•
Horizontal distance to the surface projection of the rupture (Joyner-Boore distance), R_{JB}	•	•	•	•	
Horizontal distance to top edge of rupture measured perpendicular to the strike (site coordinate), R_X	•			•	
Hanging wall flag	•			•	
Site parameters:					
Time-averaged shear-wave velocity over the top 30 meters of the subsurface, V_{S30}	•	•	•	•	
Depth to V_S = 1.0 km/s ($Z_{1.0}$)	•			•	
Depth to V_S = 2.5 km/s ($Z_{2.5}$)	•		•		
PGA (or *PSA*) on rock, as baseline for nonlinear site response	•	•	•	•	

MAGNITUDE RANGE

What is the minimum magnitude to consider?

- Most of the GMPEs are valid above M~5
- In order to properly reproduce the scaling with magnitude **need to include small events** (Bommer et al., 2007)
- Example NGA => NGA2 include more small magnitude events
- For small magnitude events the **metadata may be of poor quality**

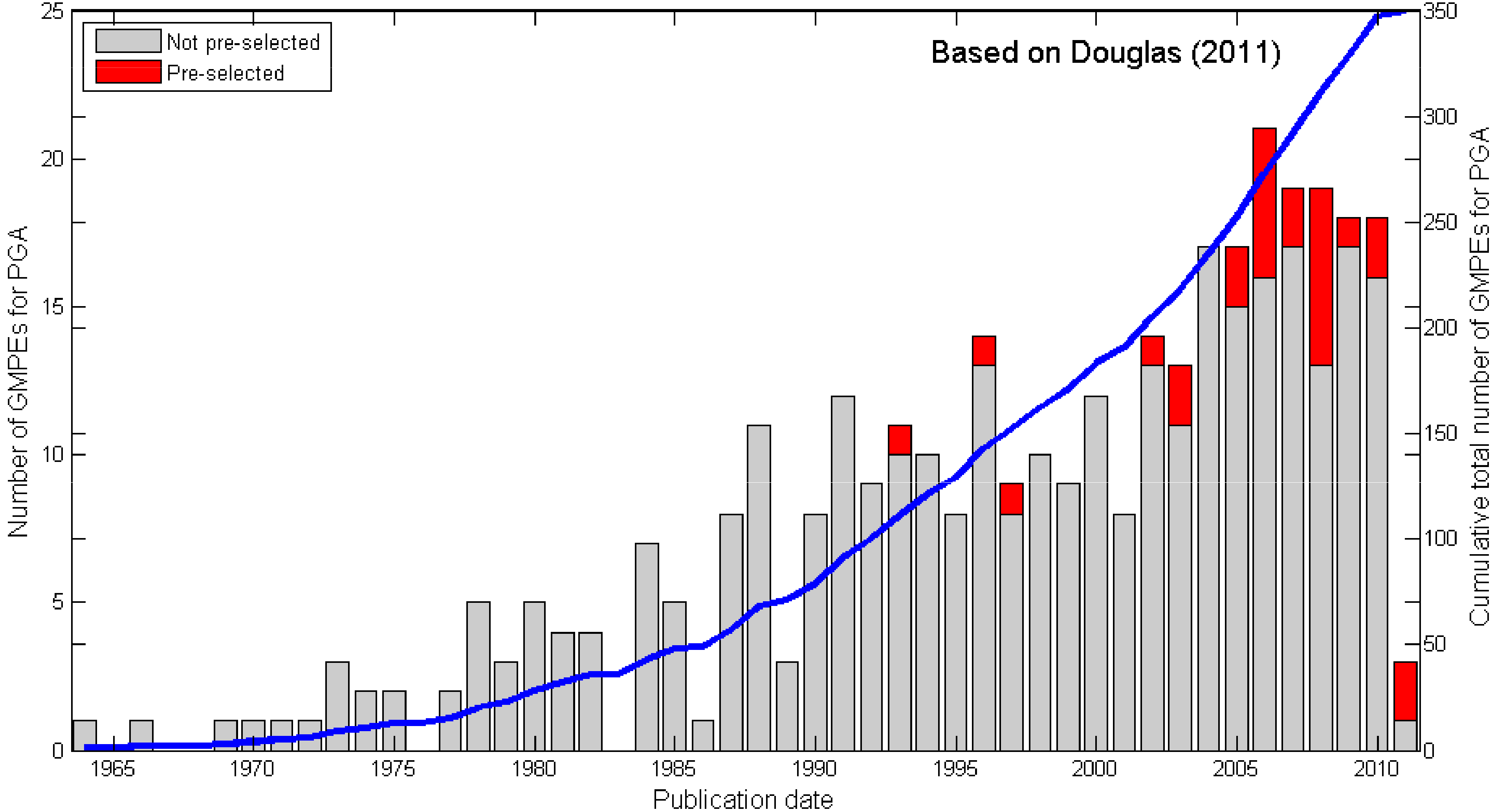


Bommer *et al.* (2007)

AVAILABLE MODELS

The number of GMPEs is rapidely increasing (Douglas, 2011)

- Need a scheme to transparently select GMPEs



SELECTION OF GMPES

How to select GMPEs?

- Need to capture the whole range of possible ground-motion for each period/magnitude/distance
- None of the single GMPE is expected to represent the full range
- **Use the smallest number of GMPEs that represent the full range of possible ground-motion** (PSHA logic-tree framework)
- **Pre-selection**, identify all available GMPEs and apply **exclusion criteria** (Cotton et al., 2006; Bommer et al., 2010)
- Review of **applicability range of GMPEs** (magnitude, distance, site conditions, period) => **fulfill requirements from PSHA analyst, PSHA tool (Openquake)?**
- **Adjustments** for parameter compatibility (if needed). Note that any adjustement will lead to an increase of uncertainty.
- Process used in GEM1 (Douglas et al., 2010, GEM Report) and SHARE (Delavaud et al., 2012)

EXCLUSION CRITERIA

Cotton et al. (2006), Bommer et al. (2010)

- Some criterias
  - From irrelevant tectonic regimes
  - Not published in international peer-reviewed journals
  - Published without dataset or adequate documentation
  - Superseded by more recent publications
  - Covering inappropriate frequency range for application
  - Has an inappropriate functional form
  - Has inappropriate regression method or coefficients
  - Uses inappropriate parameter definitions
  - Not appropriate for extrapolation in M-R space
  - Based on small dataset (empirical equations)
- In the practice some may be relaxed or strenghthened in order to end up with a manageable number of models

ADJUSTMENTS

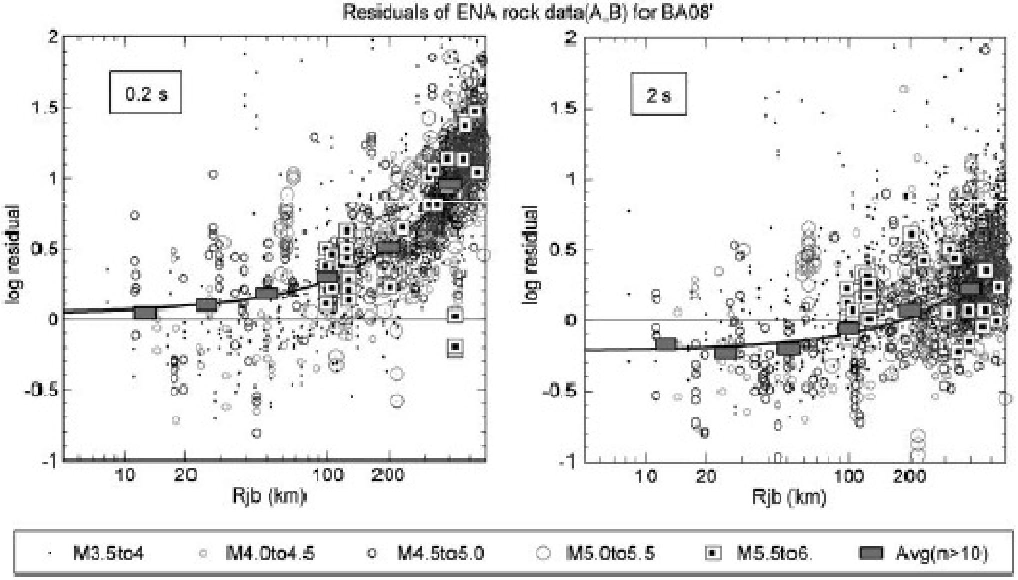
Adjustments may be required, warning leads to increased uncertainty

- Examples of parameter adjustments:
  - Magnitude scale: Propagate the uncertainty on the conversion to the GMPE uncertainty
  - Adjustment for common horizontal component definition (Beyer & Bommer, 2006)
  - Include style-of-faulting in GMPEs (Bommer et al., 2003)
- Adjustment to regionally adjust the GMPE. Reference approach (Atkinson & Boore, 2011)
- Site condition adjustment (v_{S30} and kappa, Van Houtte et al., 2011)

$$\sigma_{adjusted} = \sqrt{\sigma_{GMPE}^{2} + \left(\frac{\partial \log_{10}(Y)}{\partial M}\right)^{2} \times \sigma_{M}^{2}}$$

$$\left(\frac{Sa_i(T_j)}{Sa_{GM}(T_j)}\right)_{\text{median}} = \qquad (9)$$

$$\begin{cases} C_1 & T_j \text{ sec} \le 0.15 \text{ sec} \\ C_1 + (C_2 - C_1)\dfrac{\log(T_j/0.15)}{\log(0.8/0.15)} & 0.15 \text{ sec} < T_j < 0.8 \text{ sec} \\ C_2 & 0.8 \text{ sec} \le T_j \le 5.0 \text{ sec} \end{cases}$$



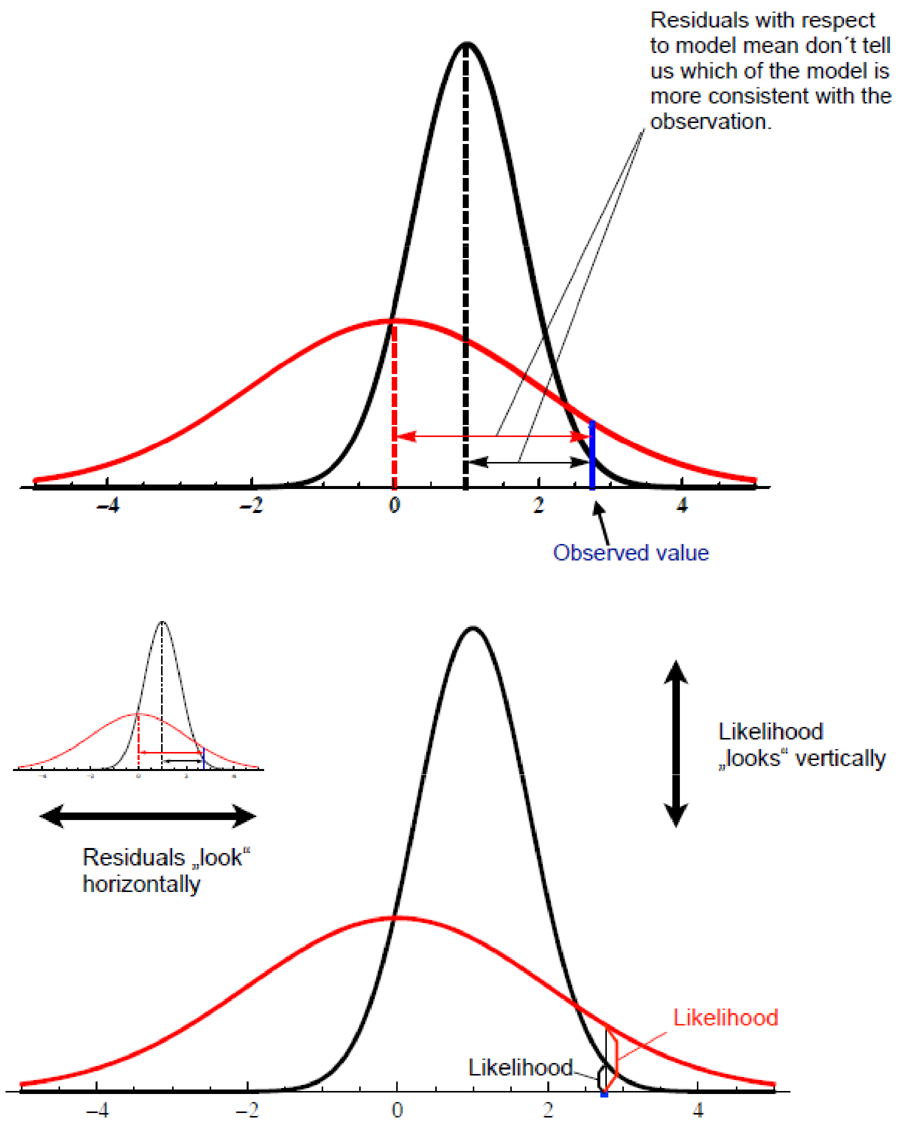
$$\log_{10}(F) = c(T) + d(T) \times R_{JB}$$

GEM

TESTING GMPES

How to evaluate relative performance of GMPEs and assign weights?

- **Expert judgment** (subjected to bias + defining weights scheme, see Scherbaum & Kuehn, 2010)
- Comparison with data. **Statistical analysis of the residuals**.
- Methods to determine a **data-driven ranking** of the GMPEs (Scherbaum et al., 2004, 2009)
- Use Expert judgment and ranking results in order to affect **weights** to be used within the logic-tree (example in Share Delavaud et al., 2012)

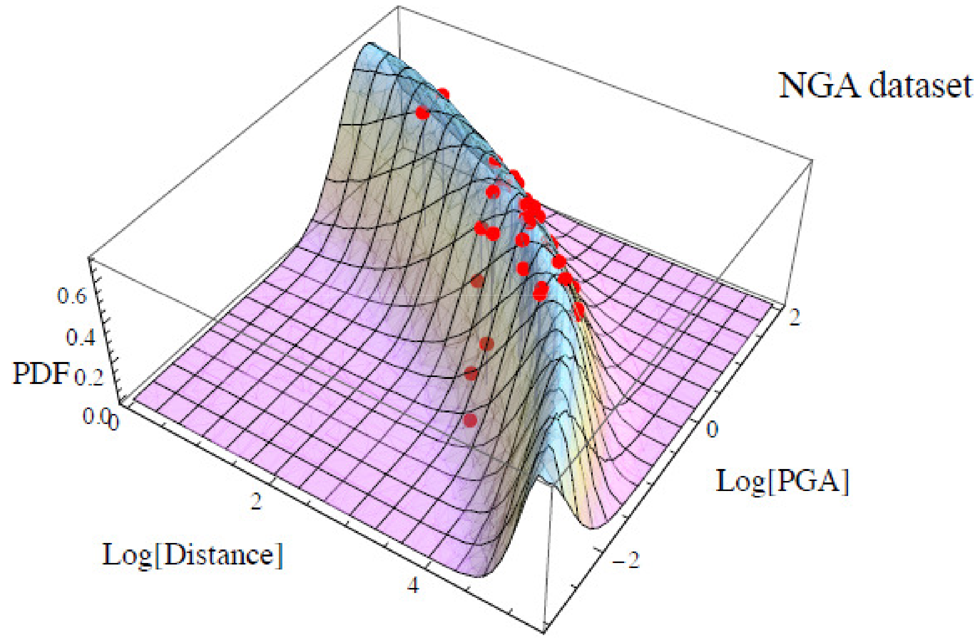


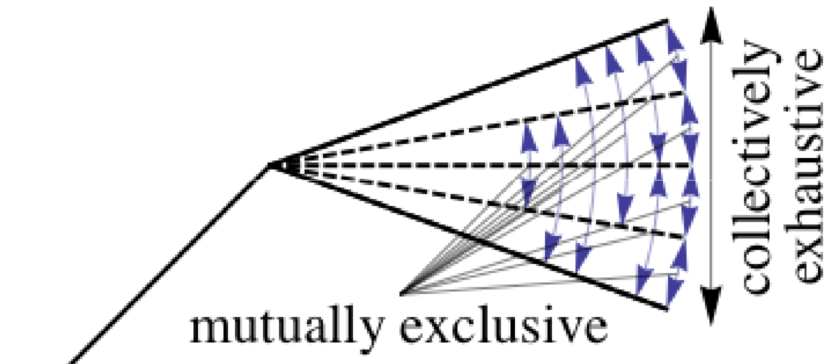
GEM

LOGIC-TREE

Tool to capture epistemic uncertainty

- Select the models to populate the different branches
- Aleatory uncertainty in included in each branch through the uncertainty given in the GMPEs
- Assign weights to each branch
- Going towards a node for median amplitude and another for aleatory uncertainty (single-station sigma, Bommer et al., 2013)





Details: Bommer, J. J. and F. Scherbaum (2008). The use and misuse of logic trees in probabilistic seismic hazard analysis, Earthquake Spectra 24 (4), pp 997-1009.

ACTIVITIES

WORKING GROUP CONFORMATION → DEVELOPMENT OF THE SOUTH AMERICA'S STRONG MOTION DATABASE (SASMDB) → SELECTION OF STRONG MOTION EQUATIONS

- **WORKSHOP I /II** (month 3)
  - Seismic Hazard and Strong Motion Fundamentals
  - Presentation of available data by each national group
  - Conceptual design of the South America's Strong Motion Database (SASMDB).
- **WORKSHOP III** (month 6)
  - Strong Motion Modelling (uncertainties, logic tree,..)
  - Advances in the SASMDB
- **WORKSHOP IV** (month 12)
  - Selected Ground Motion Predictive Equations (GMPEs) for SA.
- **WORKSHOP V** (month 15)
  - Selection and adjustment of GMPEs for SA
  - Logic-tree weights

IDENTIFIED POSSIBLE COLLABORATORS

COORDINATION
Stéphane Drouet
Ruben Boroschek
María Cristina Dimaté

ARGENTINA
INPRES, San Juan
Mario Bufaliza
Mario Araujo

ECUADOR
Instituto Geofisico EPN, Quito
Hugo Yepes

CHILE
Universidad de Chile
Ruben Boroschek
Luis Abdón Cifuentes

BOLIVIA
Observatorio San Calixto, La Paz
Percy Aliaga
Estela Minaya

PERÚ
Instituto Geofisico del Peru, Lima
Hernando Tavera

BRAZIL
ON, Rio de Janeiro
Stéphane Drouet
IAG/USP, São Paulo
Marlon Pirchiner
Marcelo Assumpção
UFRN, Naral
Jordi Julià
Joaquim Mendes Ferreira
UnB, Brasilia
Lucas Barros
Kate Tomé de Sousa

COLOMBIA
Univ. Nacional de Colombia, Bogotá
María Cristina Dimaté
Servicio Geológico Colombiano, Bogotá
Carlos Lozano

VENEZUELA
FUNVISIS, Caracas
Cecilio Morales
Herbert Rendón
Florian Olbrich
Universidad de Carabobo, Valencia
Adalgiza Pombo

WORKING GROUP CONFORMATION

To be completed rapidely

- Identification of human and institutional resources
- Agreement on activities, responsabilities and compromises
- Identify National Coordinators, teams
- Identify specific needs from each institution
- Identify links with other Topics and interlocutors

DEVELOPMENT OF THE DATABASE

Inventory of data and database design

- Records
  - Identify **strong-motion data** (time series) available in each country
  - **Minimum magnitude** considered?
  - Compute response spectra => **uniform processing**
  - Identify usable **frequency band**
- Associated metadata (from Topic 4?)
  - Event origin date and time, localization, magnitudes
  - Focal mechanism, fault plane dimensions
  - Station localization
  - Station characteristics (geology, geotechnical information, site classes, v_{S30}...)
- Database format
  - Simple .xls file (NGA)
  - Real database

PROCESSING OF THE RECORDS

Classical sequence for processing

- **Instrument correction**
- **Baseline adjustment**
- **Filtering** (avoid amplification of noise during integration):
  - Determination of **corner frequencies** (on record to record base, use Signal-to-noise ratio from Fourier spectra)
  - **Zero padding**
  - **Tapering** between padded and original traces
- **Integration** to velocity and displacement
- Determination of **PGA, PGV, PGD**
- Calculation of **response spectrum**
- Determination of **usable frequency bandwidth** of response spectrum

GMPEs selection

- Defing the **target tectonic contexts**
  - Active crustal region
  - Subduction zone
  - Stable Continental region
  - Do we need to consider Volcanic area?
- Define the **target ground-motion parameters**
  - PGA, PGV?, PGD?
  - Spectral accelerations (for which periods?, horizontal components?, vertical?)
- Pre-selection:
  - GEM1 Douglas et al. (2011)
  - Share Delavaud et al. (2012)
  - Additional GMPEs developed for South America
- Develop common tools to implement GMPEs. OpenQuake utilities?
- Develop common tools to implement the testing

GMPEs already included in OpenQuake

A number of GMPEs are already available

- Shallow Active Region
  - Abrahamson & Silva (2008)
  - Akkar & Bommer (2010)
  - Akkar & Cagnan (2010)
  - Boore & Atkinson (2008)
  - Cauzzi & Faccioli (2008)
  - Chiou & Youngs (2008)
  - Faccioli et al. (2010)
  - Sadigh et al. (1997)
  - Zhao et al. (2006)
- Subduction zone
  - Atkinson & Boore (2003)
  - Lin & Lee (2008)
  - Zhao et al. (2006)
- Stable Continental Region
  - Atkinson & Boore (2006)
  - Campbell (2003)
  - Toro (2002)

TESTING AND LOGIC-TREE

- Define the expert (one for each country?) a priori weights for the sets of GMPEs for each tectonic context
- What is hapening at the boundaries between regions (i.e. Boundary active/stable regions). See the OpenQuake tool.
- Compute the residuals and apply the statistical tests
- Results of the testing
  – Best-fitting GMPEs
  – Regional variations
- Update the weights according to the testing
- Release the final logic tree

LOCAL STRONG MOTION NETWORKS AND GMPEs

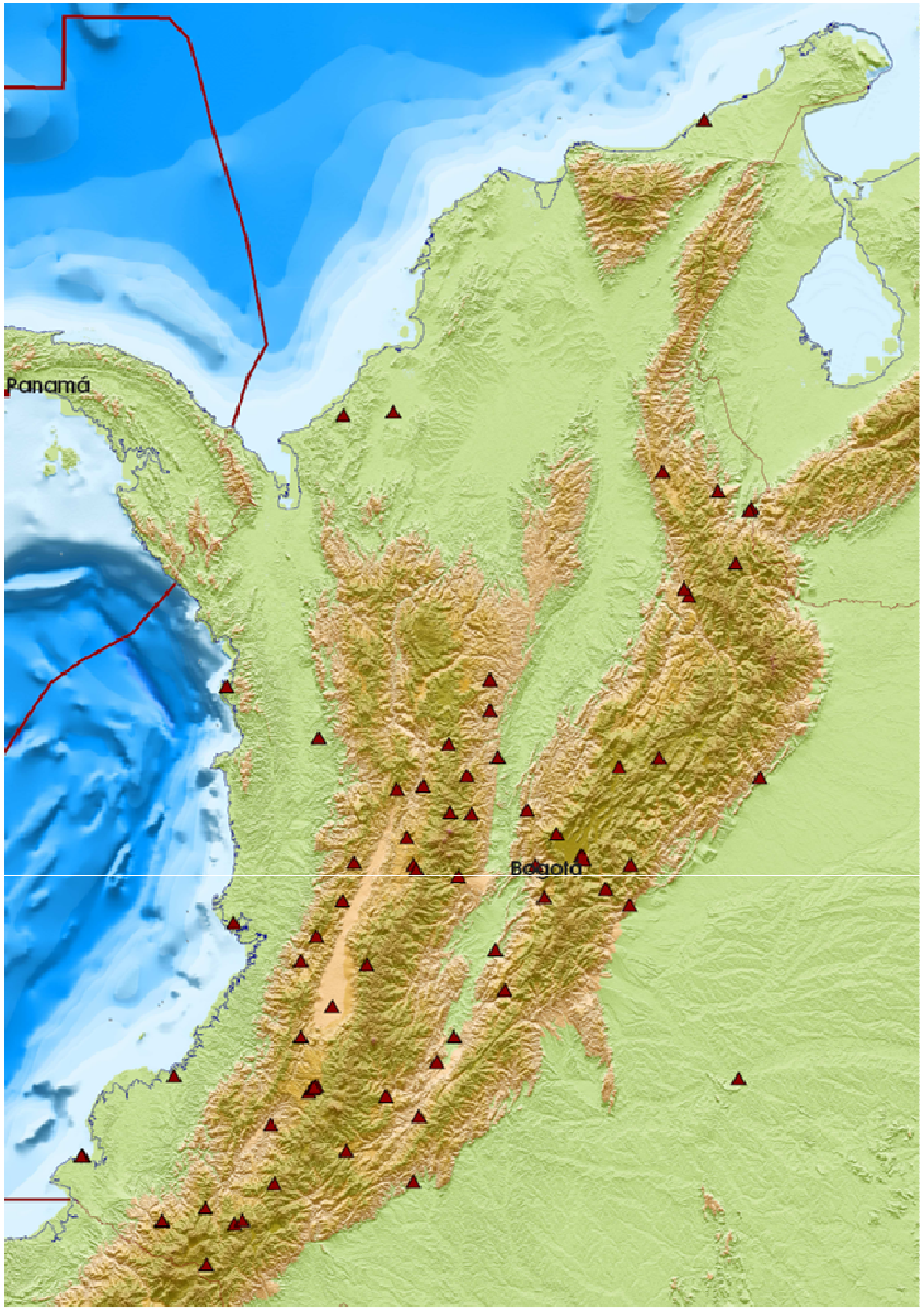
COLOMBIA

STRONG MOTION NETWORK

Currently (2008) has 78 stations, most of them recording on site.

6 transmit data to Bogota.

Information provided by M.L. Bermúdez, National Accelerographic Network, Colombian Geological Service, 2011.

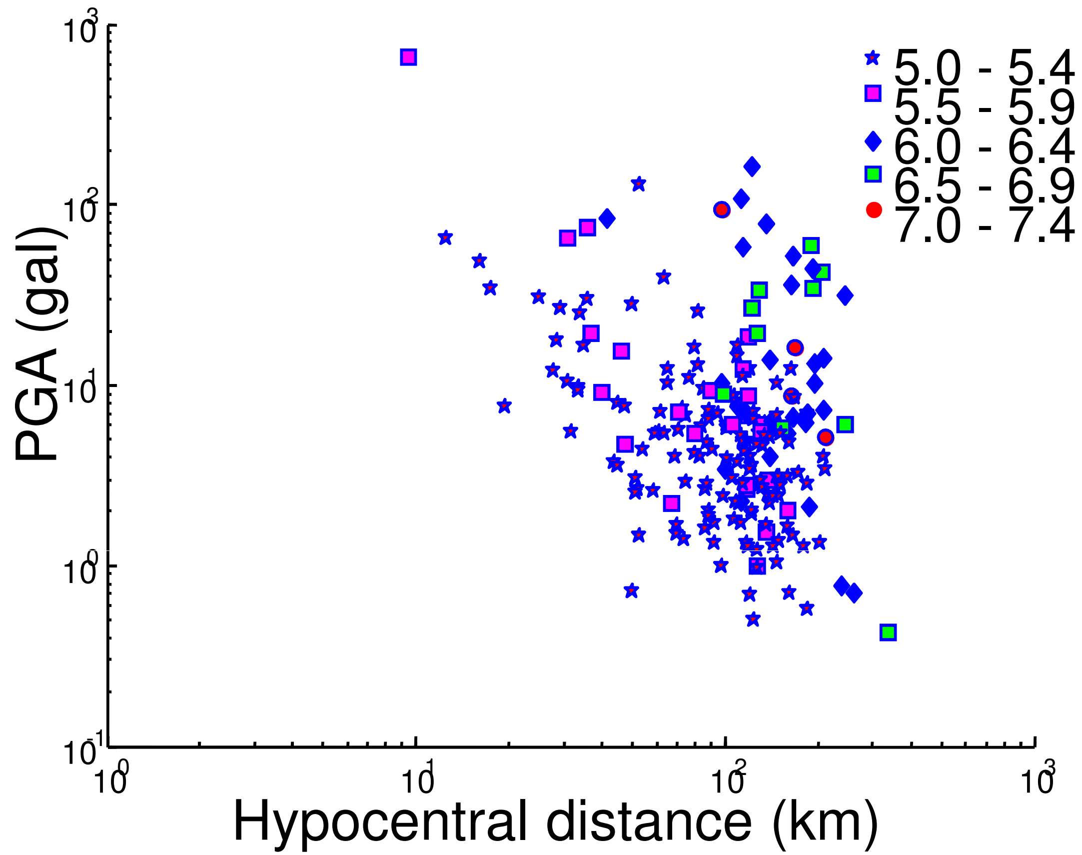


COLOMBIA

DATA AND METADATA AVAILABLE

- 1343 events recorded (2008)
- Few truly strong motion
- 193 earthquakes with ML ≥ 5.0
- Few recorded on rock

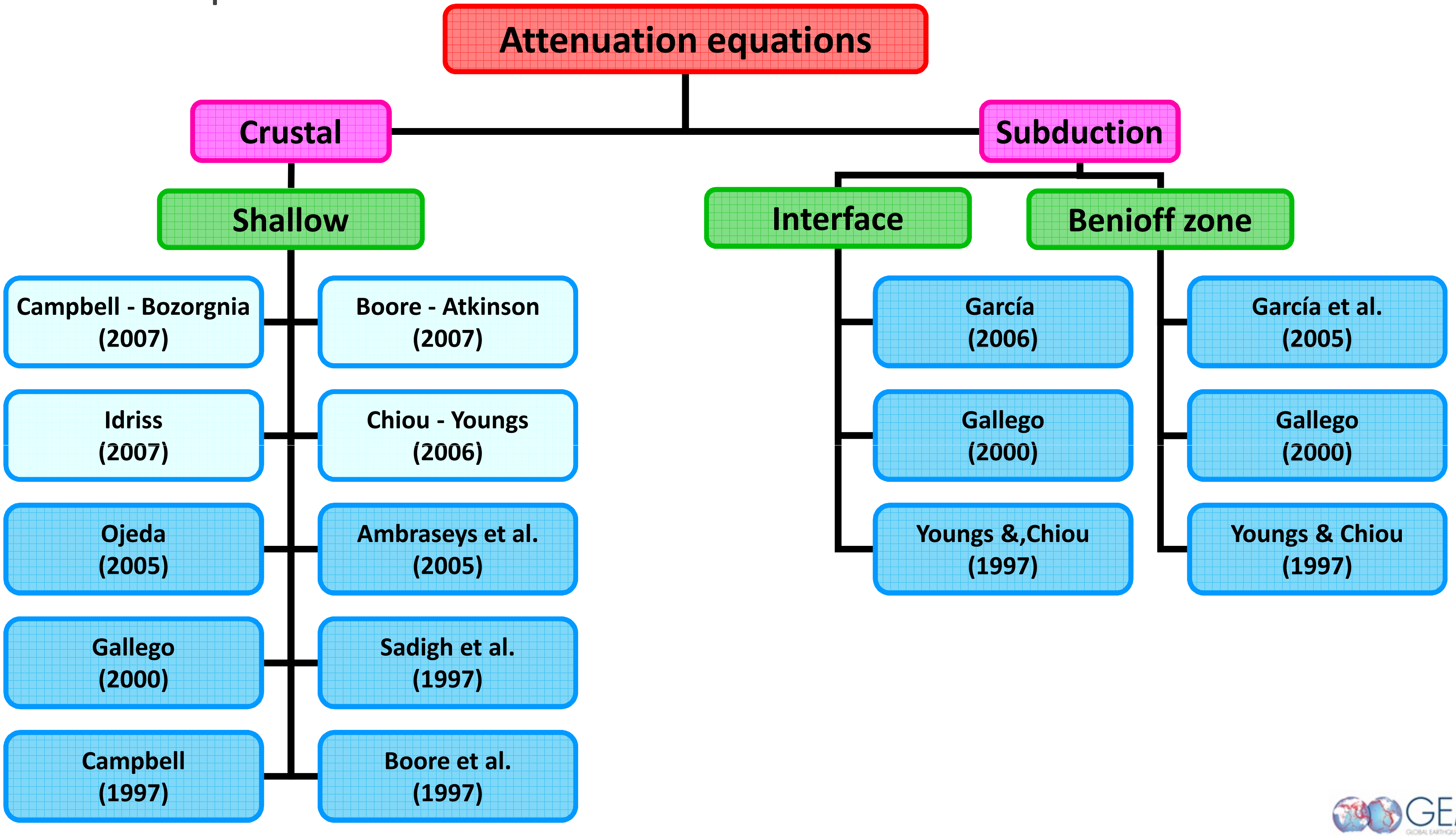
STRONG MOTION DATA DISTRIBUTION



COLOMBIA

GROUND MOTION PREDICTION EQUATIONS FOR THE 2011 NATIONAL HAZARD MAP

- Test of attenuation equations from international literature supported on most complete data bases



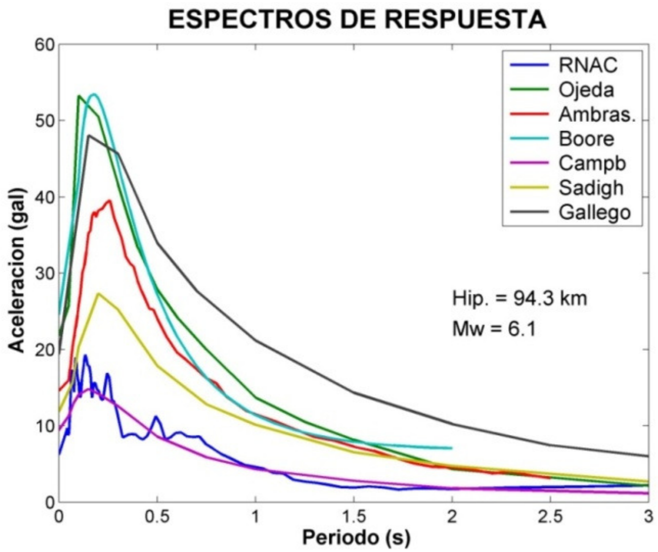
COLOMBIA

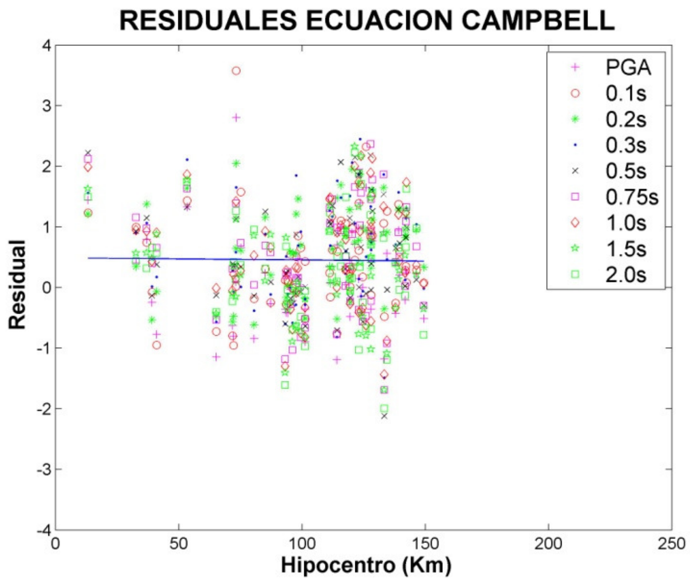
METHODOLOGY TO SELECT BEST FITTING EQUATIONS

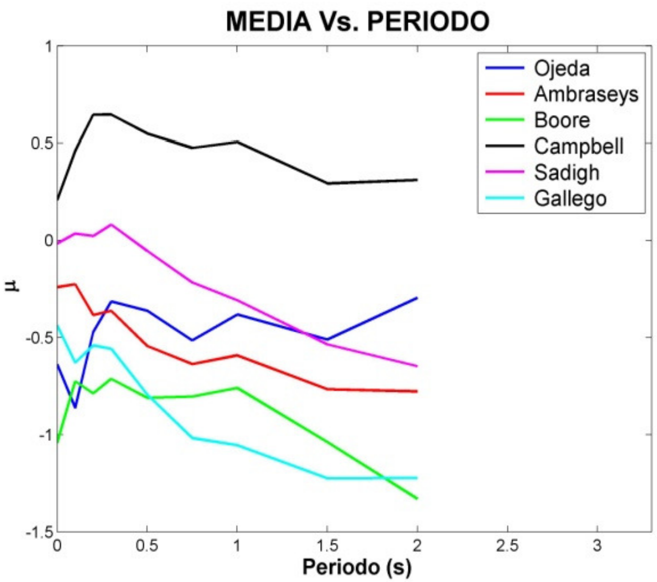
METHOD	ACCELEROGRAMS
Areal difference between Observed and Calculated Spectra	Área Estimada – Área Observada
Residual analysis	$Residual = \ln(\frac{SA_{obs}}{SA_{est}})$
Slant analysis	$\mu = \frac{1}{N}\sum_{i=1}^{N}\ln\left(\frac{SA_{obs}}{SA_{est}}\right)$
Standard deviation analysis	$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\ln\left(\frac{SA_{obs}}{SA_{est}}\right)^2}$

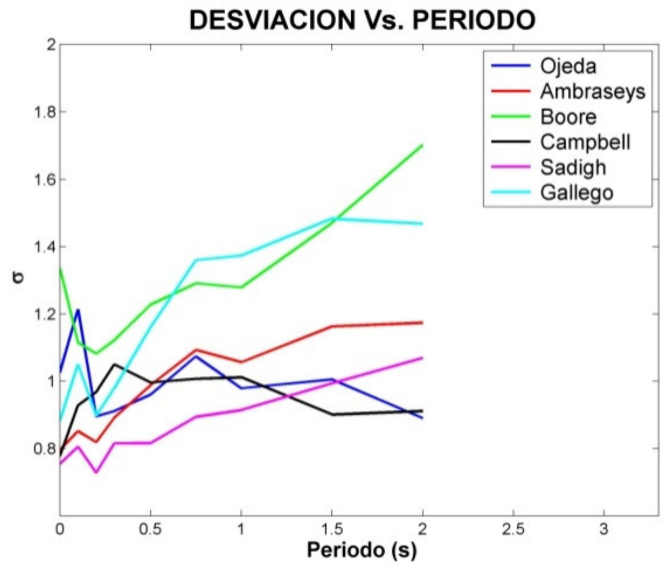
COLOMBIA

Comparative analysis





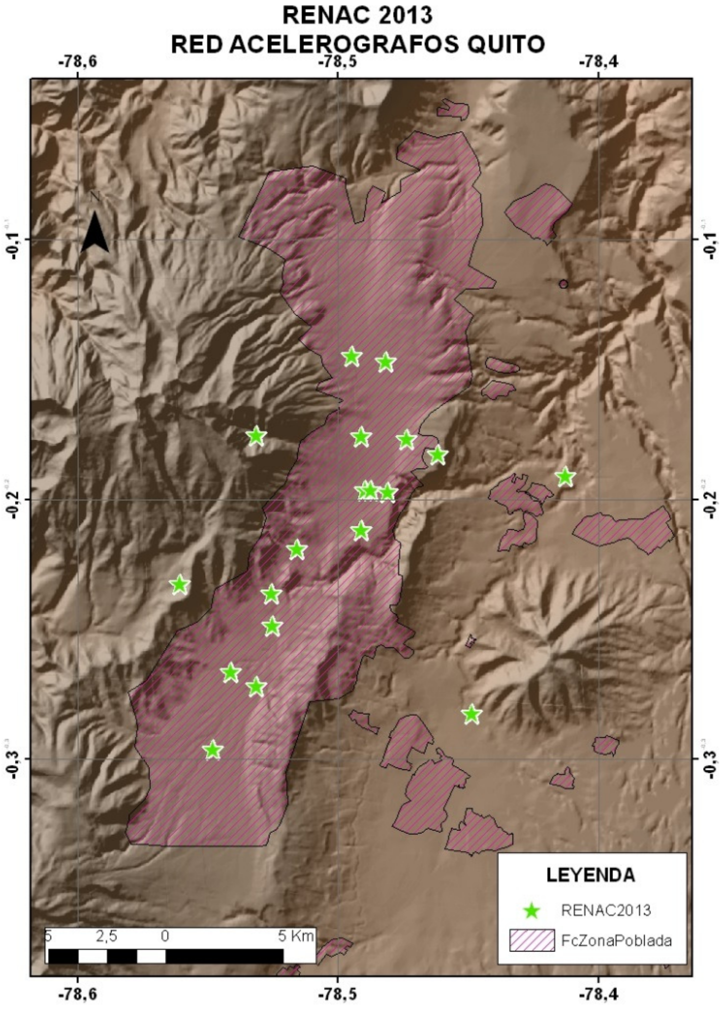


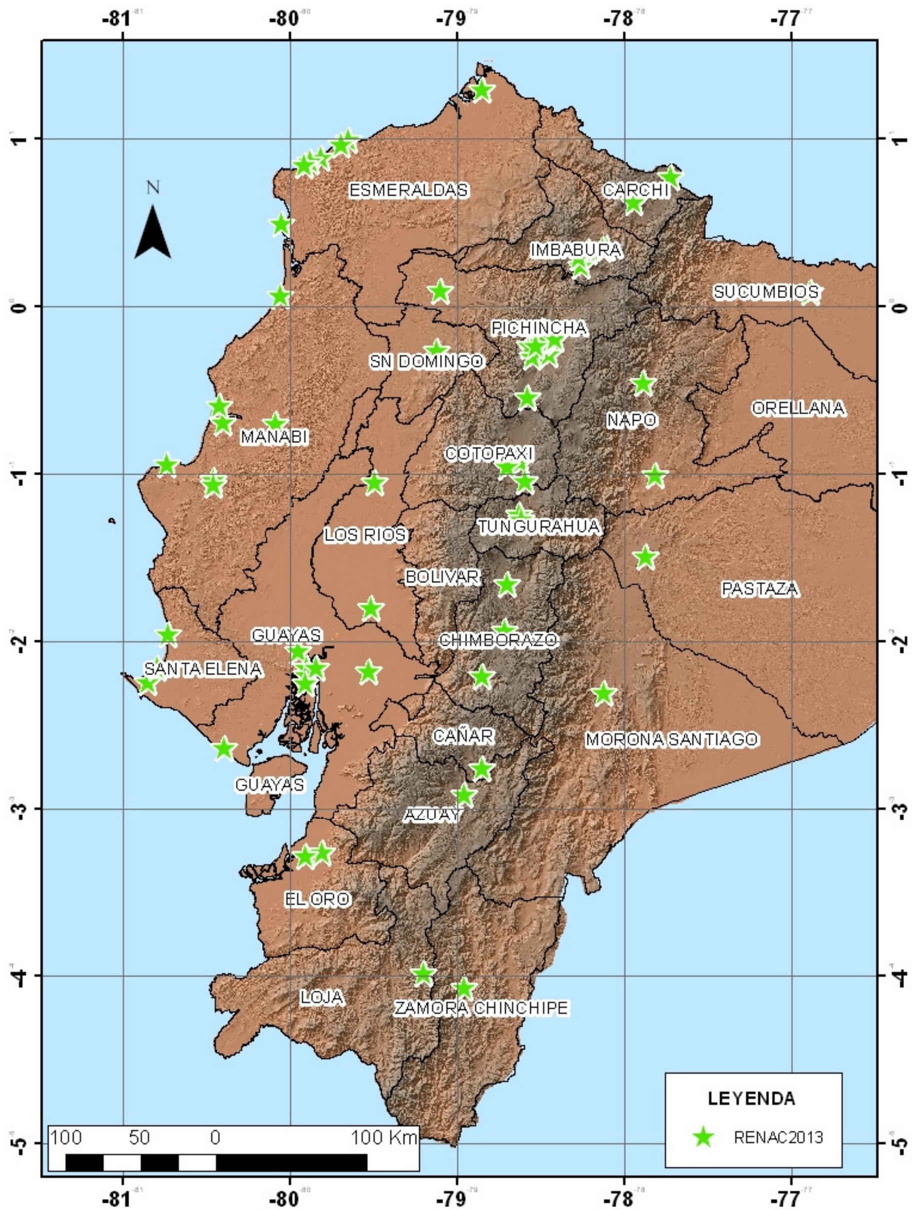


ECUADOR

RENAC

- 56 stations
- 20 stations in Quito





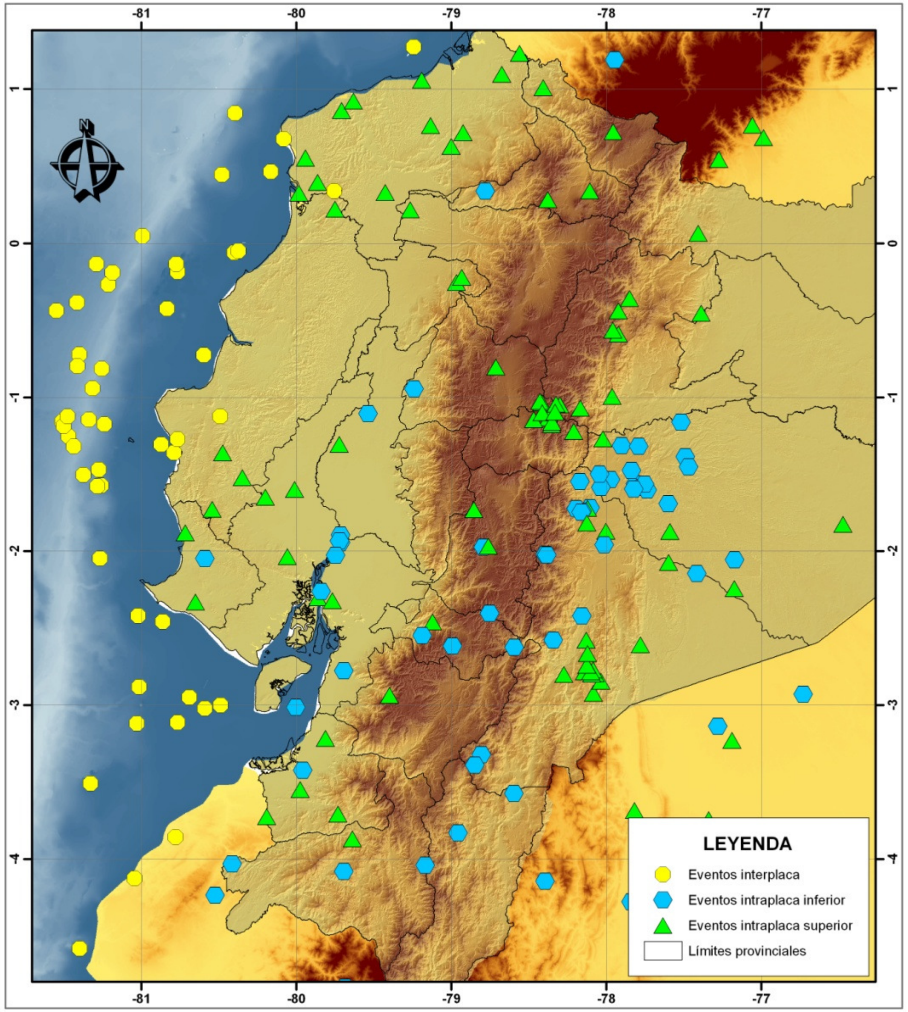
GEM

ECUADOR

GMPEs

- 25 BB stations and 7 accelerometers
- Events with m_d>4
- Fuente se considera puntual.
- V30s = 360 – 760 m/s para la costa
- V30s = 760 -1500 m/s para la sierra (NEHRP, 1993).

ZONA	FUENTE GENERADORA	EVENTOS	REGISTROS
1	Subducción, eventos interplaca	68	248
2	Subducción, eventos intraplaca	51	468
3	Corticales, eventos intraplaca	60	492
	TOTAL	179	1212



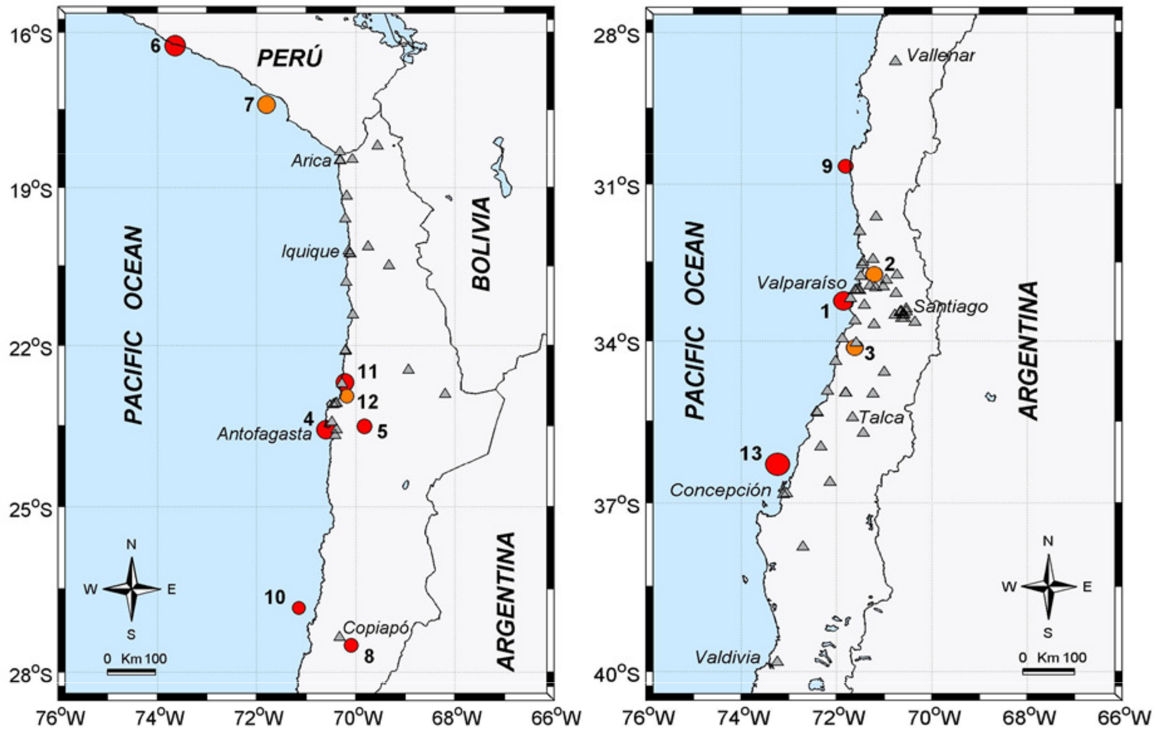
ECUADOR

GMPE	Límites de magnitud	Rangos de frecuencia	Distancia máxima Fuente-sitio	Región de origen de los datos	Zona de aplicación
Chiou and Youngs (2008) (CY08)	4.0–8.0	0.1–100.0	200 (R_{RUP})	Mundiales corticales	3
Campbell y Bozorgnia (2008) (CB08)	4.0–8.0	0.1 - 10.0	200 (R_{RUP})	Mundiales corticales	3
Atkinson y Boore (2003) (AB03)	5.0-8.3	0.1-100.0	550 (R_{jb})	Cascadia Subducción	1 y 2
Zhao et al. (2006) (ZAE06)	4.9-8.3	0.2-20.0	300(R_{Rup})	Japón Subducción	1 y 2

CHILE

Data Base from Depart. De Ingenieria Civil, Univ. Do Chile

- Public data base 1994-2010
- Processed time series
- Station information for 11 stations
- Interplate subduction events used in Contreras & Boroschek (2012)



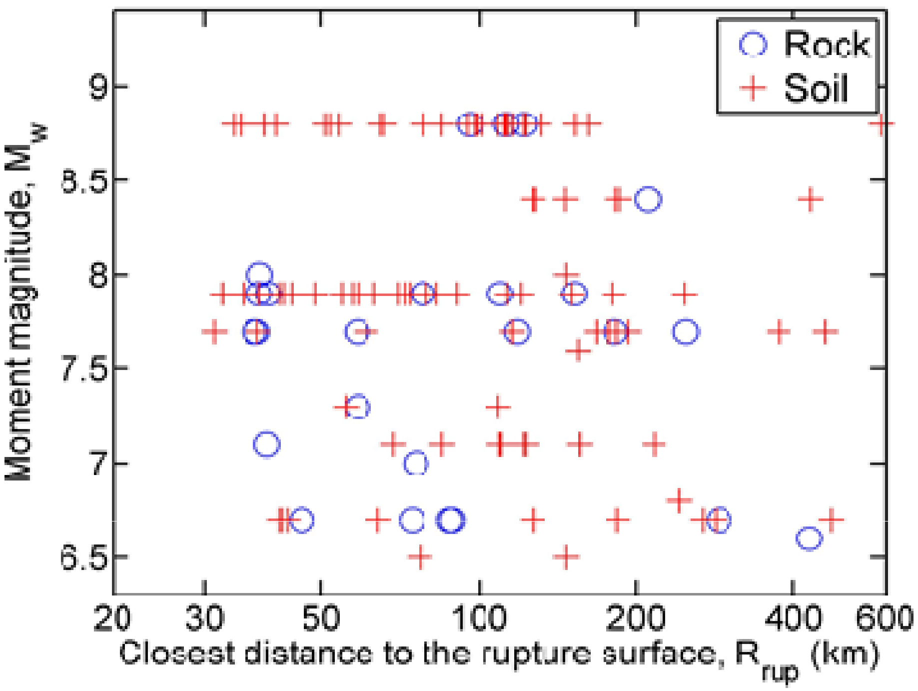
Map of north and central Chile showing epicenters (listed circles) of earthquakes used in this study. Red circles correspond to main events and orange circles correspond to aftershocks. The circles size is proportional to the Magnitude. Grey triangles represent the strong motion stations.
Reference: V. Contreras & R. Boroschek Strong Ground Motion Attenuation Relations for Chilean Subduction Zone Interface Earthquakes. 15 World Conference on Earthquake Engineering.

GEM

CHILE

Distribucion de Eventos para GMPE (Contreras & Boroschek, 2012, 15WCEE)

- Subduction zone interface events



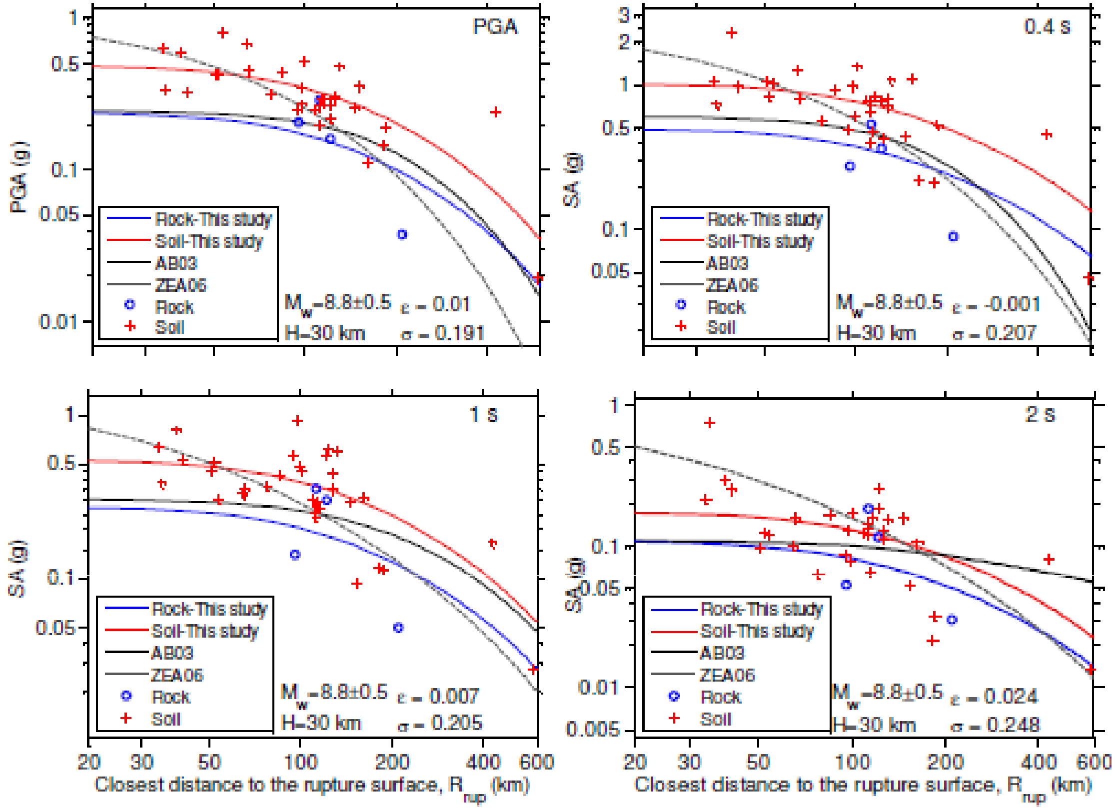


Figure 4.3. Comparison between predicted and observed accelerations (Mw=8.8±0.5, H=30 km). The mean of residuals (ε) and the standard deviation of residuals (σ) for the data shown are indicated.

Database for subduction events

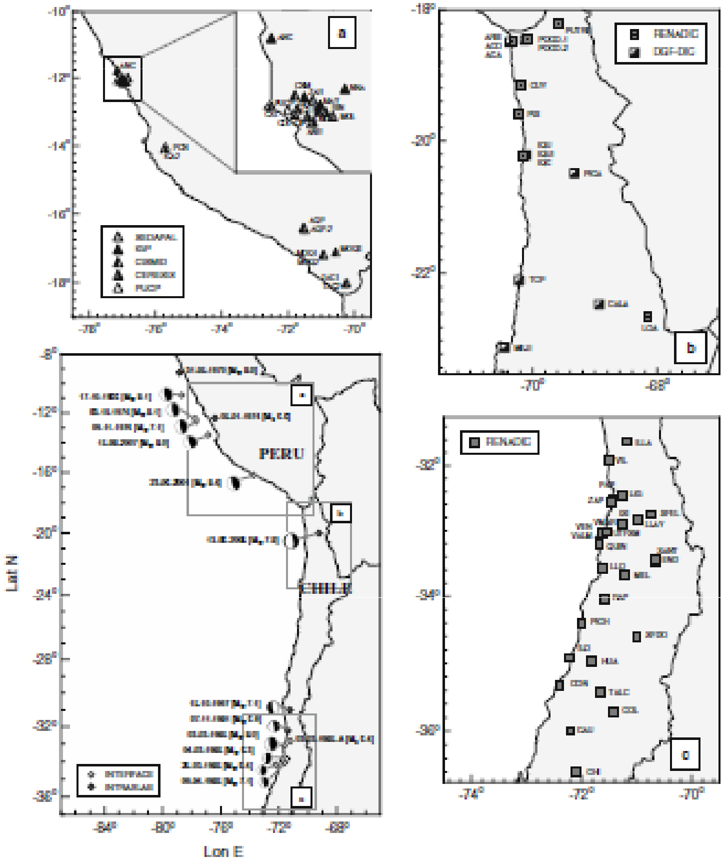
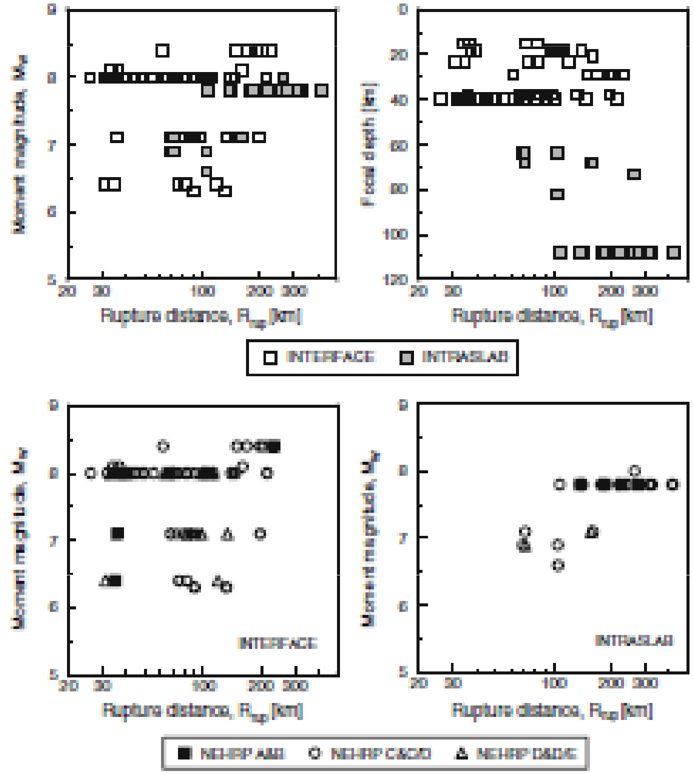


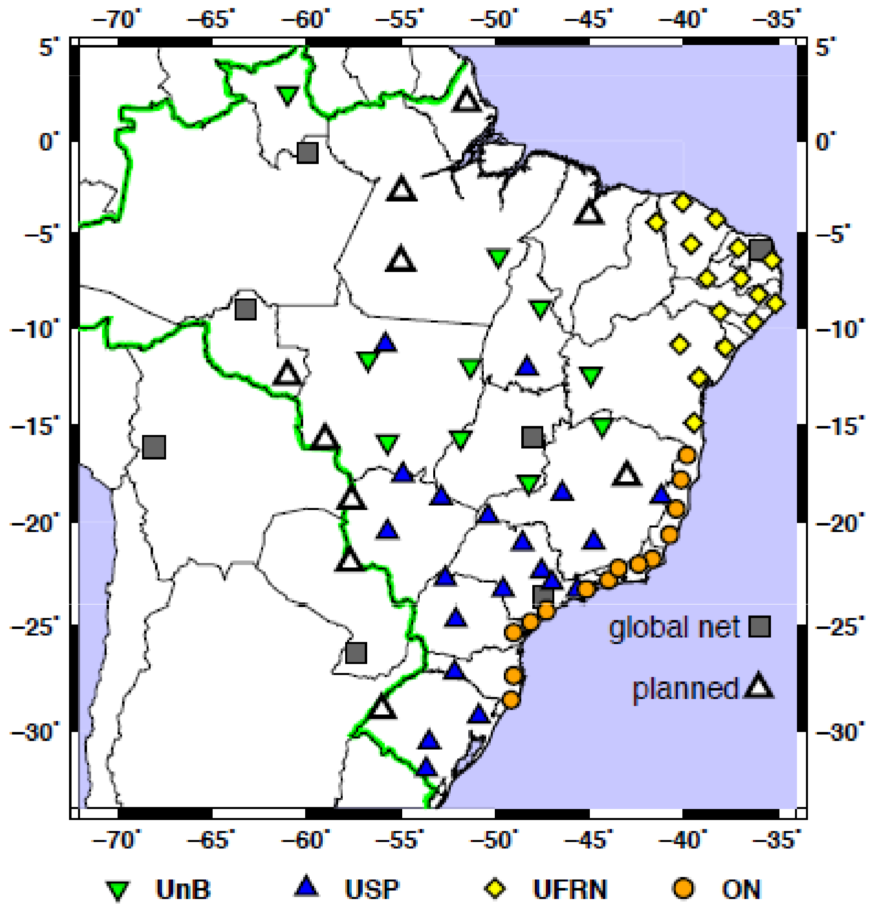
Fig. 2 Location of the strong-motion stations used in this study. The panels show the stations located in a Central and Southern Peru; b Northern Chile and c Central Chile. The locations and focal mechanisms of the events contributing data to this study are also shown



BRAZIL

Rede Sismografica Brasileira

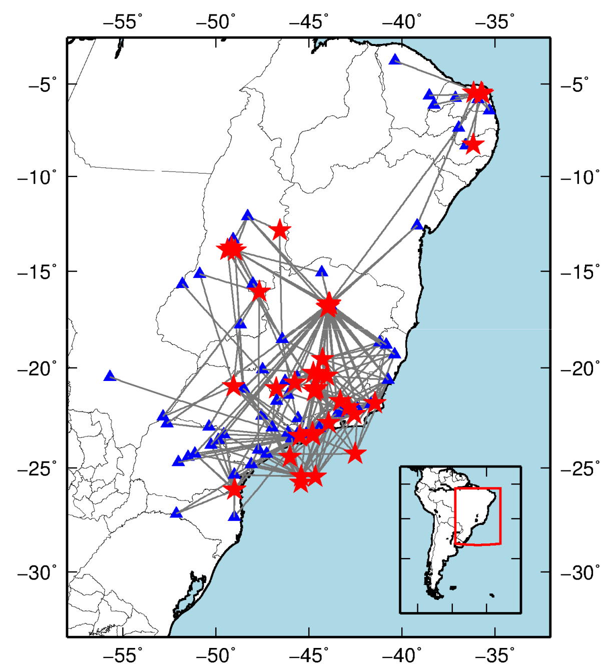
- Development during the last 3 years
- 4 institutions
  - IAG/USP, São Paulo
  - ON, Rio de Janeiro
  - UFRN, Natal
  - UnB, Brasilia
- About 60 broadband stations distributed all over Brazil
- Most of the stations are already installed
- Real time communication in progress

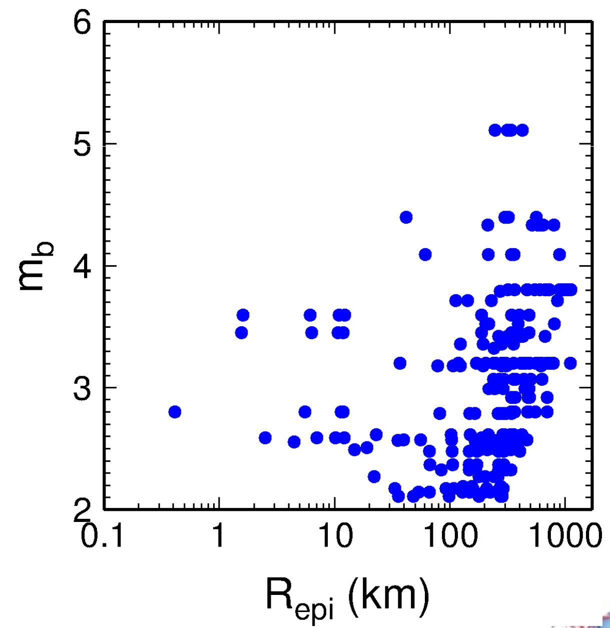


BRAZIL

Data and Metadata available

- Earthquake catalogue from IAG/USP including magnitude m_b or m_R (Assumpção, 1983)
- 42 events with m_R between 2 and 5 and recorded at R_{epi} from 0.5 to 1100 km
- Some metadata are estimated through inversion of Fourier spectra (moment magnitude, site characteristics) (Drouet & Assumpção, 2013)
- Response spectra are computed from velocity data converted to acceleration (tests with colocated sensors broadband/accelerometric may be interesting)
- There are more recorded data but still not available

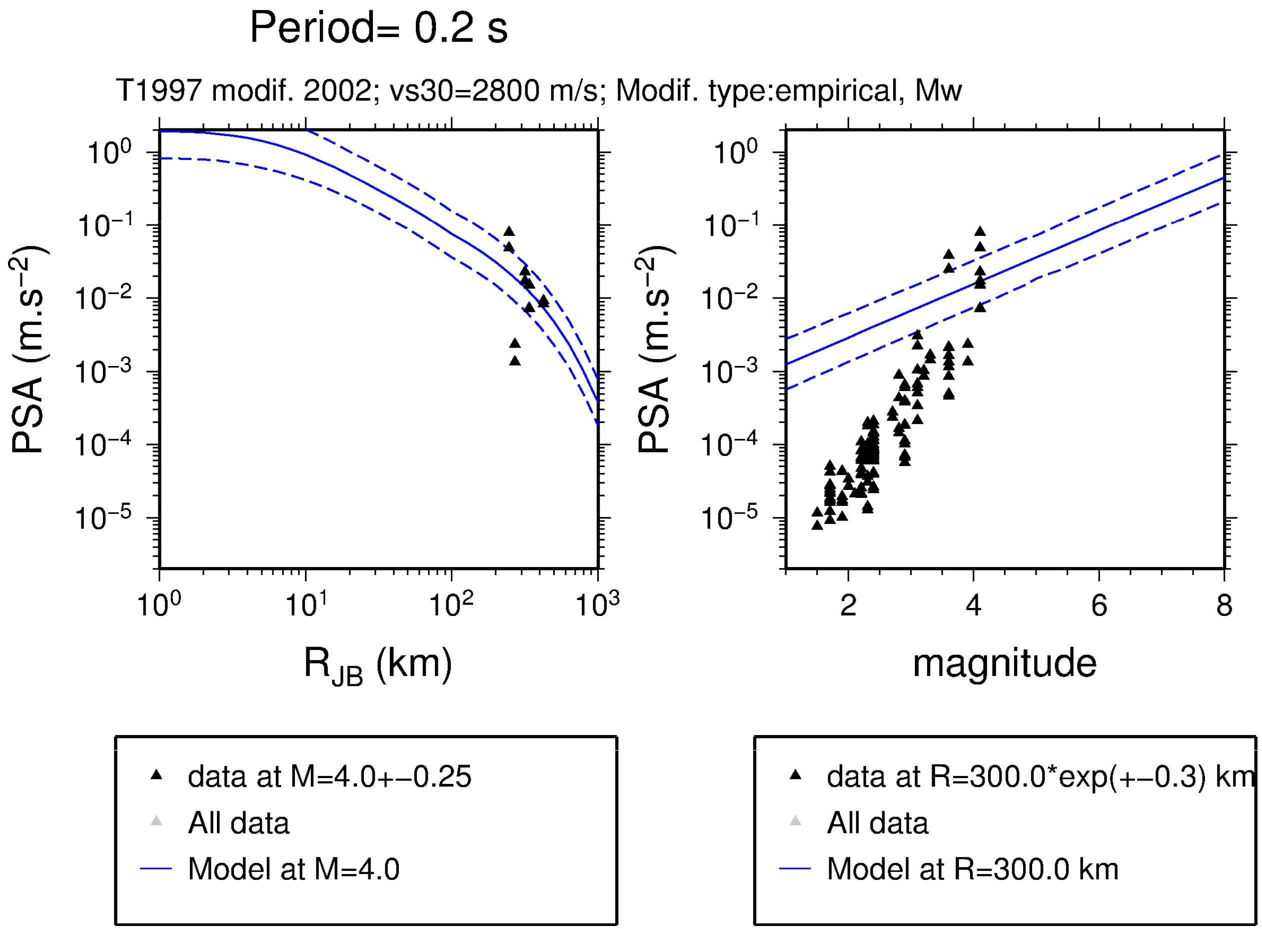




BRASIL

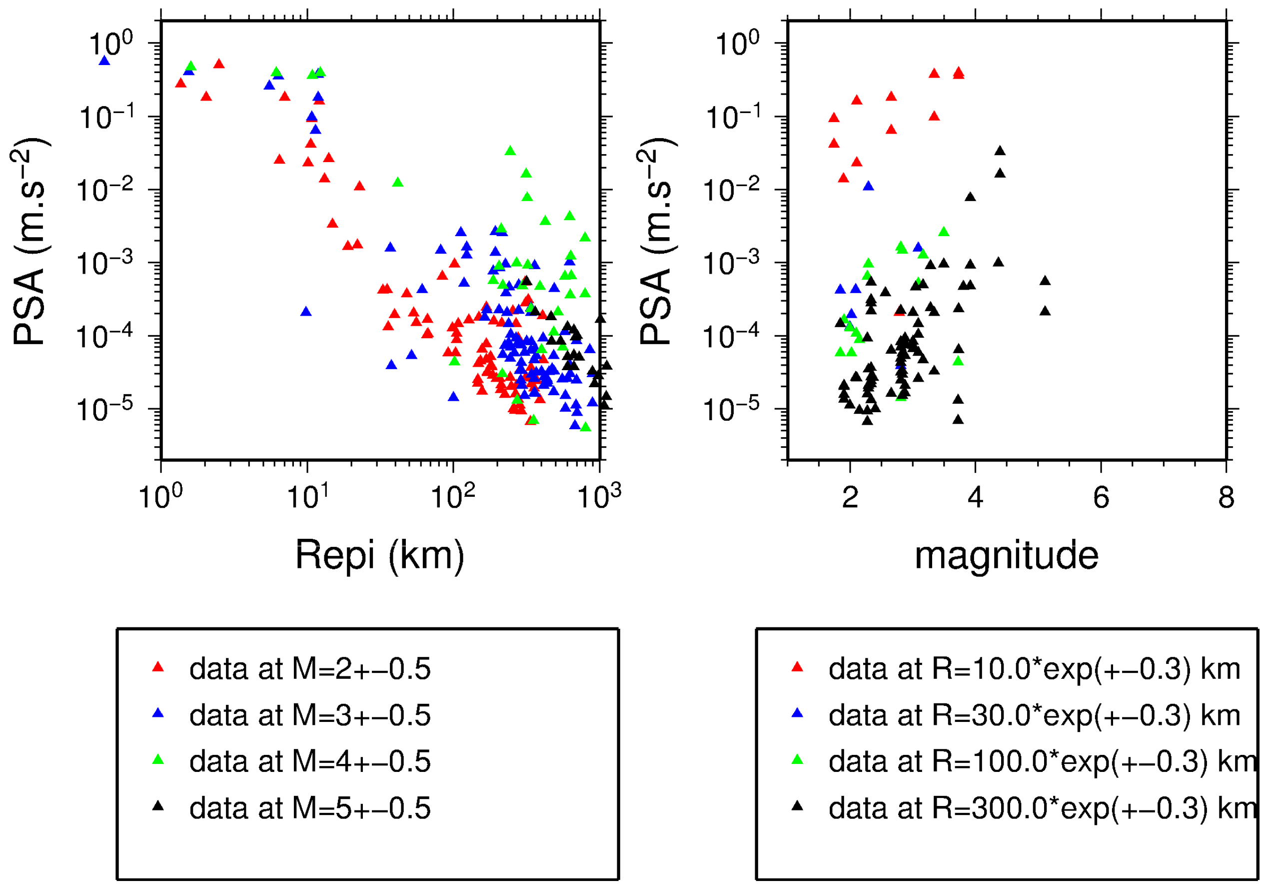
GMPEs

- The Toro et al (1997) equation is used in Brazil because it can use m_b as input magnitude
- This GMPE is valid for magnitudes greater than 5. Is comparison with recorded data meaningfull? What does this tell us about the ability to predict stronger ground motion?



GEM

Period= 0.01 s



10^0
10^−1
10^−2
10^−3
10^−4
10^−5
PSA (m.s^−2)
10^0
10^1
10^2
10^3
Repi (km)
2
4
6
8
magnitude
data at M=2+−0.5
data at M=3+−0.5
data at M=4+−0.5
data at M=5+−0.5
data at R=10.0*exp(+−0.3) km
data at R=30.0*exp(+−0.3) km
data at R=100.0*exp(+−0.3) km
data at R=300.0*exp(+−0.3) km

TOOLS AND DATA

AVAILABLE

- OpenQuake Platform. http://www.openquake.org
- Global results provided by GEM (Global GMPEs.component)

ADDITIONALY REQUIRED

- Commitment on sharing local databases
- Strong motion database platform development
- GMPEs supported by local data and documented procedures

ESCENARIO DE SISMICIDAD	FUENTE	MODELOS DE ATENUACION	
		OPCION 1	OPCION 2
CORTICAL	Tipo 1	Campbell (Reverse/Strike/General)*	Sadigh (Reverse/Strike/General)
	Tipo 3	Campbell (General)*	Sadigh (General)
INTERFASE	Tipo 2	Campbell (Reverse)*	Youngs (Superficial)
INTRAPLACA/PROFUNDA	Tipo 2	Garcia	Gallego (Subduccion)
Nota: (*) Ecuación ajustada según registros disponibles por la RNAC.			