Seismic hazard reevaluation for Angra NPP site

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Geology and Seismology
Characteristics of the Region

Initial studies by Weston Geophysical Research, 1970s -'80s – site characteristics – for Central Nuclear Almirante Alvaro Alberto (CNAAA) location:

- Geologically Stable Continental Region (SCR), intraplate,
- Far from tectonic plates boundaries,
- Without geological faults that could produce high-magnitude earthquakes.
- Residual tectonic activities: accommodation of blocks moved during the Tertiary.

Characteristics of the Region (cont.): Low-seismicity

• Closest active fault to NPP - Monsuaba, 24 km away from site: No deformations of surface land in epicentral area; Small magnitude earthquakes (largest event < 3.0 m_b); Can not be associated with moderated to large earthquakes or with sustained seismic activities. => Not a capable fault (acc. to USNRC concept).

• Regional seismic events (d < 320km, magn.> 4.0 m_b):

Location	Date (Year)	Dist. (km)	Intensity (MM)	Magnit. (m_b)
Lorena / SP	1861	91	V - VI	4.4
São Pedro-SP RJ	1886	87	V - VI	4.3
Mogiguaçu/ Pinhal / SP	1922	283	VI	5.1
Cunha / SP	1967	65	VI-VII	4.1
Atlantic Ocean	2008	304	-	5.2

Seismic Design Bases

• Original deterministic design criteria:

   0.10 g horizontal acceleration (outcropping rock)

• Design spectrum defined by Weston Geophysical Research (Basis: U.S. standards; similar to Reg. Guide 1.60, 1973)

Late 90s:

- Updated geological and seismological database,
- Latest regional faults (neotectonic) incorporated and
- Probabilistic seismic hazard analysis (Basis: recent USNRC standards for Probabilistic Seismic Hazard Analysis - PSHA).

=> Results:

- No capable faults in the region (USNRC criteria);
- Diffuse seismicity, without clearly defined seismogenic sources;
- Adopted design acceleration level is suitable;
- Earthquake Catalog was updated (2003, 2008): seismic hazard analysis was repeated twice, without relevant changes in results.

Seismic Design Bases (cont.) - PSHA:

• Maximum potential magnitude (m_b) (upper limit for earthquake recurrence curve) for the region + adjoining areas:

- Continental part: 6.5
- Oceanic part: 7.0

• Earthquake catalog: Recent and historical events (since 1767); Seismic recurrence ⇔ Frequency x Magnitudes ($3.5 \leq m_b \leq 7$):

$$Log\left(\sum N\right) = 4.40 \ (\pm 0.03) - 1.29 \ (\pm 0.04) \cdot m_b$$

• Seismic energy attenuation (Toro, 1997), from epicenter to site:

$Ln(Y) = 2.07 + 1.2 (M-6) - 1.28 [\ln(R_M)] + 0.05 \max[\ln(R_M /100), 0] - 0.0018 R_M$

• Probabilistic Seismic Hazard (Location & Magnitude uncertainties):

$P[Y > y^*] = \Sigma_k \Sigma_l P[Y > y^* | M,R] \cdot P_M(m_k) \cdot P_R(r_l)$

Seismic Design Bases (cont.) – Seismic hazard

Peak Ground Acceleration (PGA) for Safe Shutdown Earthquake:

- Probability of 10^{-4}/year $\Leftrightarrow$ PGA < 0.06 g
- Probability of design PGA (0.10g) $\Leftrightarrow$ ~2.2×10^{-5}/year

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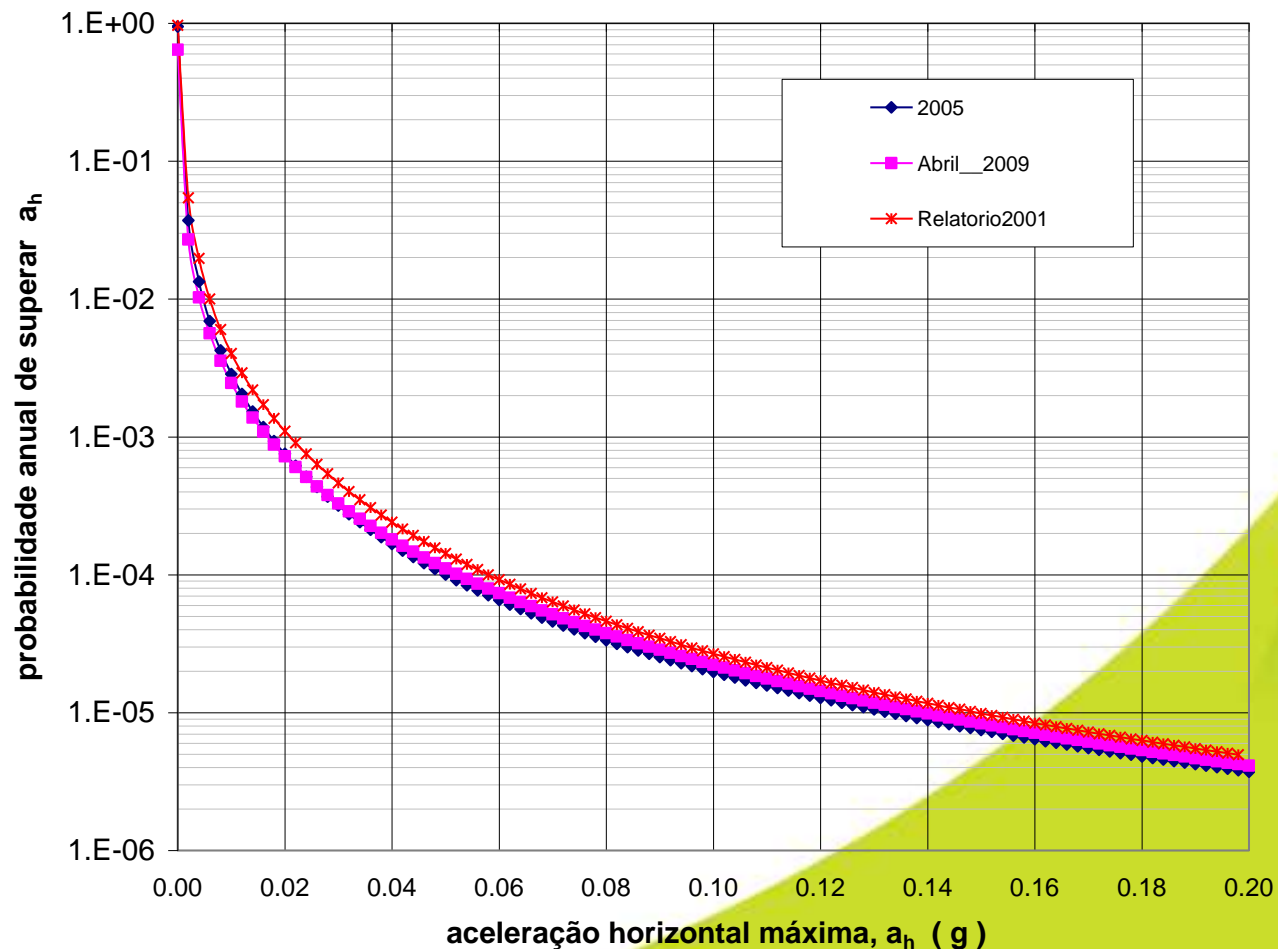
Reassessment and update program:

Evolution of Knowledge & Normative Basis: Geological (latest faults - neotectonic & their seismogenic potential) + Seismological database reassessment => Update Seismic Hazard

Geological data:

• 1980s: Regional faults affecting sedimentary surfaces & deposits in central part of Bacia de Resende, RJ, was considered as unique indication of tectonic activity in beginning of Quaternary.

• End of 80s: Changes in assumed tectonic stability of faults: Evidences of neotectonic activity of faults, incl. movements in Pleistocene & Holocene, in Bacias de Taubaté & Resende, Gráben da Guanabara, Planalto de Campos do Jordão & central part of Shear Zone of Rio Paraíba do Sul.

• Brazilian SE region has received most attentions in neotectonic studies. Necessity of review work to integrate data + Opportunity to insert these data in international database, e.g., GEM (Global Earthquake Model; Objective: public standardized database with active faults & seismic sources).

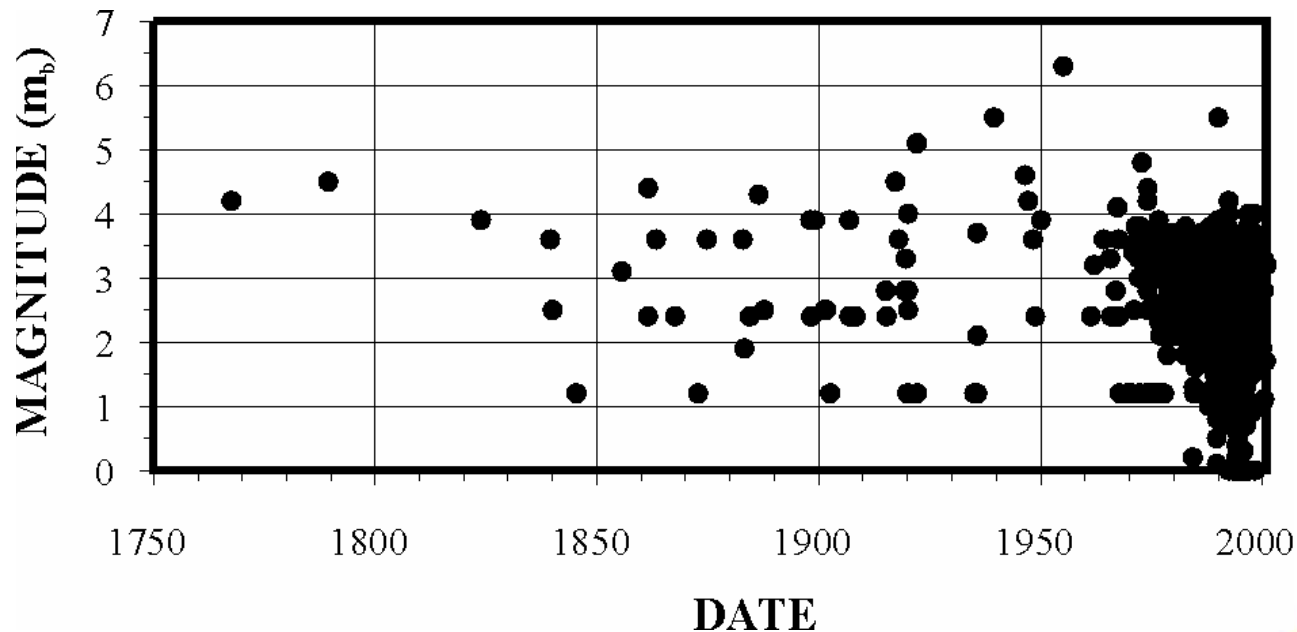**Reassessment and update program - Geological data (cont.):**
Update of geological database: regional neotectonic & associated faults, based on available geological data in literature, in a <u>3-Step Program:</u>

- Phase 1 – Database update area R < 101 km from site; map of geological faults in scale 1:500.000, representing fault extension.

- Phase 2 - Area between 101 km < R < 322 km; scale 1:2.000.000.

  - In phases 1 & 2: list each fault characteristics [fault direction, type of displacement, min. length, width & depth, age(s) of movement(s)]; correlations between faults & seismic events.

- Phase 3 – Field survey in selected inland faults; Listing and analysis of structural data; Evaluation of sedimentary soil (14C application); Determination of the geological ages of fault movements.

- Information + USNRC criteria base => Identification of capable faults.

Reassessment and update program - Seismological data:

• Seismic instrumental data in SE Brazil:
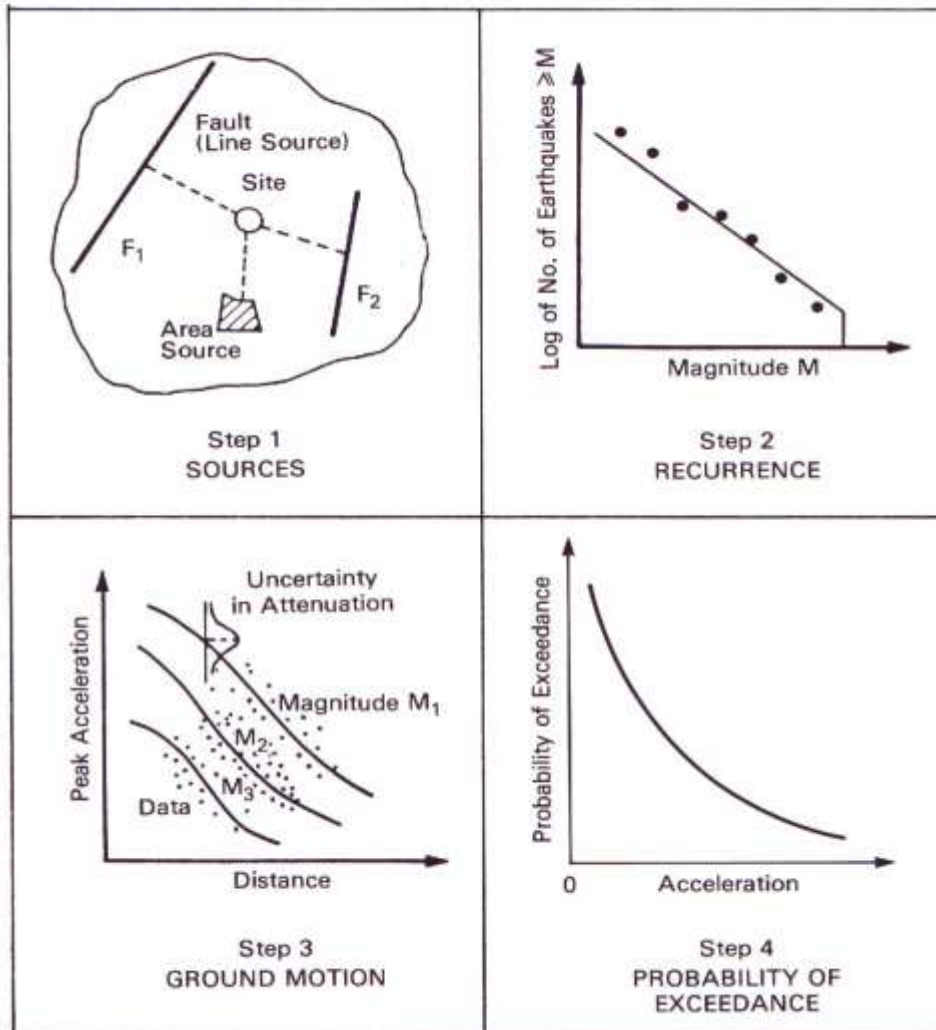
Data completeness for magnitudes $\geq$ 3.5 since 1975:

• Regional seismological data update (1767 – Dec., 2011);
• Catalog analysis => Seismic Recurrence Equations for whole region or its parts.

**Reassessment and update program - Seismic hazard analysis** review**:**
Basis: USNRC (NUREG/CR-6372, RG 1.208, …), EPRI…:
Seismic Source & Ground Motion Characterization to obtain Hazard Calculations

Reassessment and update program-Seismic hazard analysis review (cont.)**:**
• Parametric sensitivity study of the recurrence equations.
• Other attenuation equations for Stable Continental Regions (SCR) to check uncertainties involved.
• Verification of possible new seismic sources => Other seism tectonic models than unique diffuse seismicity model of PSS?
• Alternative models & associated probabilities (Logic-Trees)

| Source Geometry | Maximum Magnitude | Seismicity Model | Attenuation Equation |
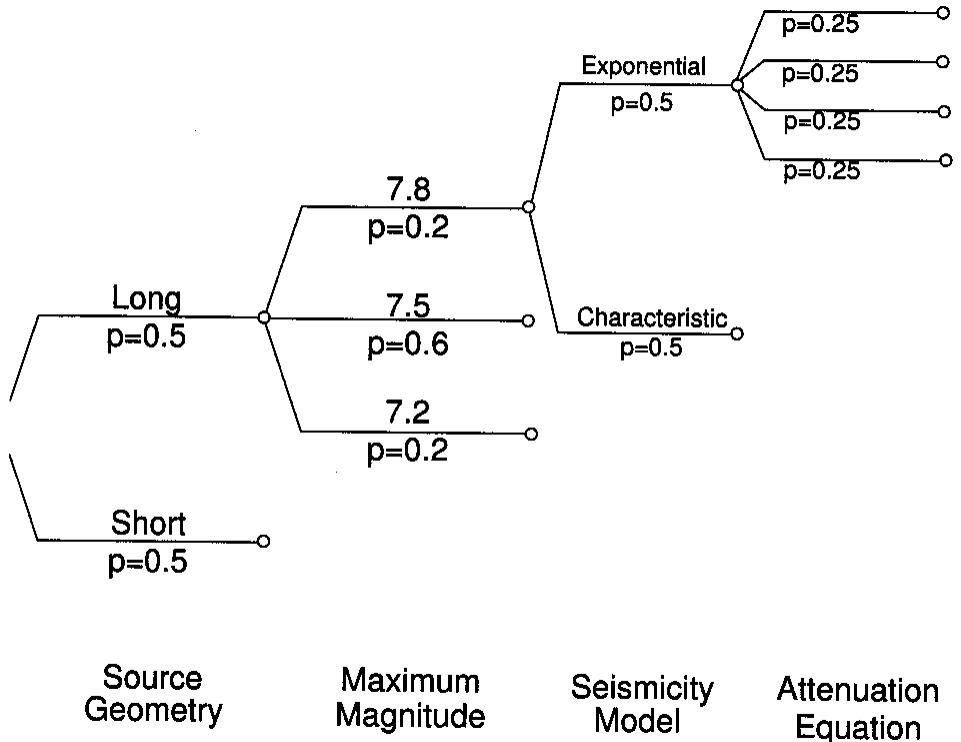
**Description of ELETRONUCLEAR´s Seismographic Station:**

• Broad band Seismographic Station close to NPP site (Estação Sismográfica de Angra dos Reis – ESAR): operated since 2002, in cooperation with IAG/USP (responsible for the Brazilian Seismic Catalog); Berrocal & Associados Co. contracted for operation, maintenance and generation of seismic reports.

• Objetive => Local & regional seismic events monitoring for:
- Determining epicenters of local small magnitude events
- Estimating regional crustal structure
- Evaluating regional seismic energy attenuation
- Obtaining a detailed regional seismic data base, for CNAAA´s PSHA

PSS (Província Sismo-tectônica do Sudeste) description:
- CNAAA in a low seismicity region;
- Geological faults & Seismic events correlation (Seismic Source Characterization) => One single diffuse seismogenic model;
- Available data is not uniformly distributed in the region (small quantity & not uniformly distributed available seismographic stations),
=> Seism tectonic province: A polygon (from 300 km - to > 600 km from site), (recurrence seismic equation anchored on minimum consistent data).

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PSS seismic events (1767 - Dec. 2011; Magnitudes 2.0 <= mb <= 5.2).
Red dots: ESAR recorded events; Blue circles: R=100, 200, 320 km from site
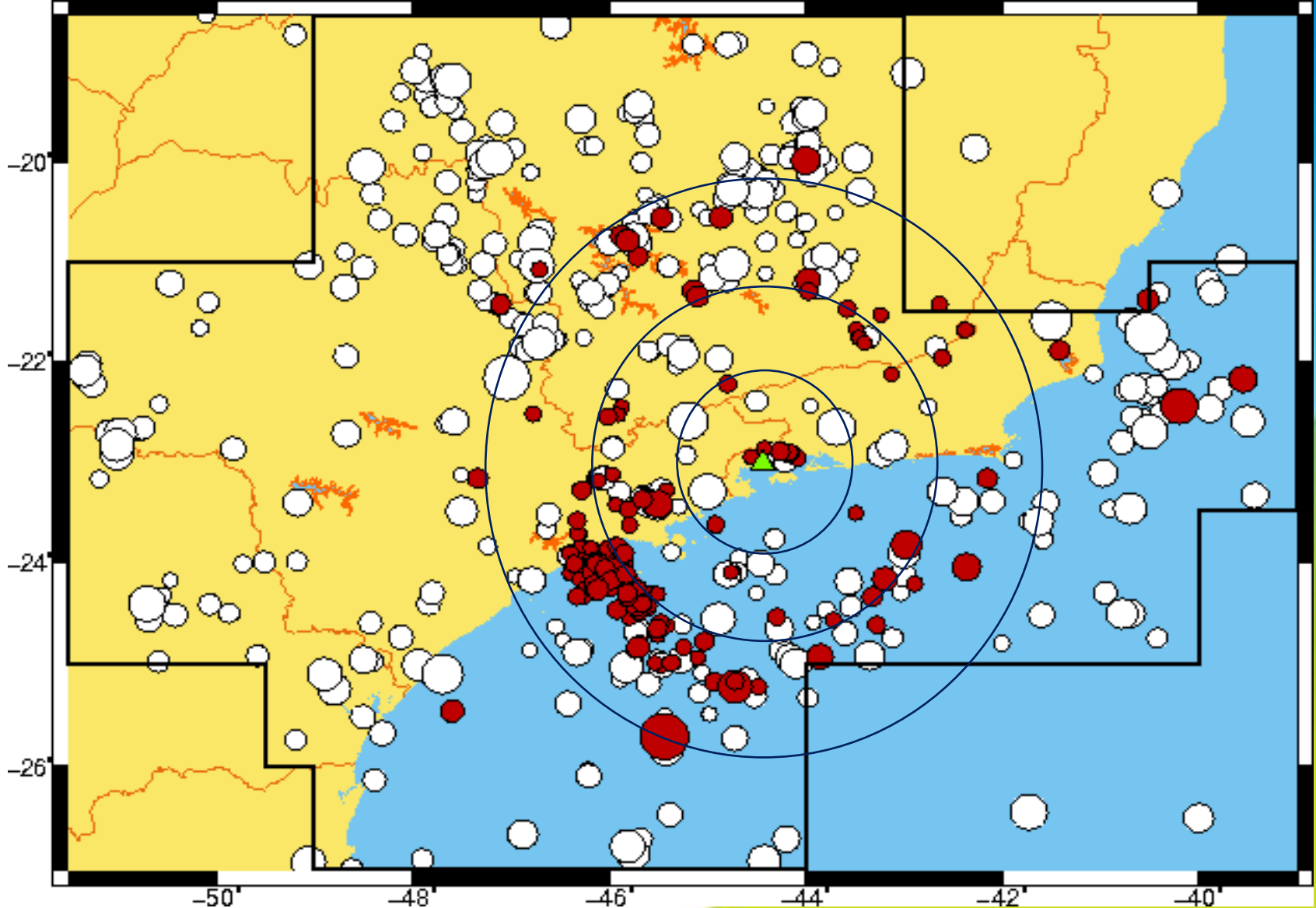
Analysis of updated seismic catalogue – Data summary:
1767 - Dec./2011 seismic events:

- $m_b \geq 2.0$:   PSS: 463 events
                            $R \leq 320$ km: 283
                            $R \leq 100$ km: 20

- $m_b \geq 3.0$: $R \leq 320$ km: 59

Magnitude (Richter)	Distance (km)		
	$12 < d \leq 60$	$60 < d \leq 180$	$180 < d \leq 320$
$3{,}0 \leq M \leq 3{,}5$		6	30
$3{,}5 < M \leq 4{,}0$		5	13
$4{,}0 < M \leq 4{,}5$		3	-
$4{,}5 < M \leq 5{,}2$			2

$\Rightarrow$ **Confirms:**
       - Low regional seismicity and
       - Majority of events < 3 m_b

Conclusion

• **Initial studies performed by Weston G.R. (70-80´s):** Site Characteristics & Seismic Design Bases (Deterministic criteria: 0.10 g acceleration & Spectrum)

• **Late 90s Results:**
 - Updated geological (neotectonic faults) & seismological database; No capable faults in the region (USNRC criteria); Diffuse seismicity, without clearly defined seismogenic sources;
 - PSHA => Adopted design acceleration level is suitable.

• **Reassessment and update program (2012+3years):**
 - Evolution of Knowledge & Normative Basis: Geological (neotectonic faults & their seismogenic potential) + Seismological database reassessment   => Update PSHA