INTERNATIONAL SCHOOL AND WORKSHOP

«NON-LIINEAR MATHEMATICAL PHYSICS AND NATURAL HAZARDS»

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The Hazard in Using Earthquakes Probabilities for Seismic Hazard Assessment

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Seismic hazard assessment

- **Seismic hazard** describes the ground shaking associated with the possible earthquakes in a given region. It is quantified by three elements: a level of ground shaking severity and its spatial and (possibly) temporal characteristics.

- There are two general approaches to seismic hazard assessment: **probabilistic** and **deterministic**

- Common elements: the characterization of seismicity in the area, the geological and geotechnical conditions and the size of the expected earthquakes.

- Recent earthquakes and case studies evidenced the limits of the currently used methodologies, based prevalently on a probabilistic approach => it seems more appropriate resorting to a scenario-based deterministic assessment of seismic hazard.

List of the deadliest earthquakes occurred since 2000

Most of them were underestimated by traditional probabilistic ground shaking estimates (GSHAP) => Need for critical appraisal of current practice in SHA

Region	Date	Magnitude	Fatalities	Intensity difference
Sumatra-Andaman "Indian Ocean Disaster"	26.12.2004	9.0	227898	4.0 (IV)
Port-au-Prince (Haiti)	12.01.2010	7.3	222570	2.2 (II)
Wenchuan (Sichuan, China)	12.05.2008	8.1	87587	3.2 (III)
Kashmir (North India and Pakistan border region)	08.10.2005	7.7	~86000	2.3 (II)
Bam (Iran)	26.12.2003	6.6	~31000	0.2 (=)
Bhuj (Gujarat, India)	26.01.2001	8.0	20085	2.9 (III)
Off the Pacific coast of Tōhoku (Japan)	11.03.2011	9.0	15811 (4035 missing)*	3.2 (III)
Yogyakarta (Java, Indonesia)	26.05.2006	6.3	5749	0.3 (=)
Southern Qinghai (China)	13.04.2010	7.0	2698	2.1 (II)
Boumerdes (Algeria)	21.05.2003	6.8	2266	2.1 (II)
Nias (Sumatra, Indonesia)	28.03.2005	8.6	1313	3.3 (III)
Padang (Southern Sumatra, Indonesia)	30.09.2009	7.5	1117	1.8 (II)

Intensity difference among the observed values and those predicted by GSHAP

Kossobokov & Nekrasova (AGU, 2011)
Wyss, Kossobokov & Nekrasova (Nat.Haz., 2012)

Evaluating hazard maps

PUBLICATIONS: SRL: OPINION

OPINION

September/October 2011

Bad Assumptions or Bad Luck: Why Earthquake Hazard Maps Need Objective Testing

doi:10.1785/gssrl.82.5.623

Bad assumptions or bad luck: why earthquake hazard maps need objective testing

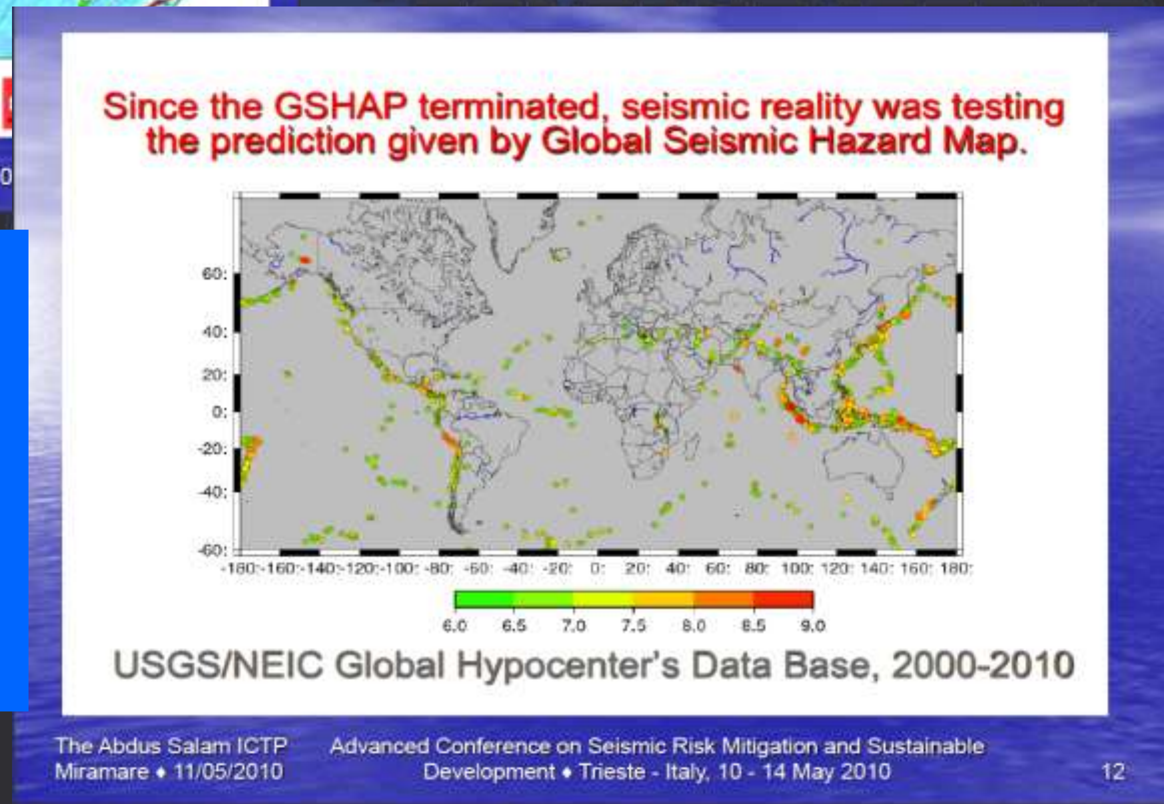
Seth Stein
Robert Geller
Mian Liu

Seism. Res. Lett., 82:5
September – October 2011

In the above cases, the maps significantly underpredicted the earthquake hazard. However, their makers might argue that because the maps predict the maximum shaking expected with some probability in some time interval, the much larger earthquakes and resulting shaking that actually occurred are rare events that should not be used to judge the maps as unsuccessful. So how should we judge a map's performance? Currently, there are no generally agreed upon criteria. It is surprising that although such hazard maps are widely used in many countries, their results have never been objectively tested.

? GSHAP ?

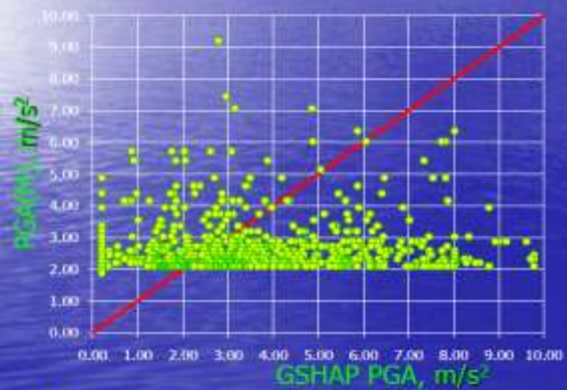
Checking forecasted values against observations



Global Seismic Hazard Assessment Program (GSHAP) was launched in 1992 by the International Lithosphere Program (ILP) with the support of the International Council of Scientific Unions (ICSU), and endorsed as a demonstration program in the framework of the United Nations International Decade for Natural Disaster Reduction (UN/IDNDR). GSHAP terminated in 1999.

Each of the 1320 shallow magnitude 6 or larger earthquakes has from 4 to 9 values of the GSHAP PGA at the distance less than 12 km from its epicenter. The maximum of these values is compared to the estimate (*Boore, Joyner and Fumal, 1997*)

$$PGA(M) = EXP(0.53*(M-6)-0.39*LN(10^2+31)+0.25)*9.8$$



On average the difference is above 1/3 m/s^2; the median equals 1.7 m/s^2

Moreover, 40 out of 56 magnitude 7.5 or larger events have the difference above this average, while for 27 events it is above 2 m/s^2

The Abdus Salam ICTP Miramare ♦ 11/05/2010 — Advanced Conference on Seismic Risk Mitigation and Sustainable Development ♦ Trieste - Italy, 10 - 14 May 2010

? GSHAP ?

Checking forecasted values against observations

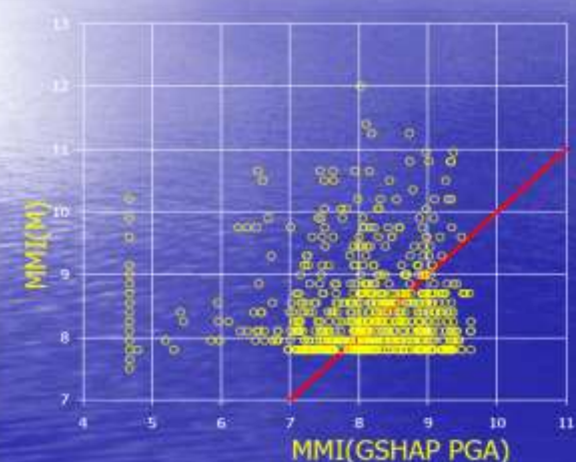
All points above the red line are the GSHAP failures-to-predict MMI, achieved in the decade 2000-2010, for earthquakes of magnitude 6 or greater.

Above the red line fall all 57 earthquakes of magnitude 7.5 or greater, of which 30 have an MMI discrepancy exceeding two units of intensity....

If we apply transforms to intensity MMI -

MMI(M) = 1.5 (M – 1) (Gutenberg, Richter, 1954)

MMI(PGA) = 1.27 Ln(PGA) – 3.74 (Shteinberg et al. 1993)



On average the difference is above 1.6; the median equals 2.5.

Moreover, 51 out of 56 magnitude 7.5 or larger events the difference is above 1, while for 30 of those it is above 2

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Probabilistic vs. Deterministic

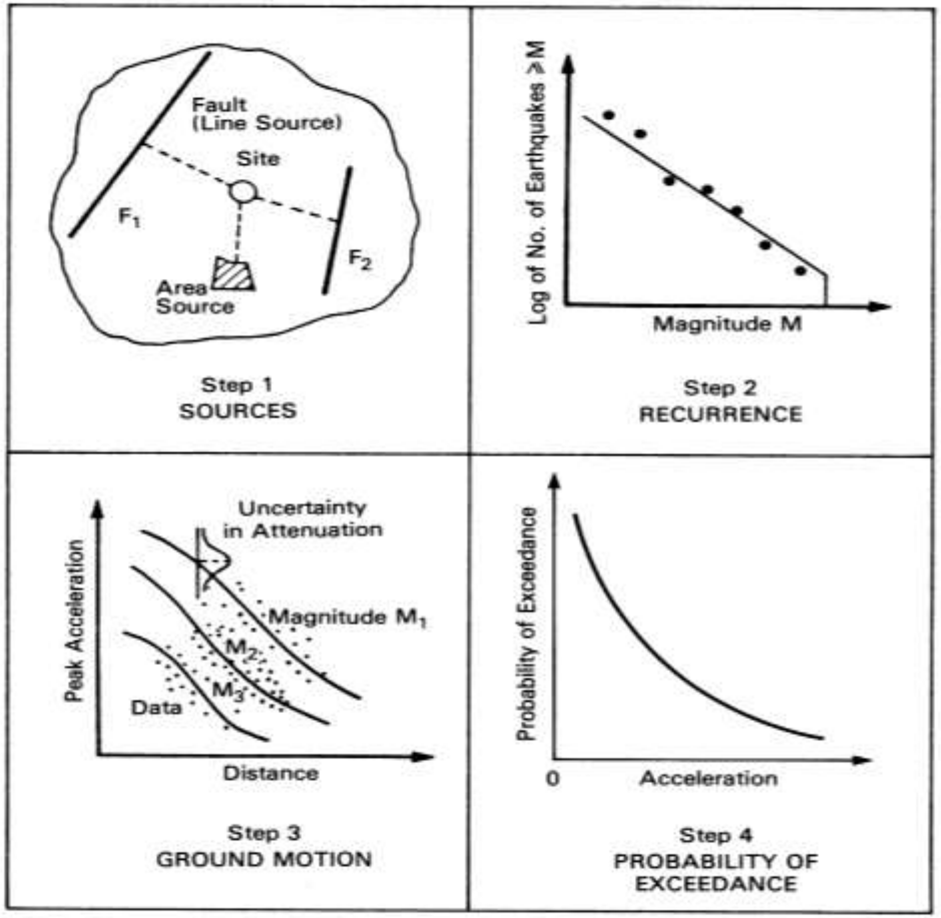


FIGURE 10.2 Basic steps of probabilistic seismic hazard analysis (after TERA Corporation 1978).

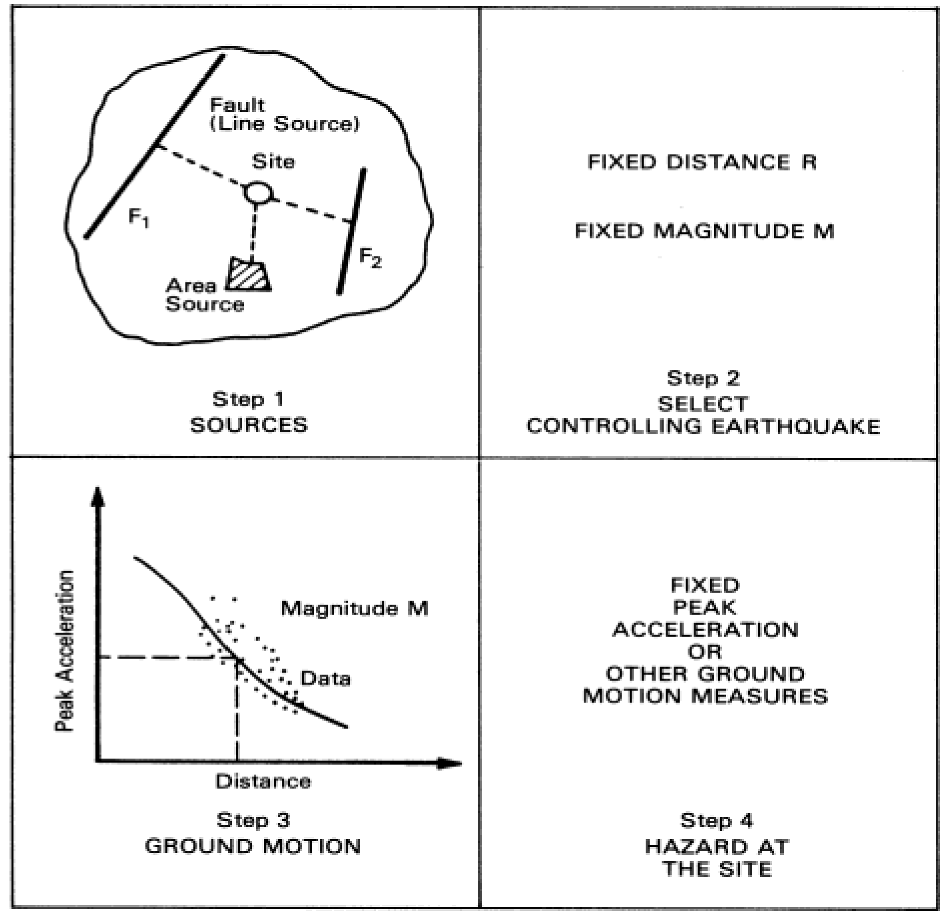


FIGURE 4.1 Basic steps of deterministic seismic hazard analysis (after TERA Corporation 1978).

Probabilistic and Deterministic procedures after Reiter (1990)

Probabilistic - PSHA

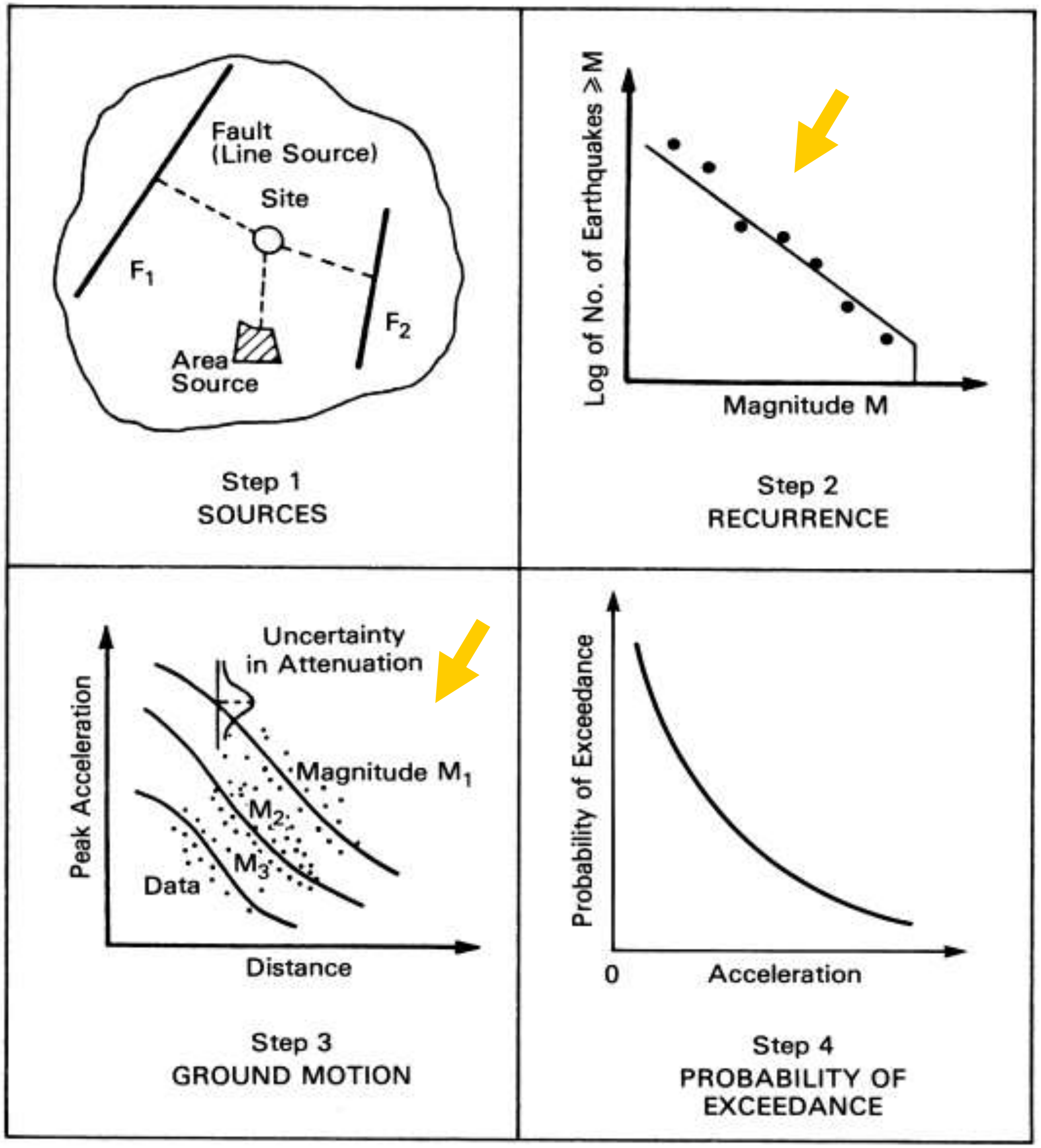


FIGURE 10.2 Basic steps of probabilistic seismic hazard analysis (after TERA Corporation 1978).

Hazard estimates: PSHA forecasts the expected value of ground shaking which has a probability P of being exceeded over a specified time interval (e.g. 10% probability of being exceeded in 50 years)

Assumptions about earthquakes occurrence:

- Earthquakes follow specific recurrence laws (e.g. the Gutenberg-Richter law)
- Poissonian occurrence of earthquakes
- Seismicity is stationary

Probabilistic - PSHA

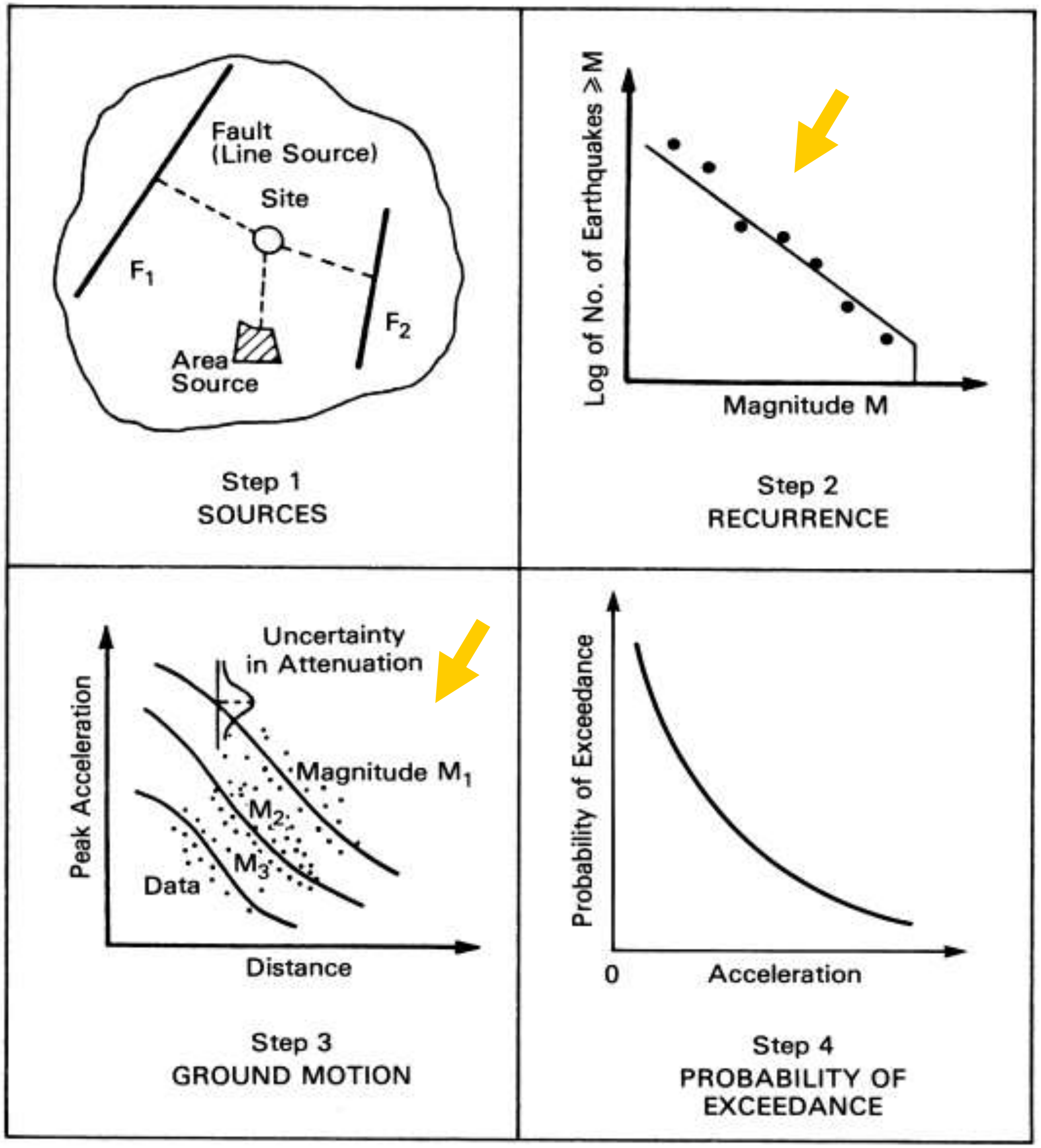


FIGURE 10.2 Basic steps of probabilistic seismic hazard analysis (after TERA Corporation 1978).

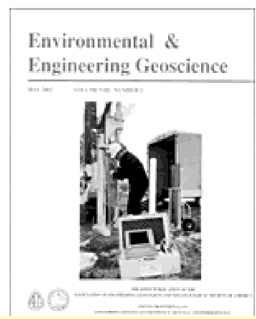
Step 2 - Recurrence can be represented by a linear relation only if the size of the study area is large with respect to linear dimensions of sources.

Step 3 - Attenuation relations: the available observations are not sufficient to properly characterize the empirical relations.

Moreover the PSHA mathematical model is inaccurate (e.g. Klügel, 2007) and violates the basic physical principles of wave propagation.

Step 4 – Probability estimates ???

Earthquake recurrence: the Gutenberg-Richter law



Environmental & Engineering Geoscience
Quarterly

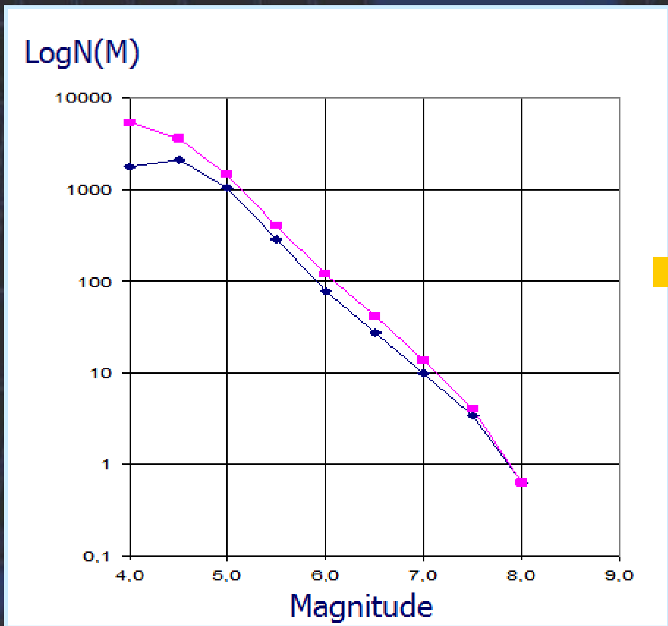
Co-published by GSA and the Association of Engineering Geologists, this respected journal presents new theory applications and case histories illustrating the dynamics of the fast-growing environmental and applied disciplines. About 700 pages annually.

The hazard in using probabilistic seismic hazard analysis for engineering

Ellis L. Krinitzsky
Waterways Experiment Station, Geotechnical Laboratory, Vicksburg, MS, United States

Nov 1998, 4, 425-443

.........The problem with seismic probability is that it relies on the Gutenberg-Richter b-line, which has severe shortcomings.........



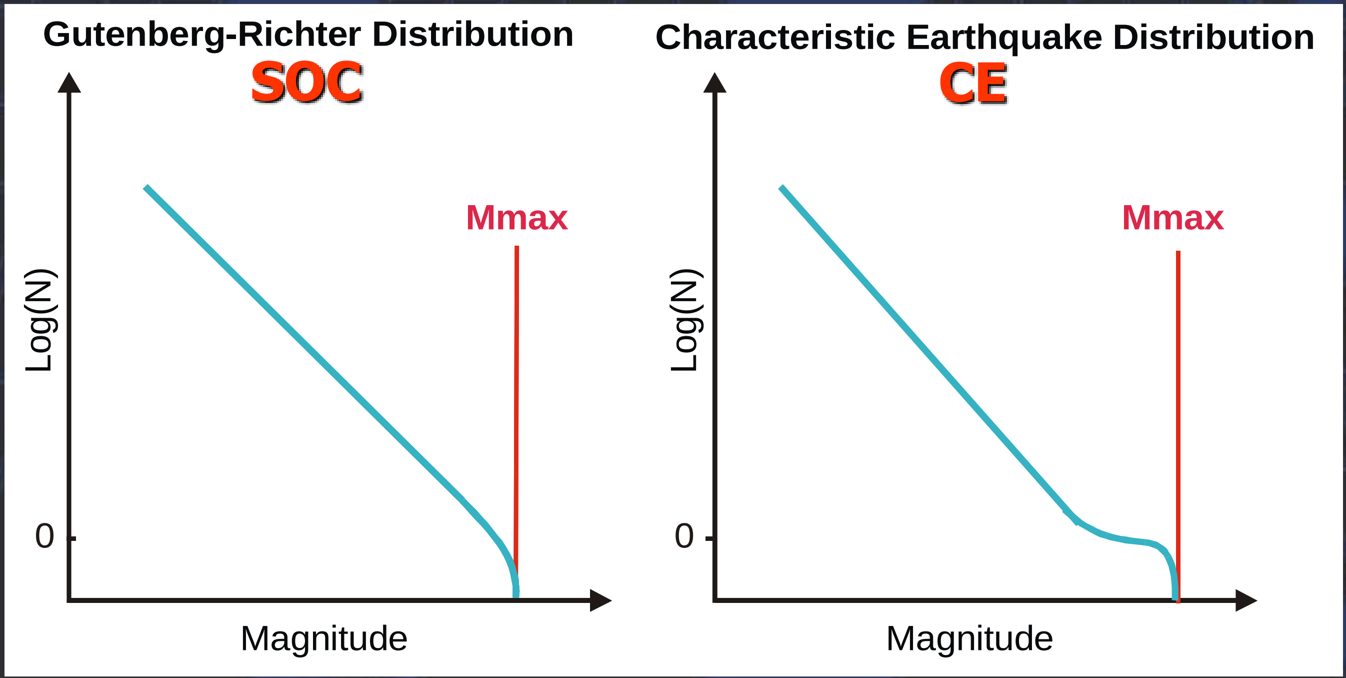
The Gutenberg-Richter Law:
Averaged over a large territory and time N(M) scales as:

$$\log_{10}N(M) = a\text{-}bM$$

No explanation to the question how the number, N, changes when zooming the analysis to a smaller size part of the space time volume.

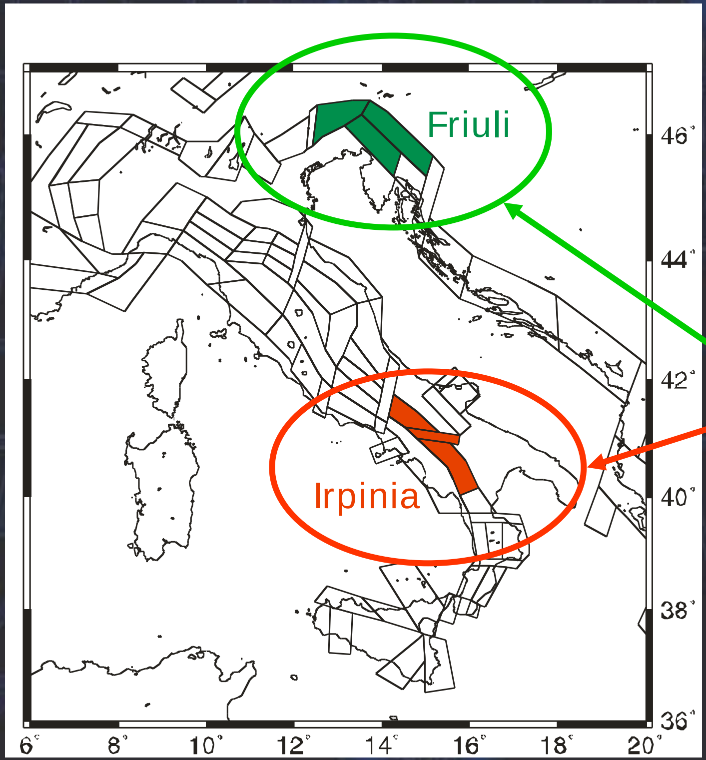
Multiscale seismicity model

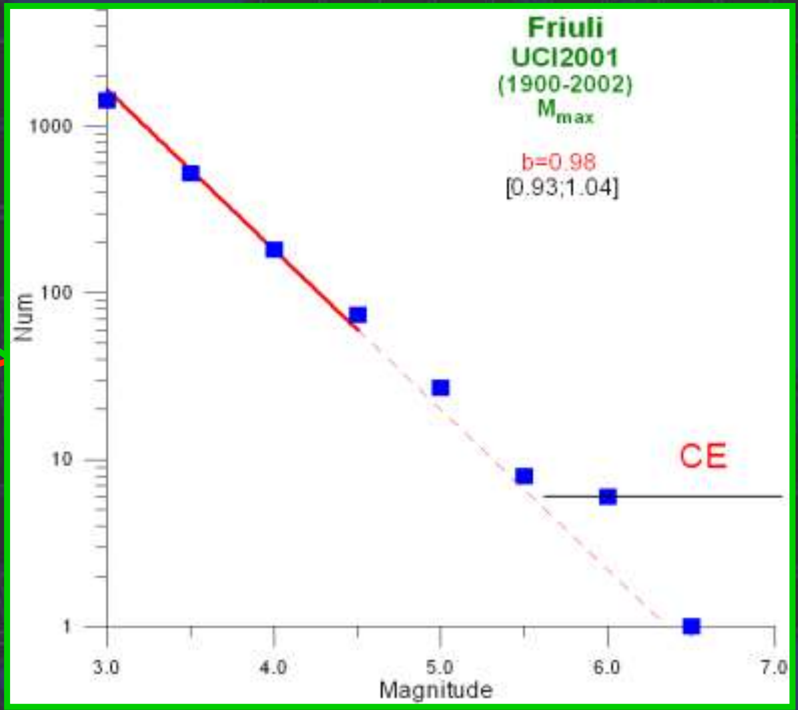
- The analysis of global seismicity shows that a single Gutenberg-Richter (GR) law is not universally valid and that a **Multiscale seismicity model** (*Molchan, Kronrod & Panza, BSSA, 1997*) can reconcile two apparently conflicting paradigms, associated with the **Characteristic Earthquake (CE)** model and the **Self-Organized Criticality (SOC)** concept.



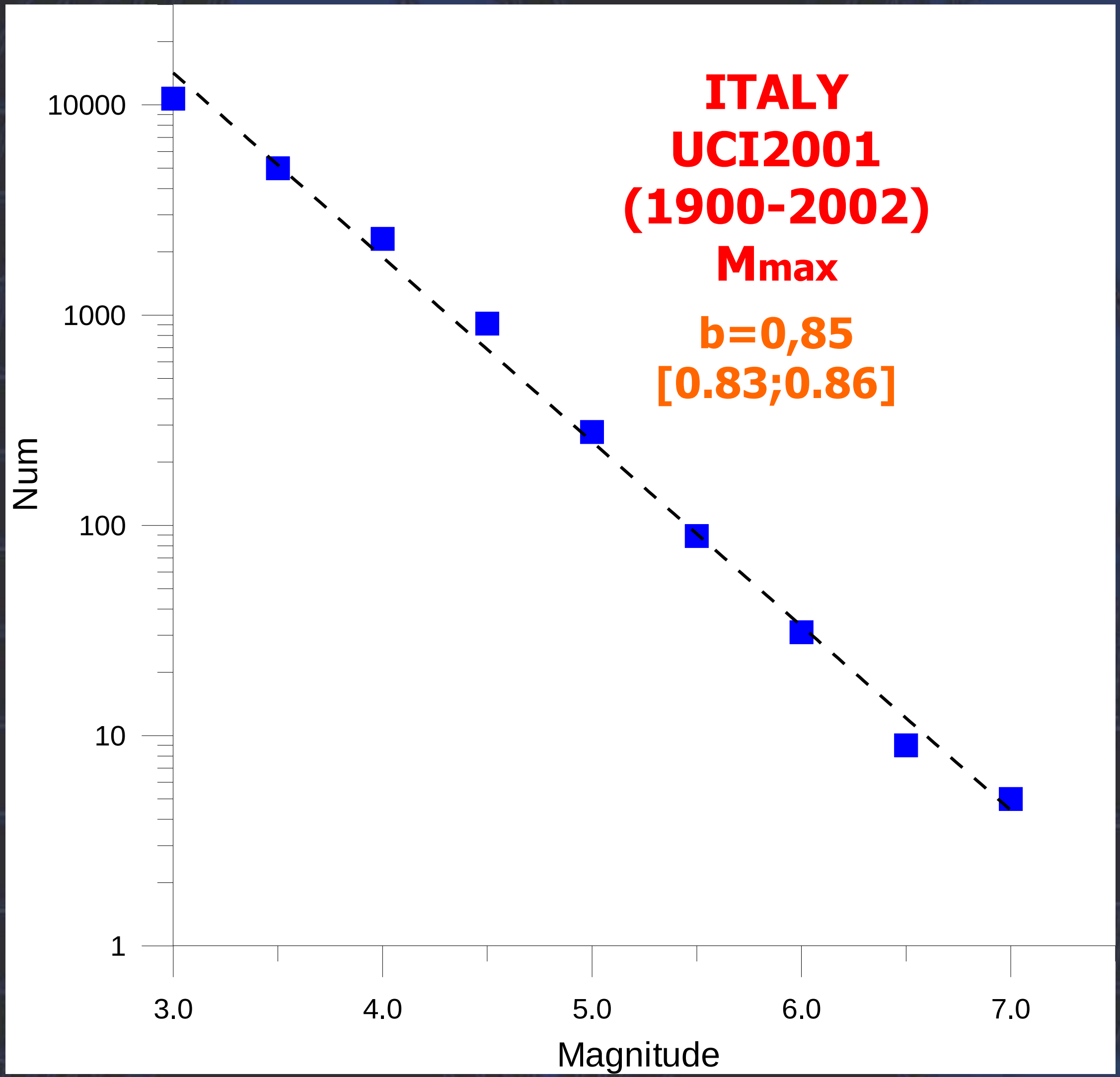
Multiscale seismicity model

- The **multiscale seismicity model**, implies that only the set of earthquakes with dimensions that are small with respect to the dimensions of the analysed region can be described adequately by the **Gutenberg-Richter law**.
- This condition, fully satisfied in the study of global seismicity made by Gutenberg and Richter, has been violated in many subsequent investigations.





Multiscale seismicity model

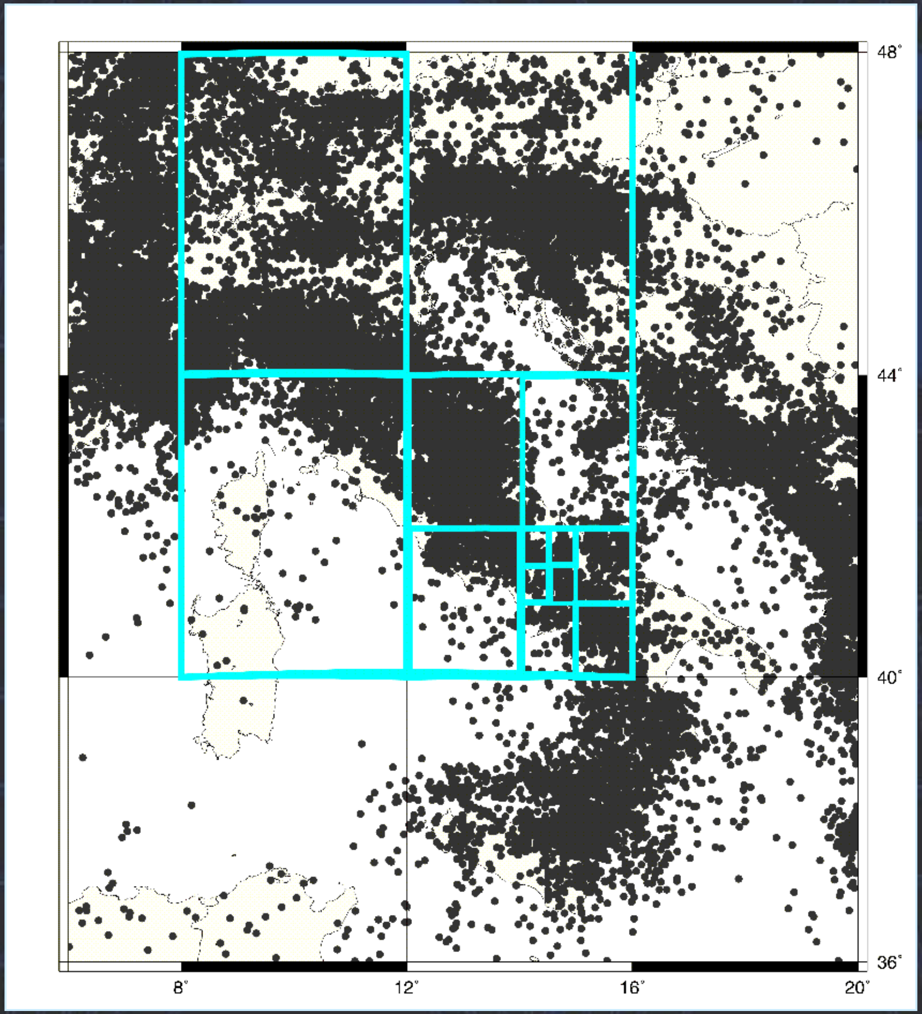


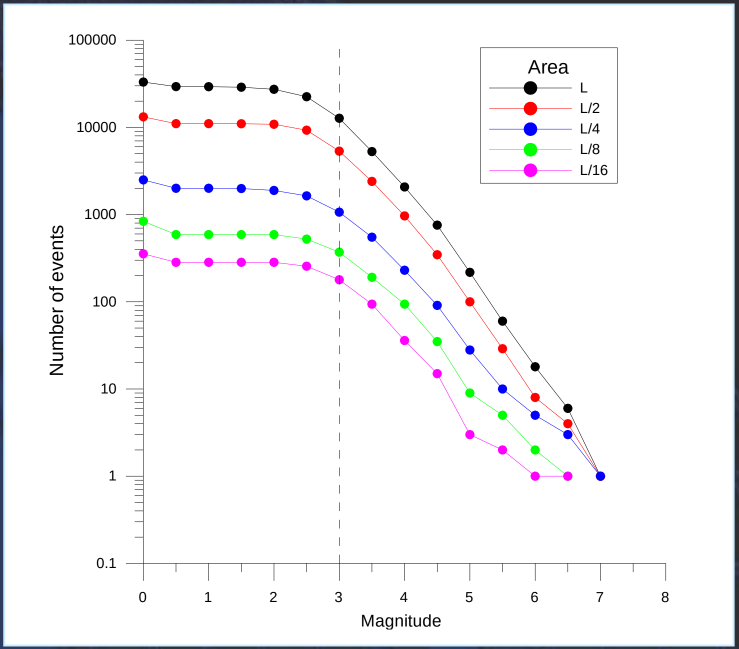
The GR law for the whole Italian territory is linear in the magnitude interval (3-7)

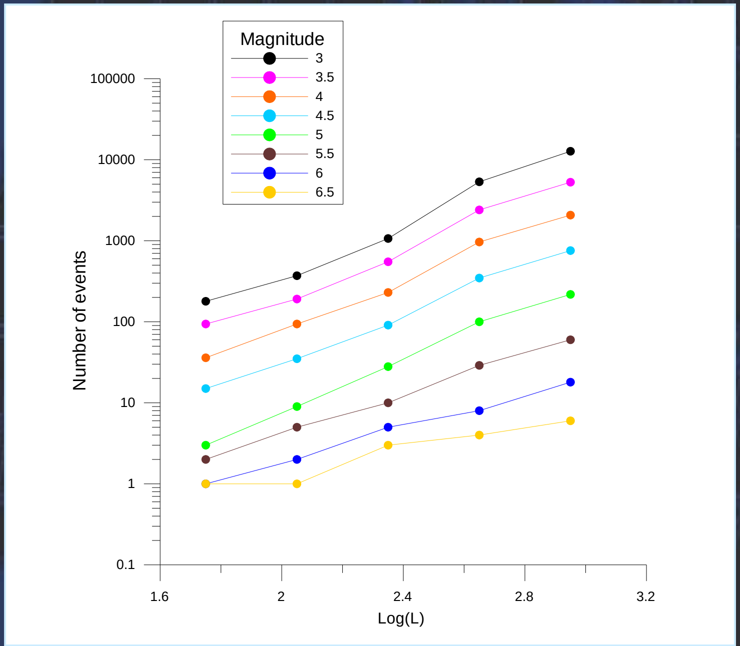
All events

Non-Cumulative

Earthquake recurrence: the multiscale seismicity model







UCI2001 catalogue
1900-2002

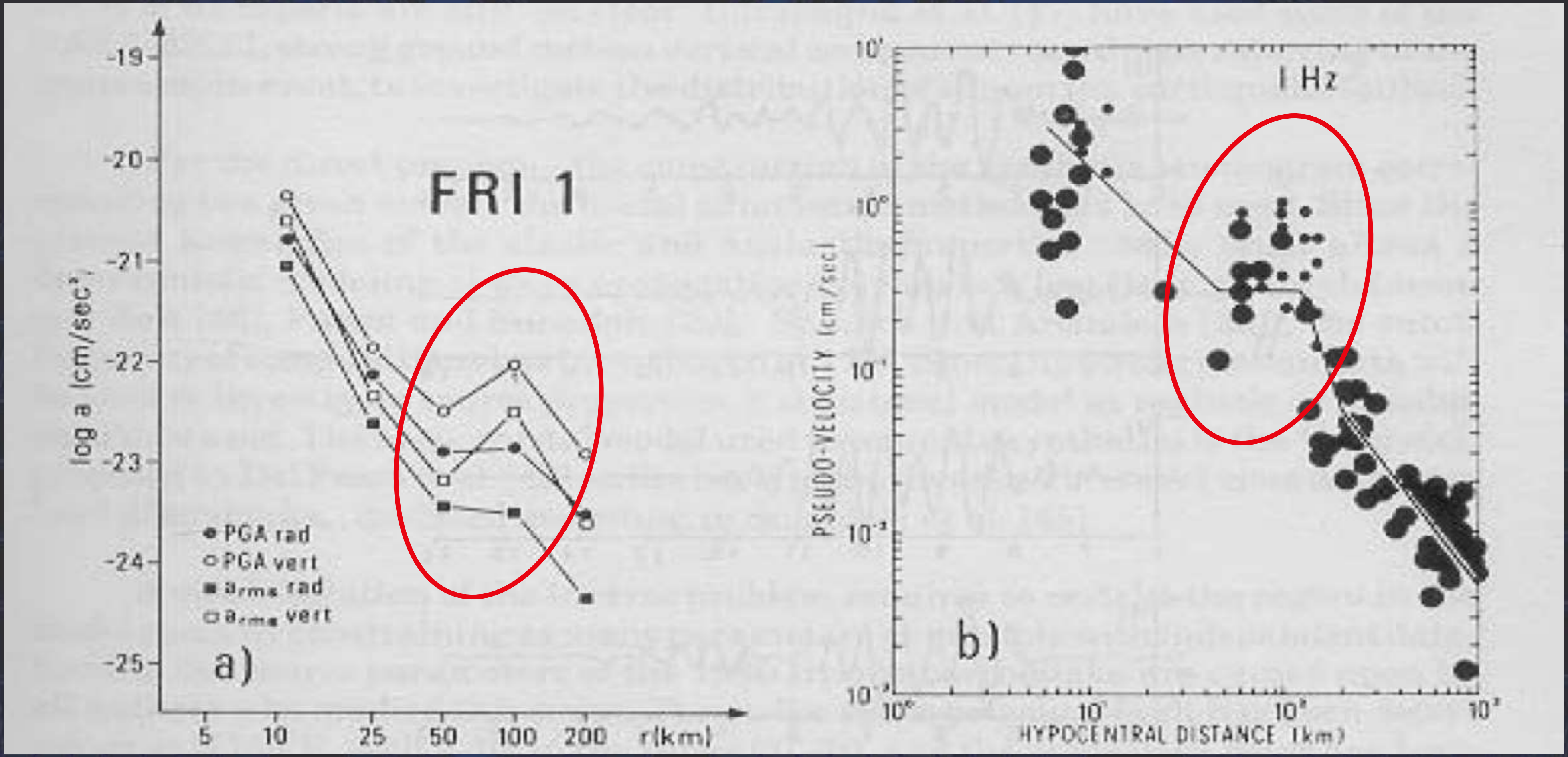
Attenuation relations

The most frequently used attenuation relations for PGA and PGV can be written as follows:

$$\log y = a + b\,M + c\log r_f + d\,D_f + e\,S$$

where:
- y is the ground motion parameter
- *a, b, c, d, e* are empirical coefficients
- r_f and D_f are two measures of source distance
- S is a binary variable (0, 1) depending on soil type

- Empirical coefficients are very sensitive to the considered data set.
- Usually regional data sets are statistically not significant, while the national or global data sets, even if statistically significant, can represent very different seismotectonic styles that therefore are not mixable.



a) Theoretical attenuation relation showing the effect of critical reflection

b) Observed attenuation relations (Burger et al., 1987, BSSA)

While the ground motion amplitudes in this distance range are usually not large enough by themselves to cause damage, they may produce damage if combined with the amplifying effects of soft soils.

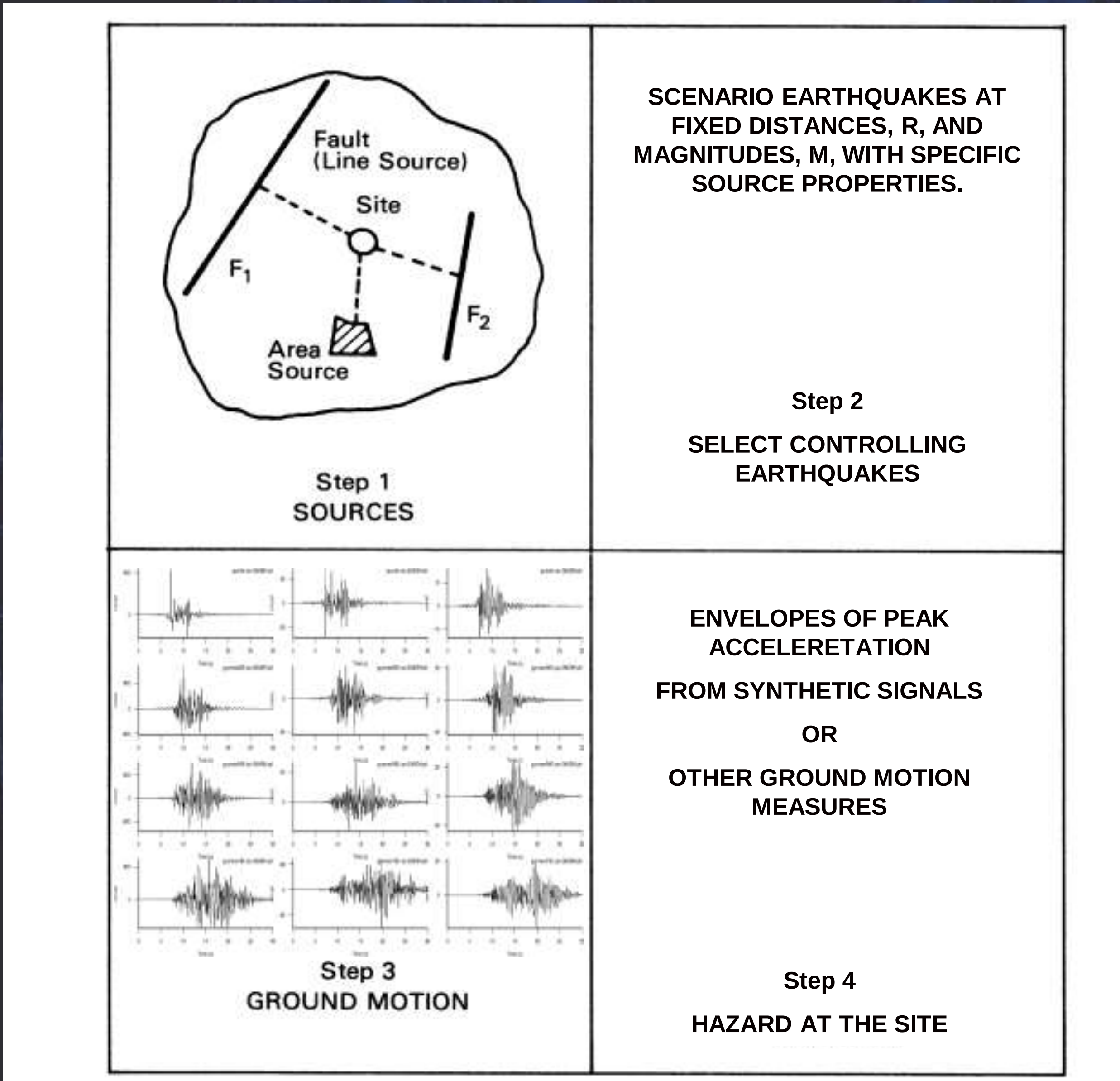
Neo-deterministic seismic hazard assessment

NDSHA

Ground shaking scenarios at regional scale

(ground motion at bedrock)

Neo-deterministic NDSHA



- Approach based on the **possibility to compute realistic synthetic seismograms** by the modal summation technique.
- The expected ground motion can be **modeled** at any site, considering a **wide set of scenario events**, starting from the available information about seismic sources and regional structural models.
- **No need for attenuation relations!**

Neo-deterministic seismic hazard assessment - NDSHA

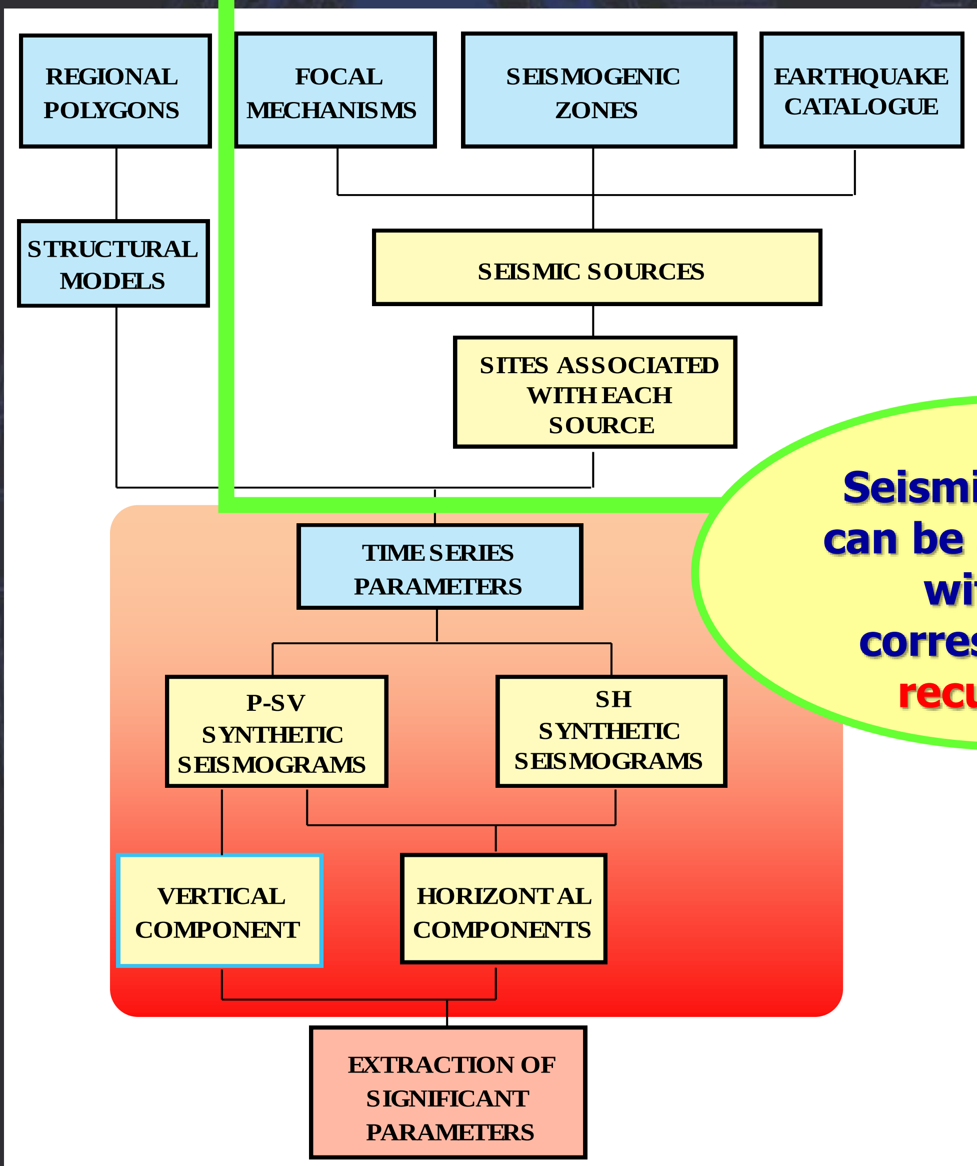
The neo-deterministic approach allows to:

- Define the hazard from the envelope of the values of ground motion parameters (like acceleration, velocity or displacement) determined considering a wide set of scenario earthquakes;
- Incorporate the newly available geological and geophysical information, including **earthquake recurrence** and the **space-time information** about impending earthquakes provided by pattern recognition analysis.

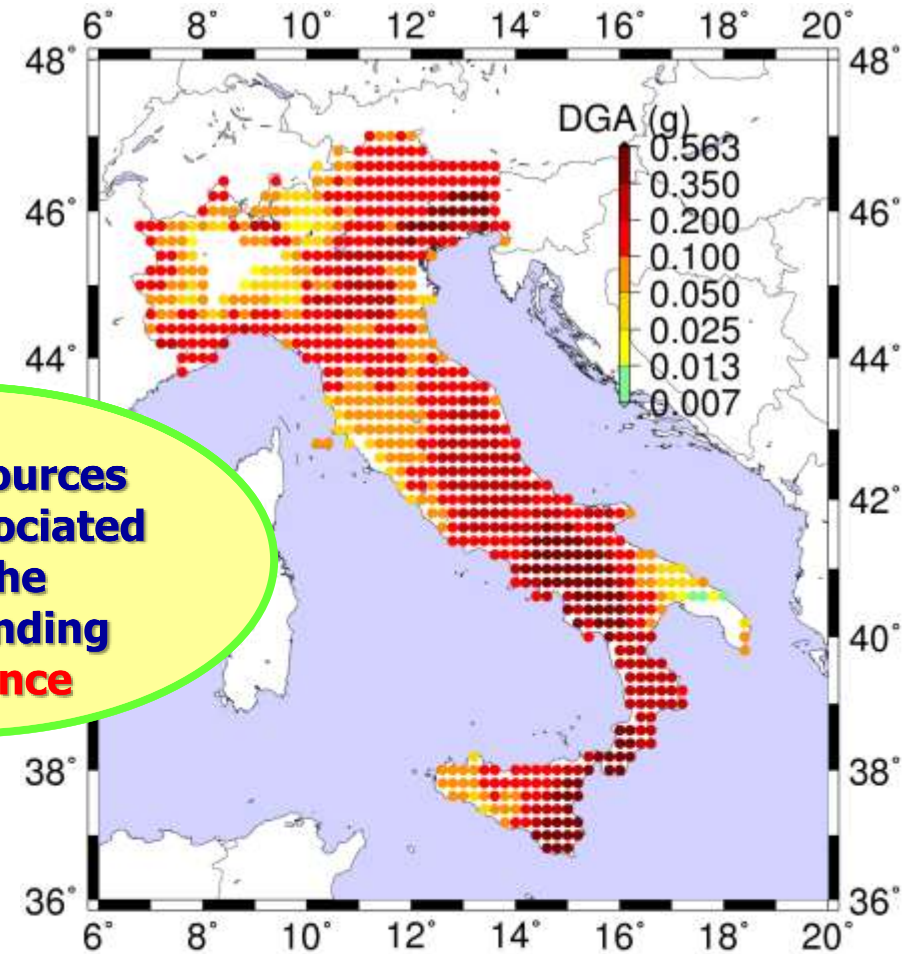
⇨ **Account for uncertainties and gaps in the available observations, by considering a wide set of scenarios and parametric tests.**

Flow chart of the standard NDSHA – Regional Scale

(1D structural models)



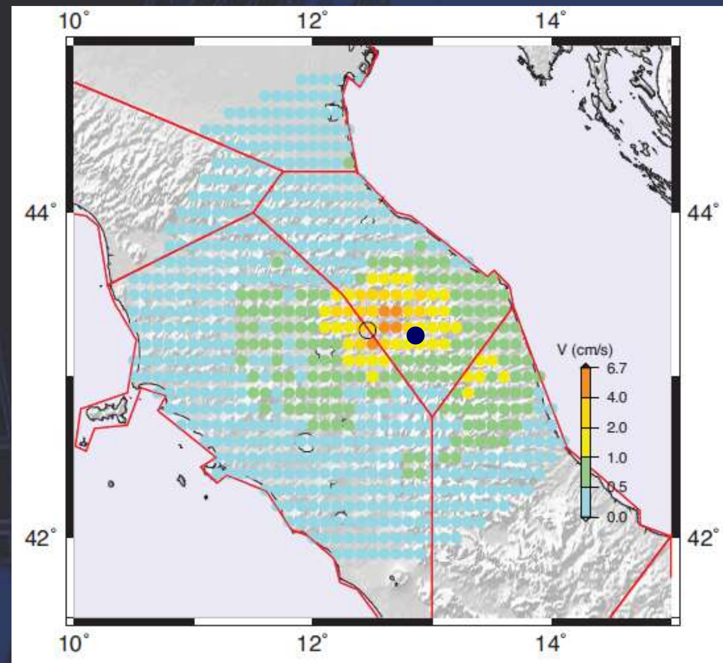
Seismic sources can be associated with the corresponding recurrence



DGA map computed using **both the seismogenic zones** (Meletti and Valensise, 2004) and **the seismogenic nodes** (Gorshkov et al., 2002, 2004).

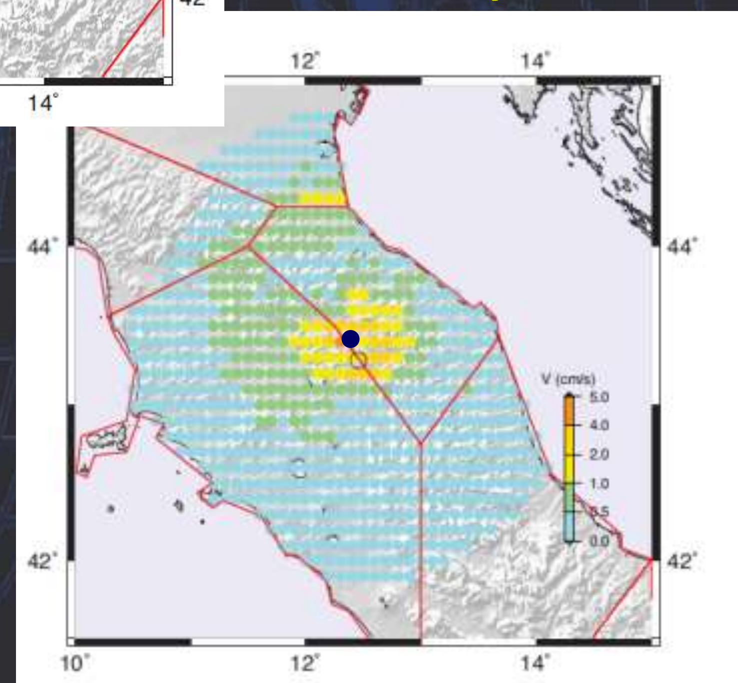
NDSHA Scenarios of Ground Shaking

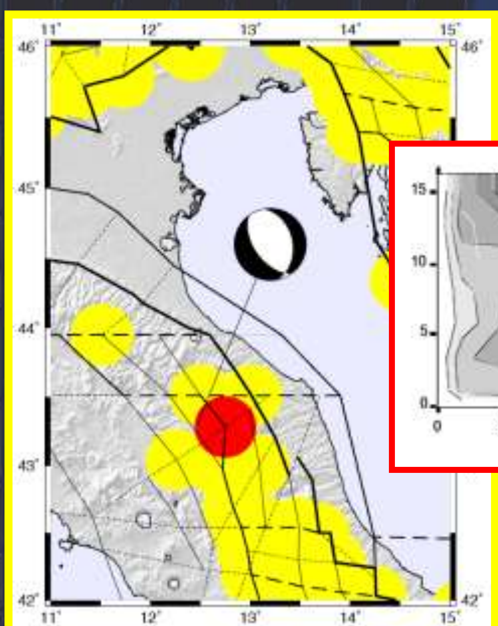
Synthetic seismograms can be computed up to 10 Hz. Extended seismic source models can be used, accounting for the rupture process at the source and the consequent directivity effect.

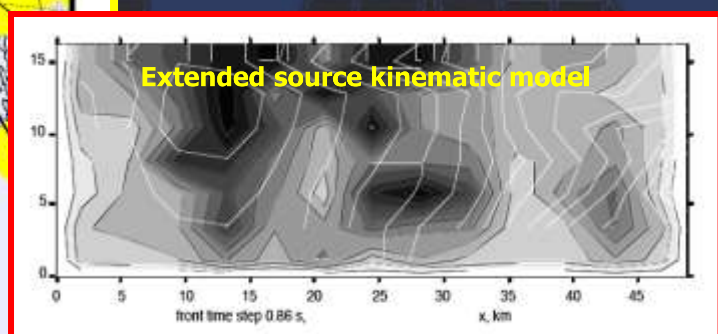


Directivity: south-east

Directivity: north-west





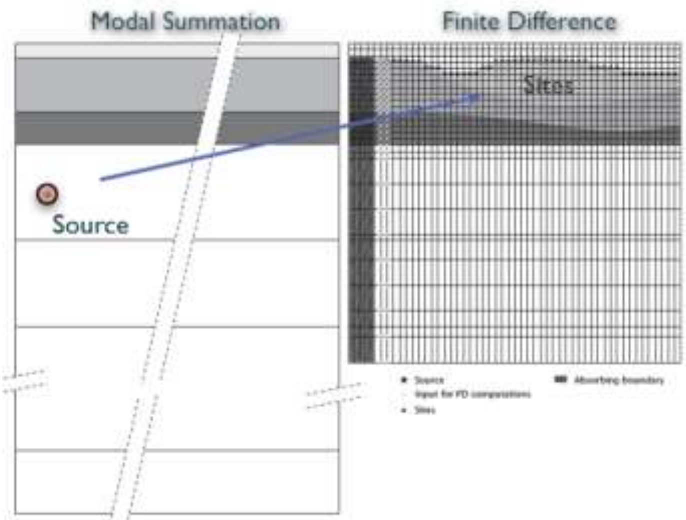


Source ITIS038 from DISS3 (Basili et al., 2008) is considered in the computations

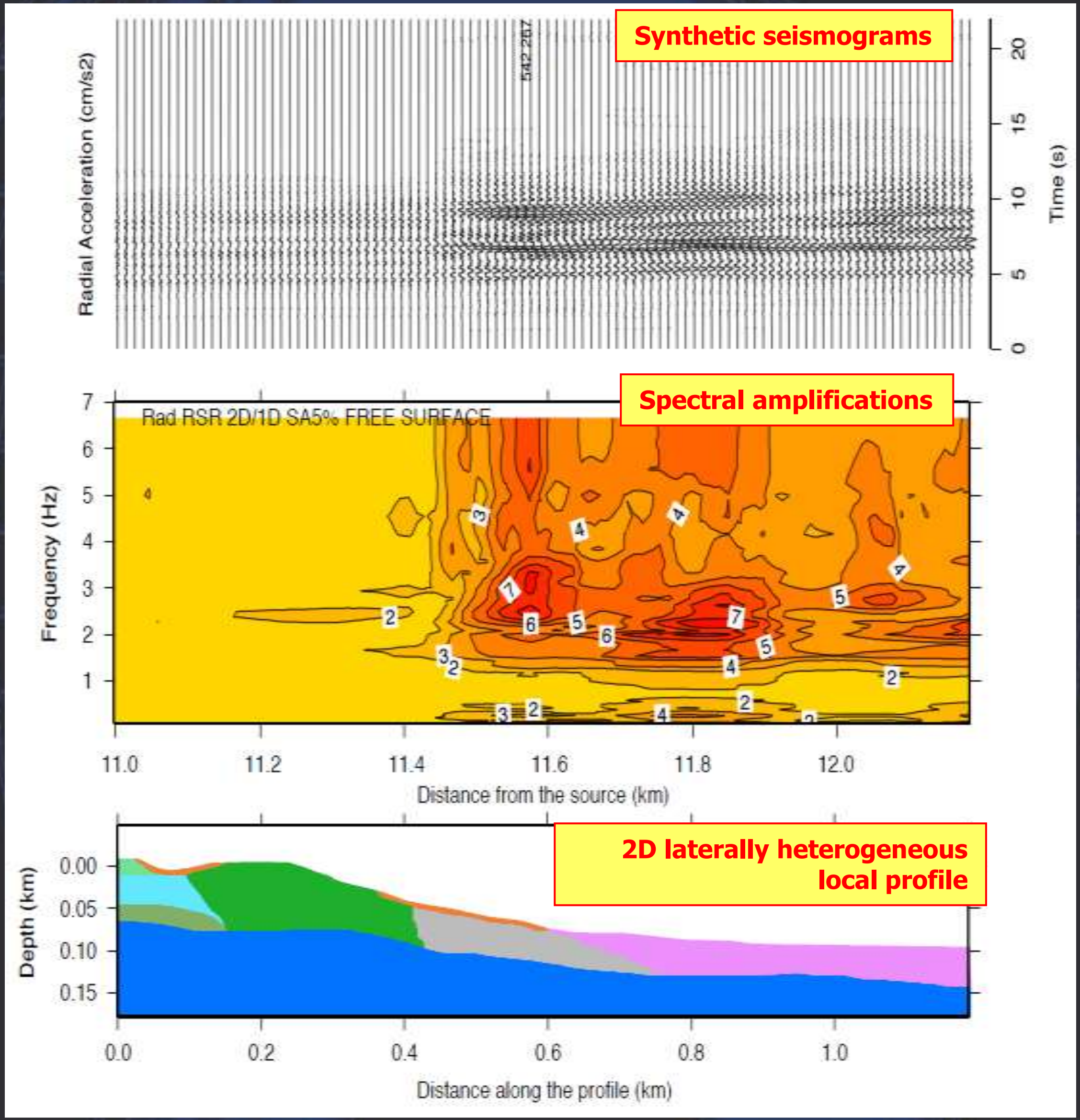
Detailed scenario of ground motion including local site effects

Detailed scenarios of ground motion, including site effects (2D sections describing the mechanical properties of the sites), can be defined at the local scale.

Hybrid Method:
Modal Summation + Finite Differences



Local ground shaking scenario for the Gubbio site



Source ITIS038 from DISS3 (Basili et al., 2008) is considered in the computations

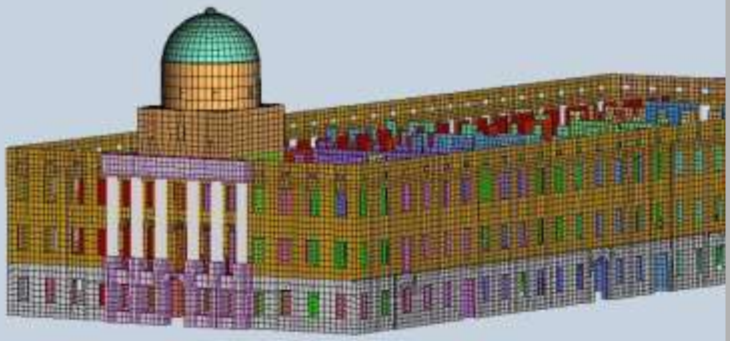
Detailed scenario of ground motion including local site effects

Engineering analysis

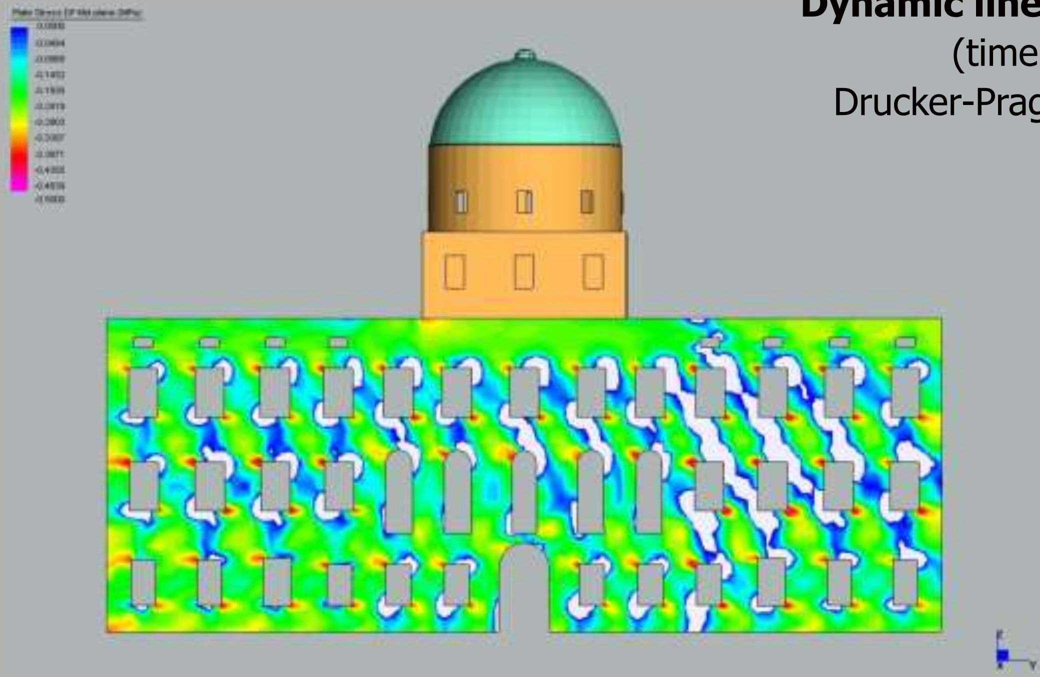
Realistic seismic input for detailed dynamic analysis of the structure

PALAZZO CARCIOTTI
(masonry)

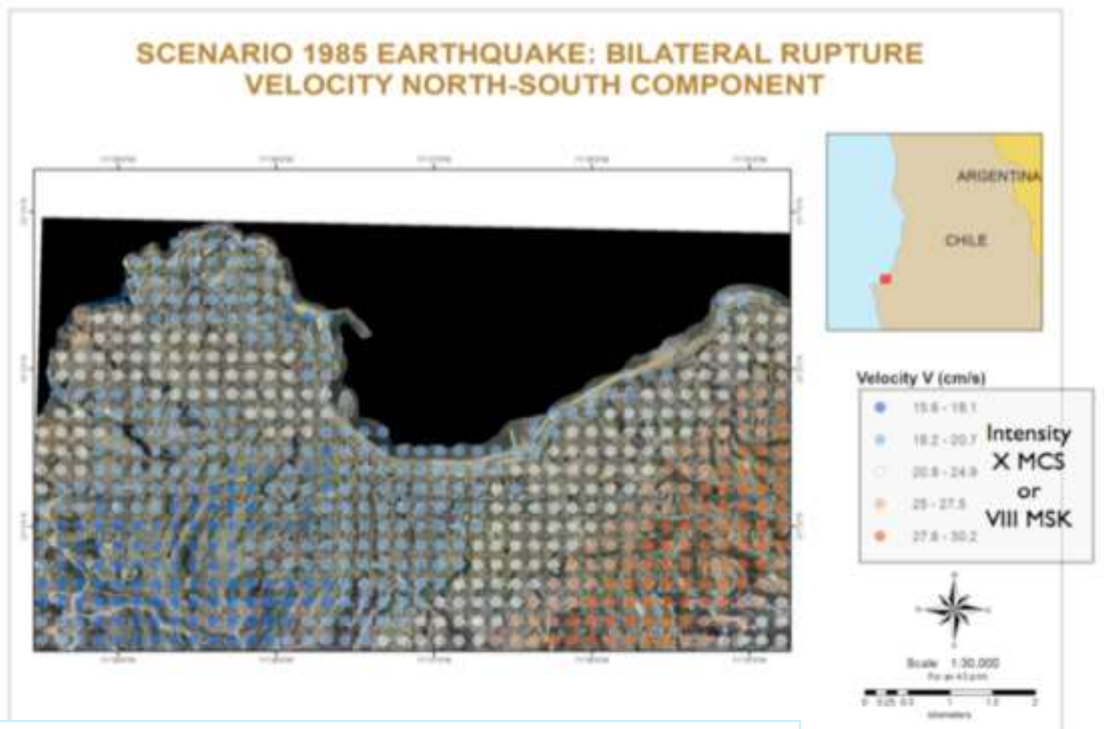
Model



Dynamic linear analysis
(time evolution of
Drucker-Prager tensions)

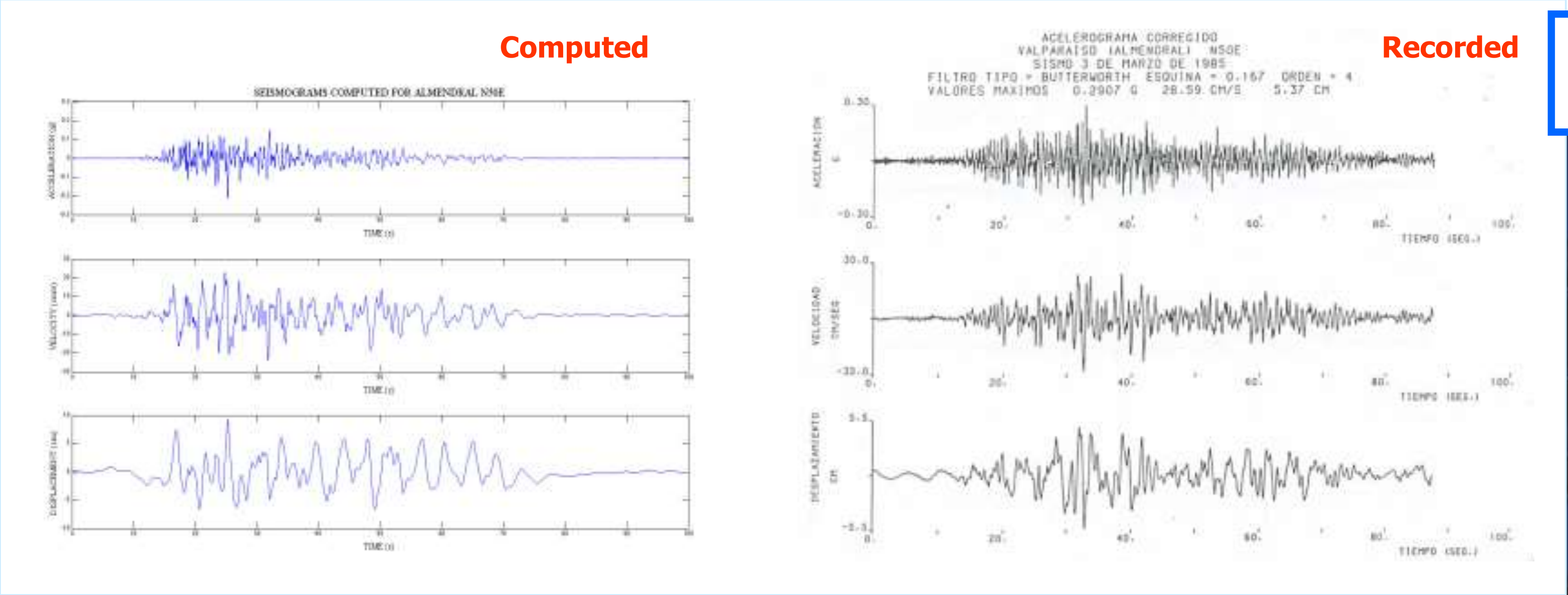


Scenario of ground motion at Valparaiso (Chile)



Groundshaking scenario at the bedrock level in the Valparaiso urban area.

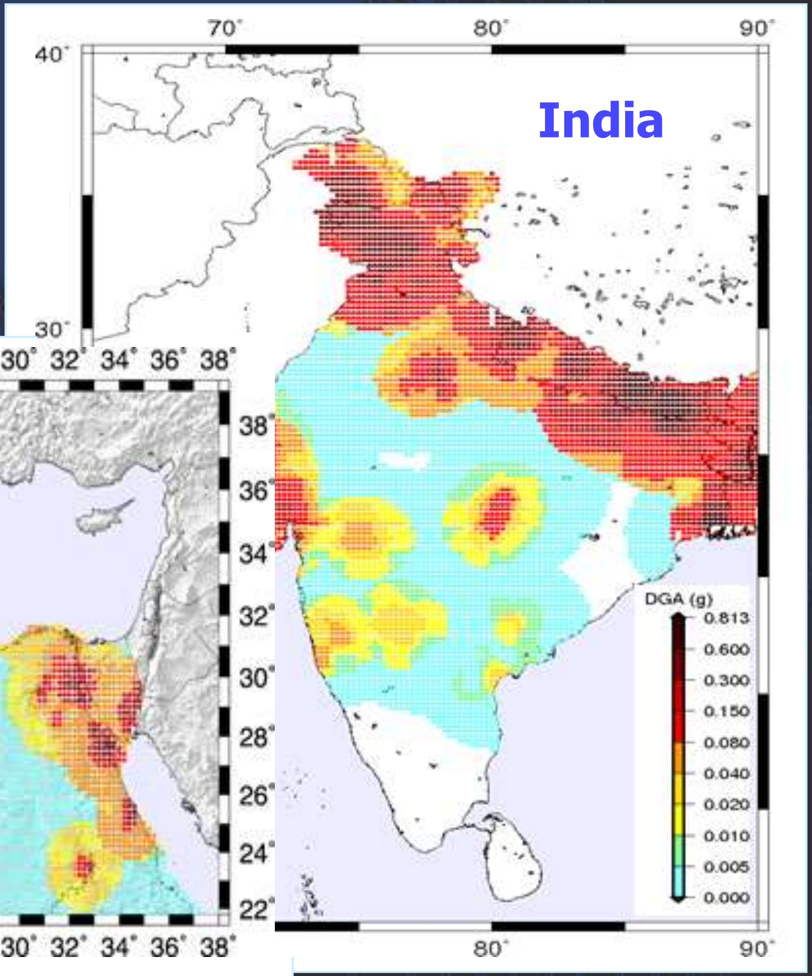
El Almendral station: acceleration, velocity and displacement for the 1985 event

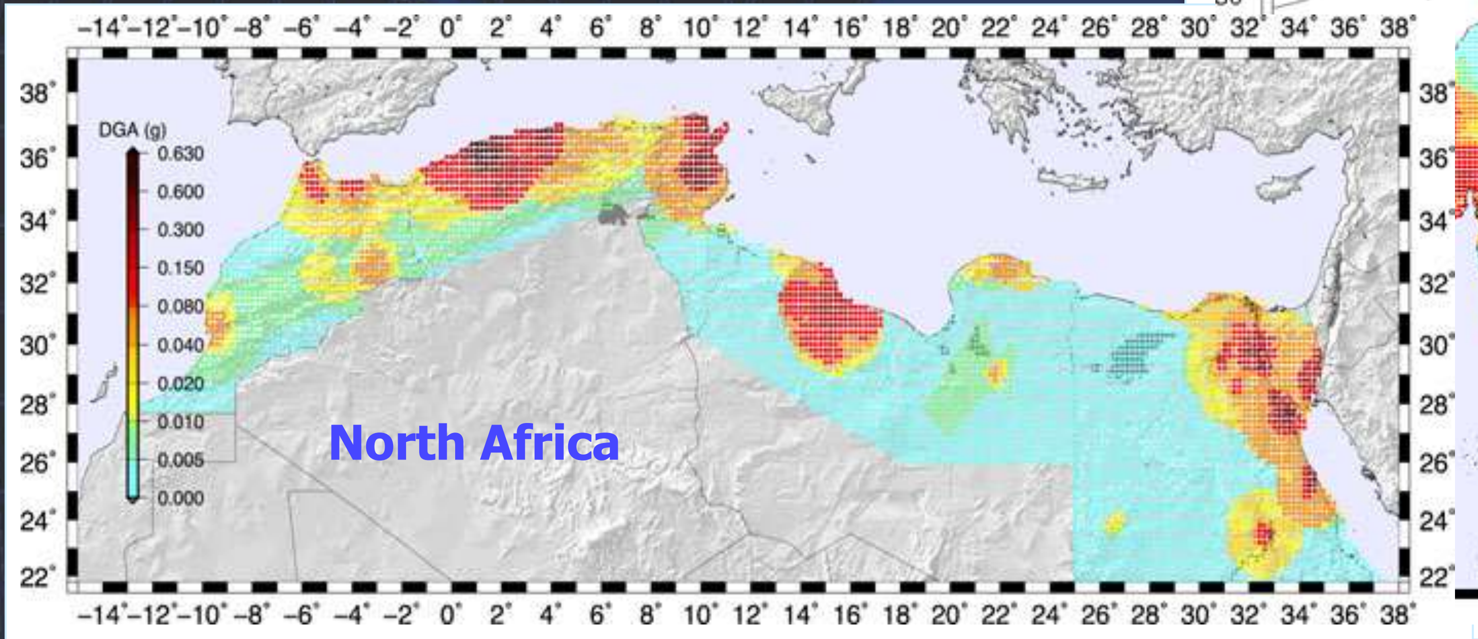


MAR VASTO Project

NDSHA has been applied in several countries, including:

- Bulgaria, Romania, Croatia, Slovenia, Hungary, Albania
- Morocco, Algeria, Tunisia, Lybia and Egypt
- India, China, Viet Nam
- Cuba, Chile, Ecuador
- Iran, Pakistan





Mourabit et al., J. of Seismology (2013)

UNESCO/IUGS/IGCP project 414

"Realistic Modelling of Seismic Input for Megacities and Large Urban Areas" Episodes, 2002, 25, 160-184.

Integrated neo-deterministic seismic hazard assessment - NDSHA

Regional ground shaking scenarios

(ground motion at bedrock)

Pattern Recognition of Earthquake Prone areas

- Pattern recognition technique is used to identify, **independently from seismicity information**, the sites where strong earthquakes are likely to occur.
- **Assumption**: strong events nucleate at the **nodes**, specific structures that are formed around intersections of lineaments.

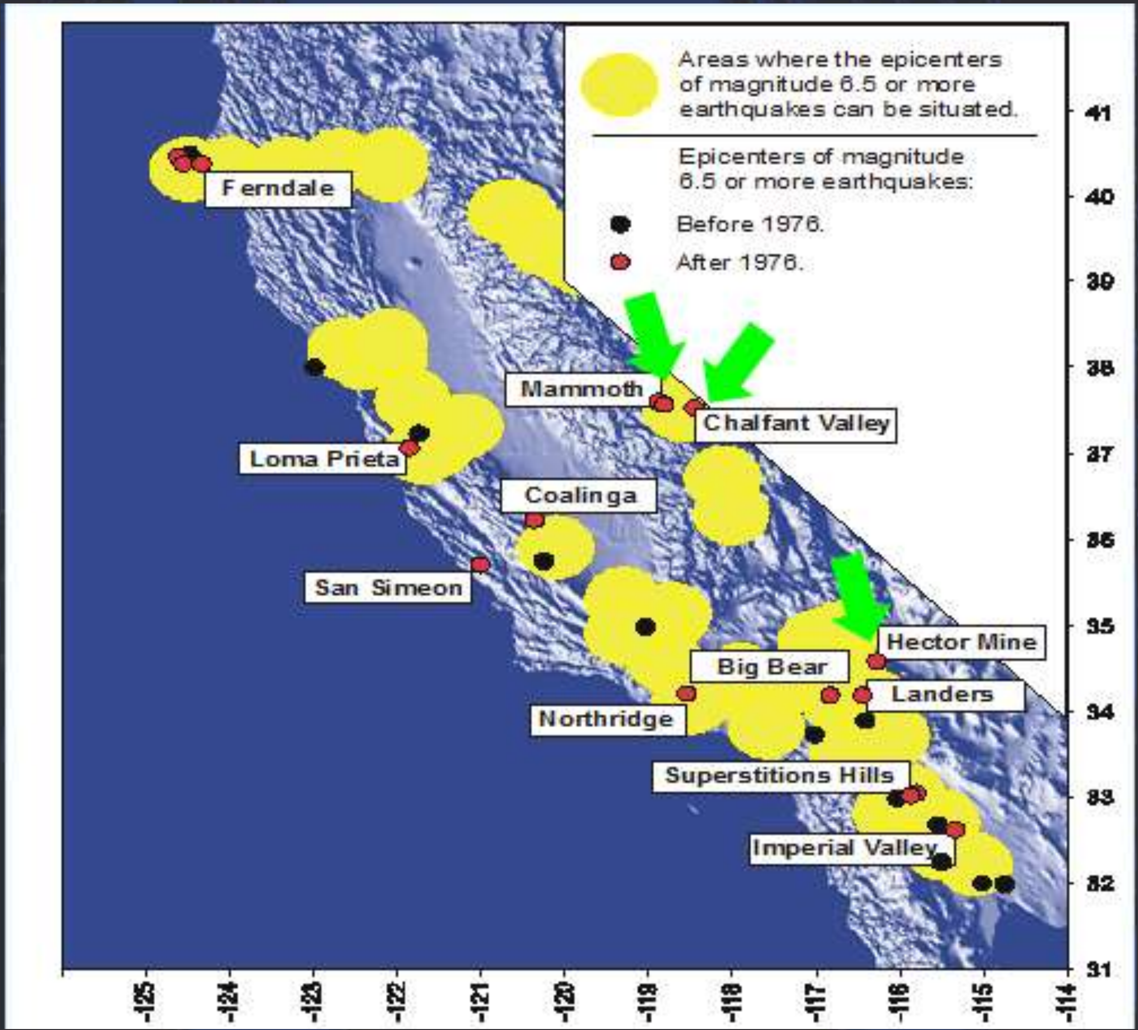
↓

- The nodes are defined by the **Morphostructural Zonation Method**, based on: topography, tectonic data, geological data.

Pattern Recognition of Earthquake Prone Areas

Post-publication earthquakes: California (1976) - M6.5+

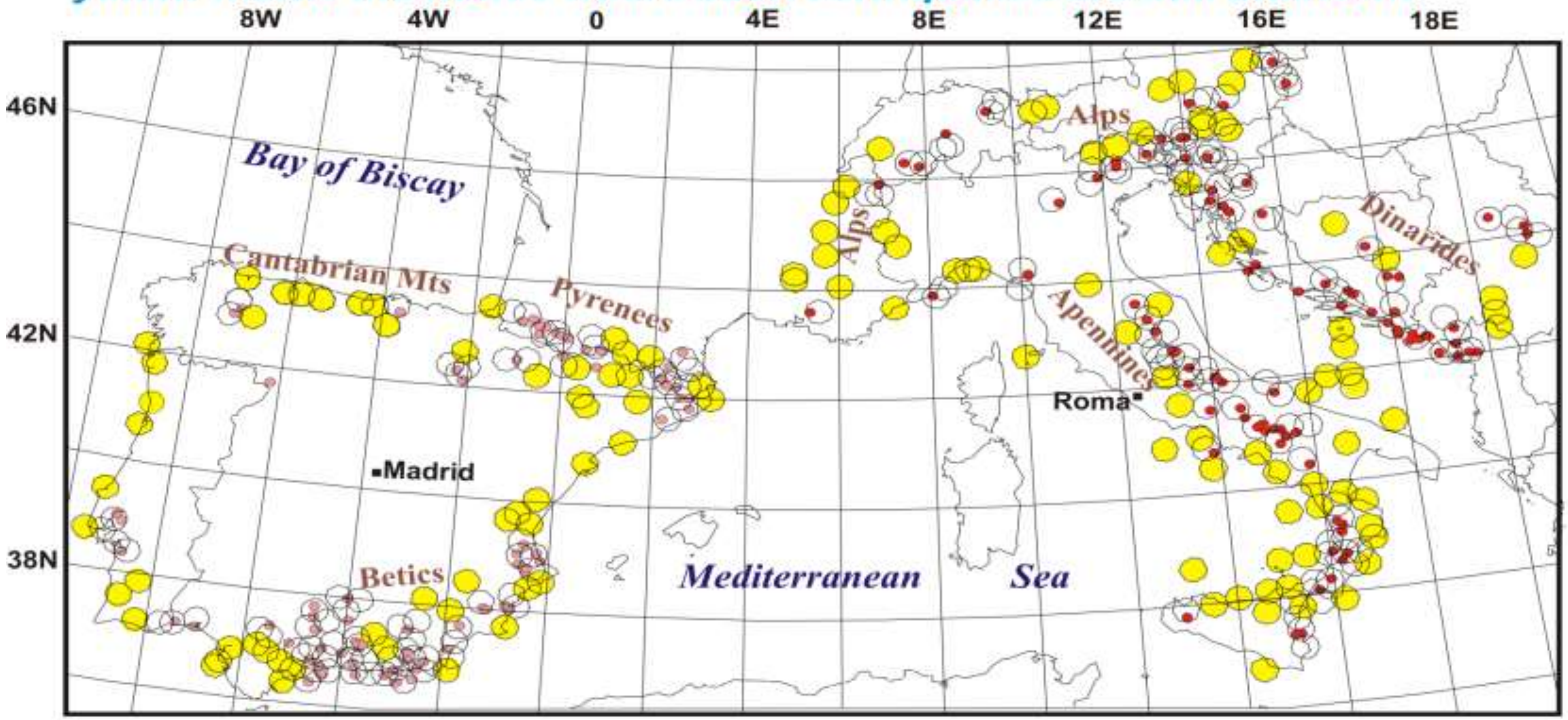
- **This approach has been successfully applied in many regions of the world, including California *(Keilis-Borok & Soloviev Eds., 2003).***
- **The identification of seismogenic nodes has been followed by many events in the last 4 decades ⇒ so far 79 out of 91 of the strong earthquakes (87% of the total) occurred in some of the previously recognized nodes.**



Recognition of nodes where strong earthquakes may nucleate in the Mediterranean area

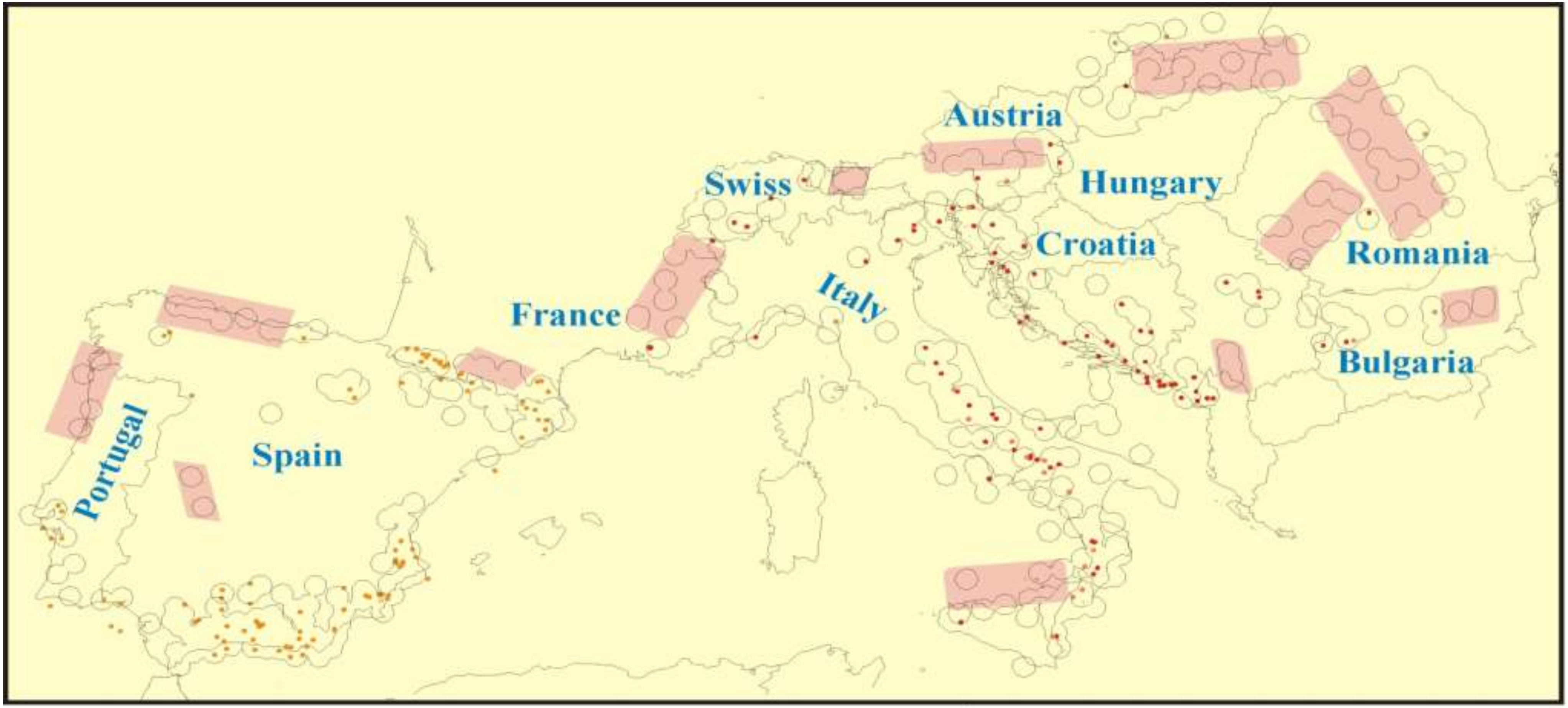
Target magnitudes: *M* ≥6.0 - Alps, Apennines and Dinarides
M ≥5.0 - Iberia

circles show earthquake-prone nodes
dots mark target earthquakes
yellow marks the nodes where such earthquakes are still unknown



References
Gorshkov A.I., Panza G.F., Soloviev A.A. & Aoudia A. (2002). Morphostructural zoning and preliminary recognition of seismogenic nodes around the Adria margin in peninsular Italy and Sicily. *JSEE:* Spring 2002, 4, No.1, 1-24.
Gorshkov A.I., Panza G.F., Soloviev A.A., Aoudia A. (2004). Identification of seismogenic nodes in the Alps and Dinarides. *Boll.Soc.Geol.Ital.* 123, 3-18.

Is the information on observed seismicity sufficient to identify the sites where large earthquakes may occur?



Recognition of morphostructural nodes where strong earthquakes may nucleate in the Mediterranean area

(Geomorphology + pattern recognition)

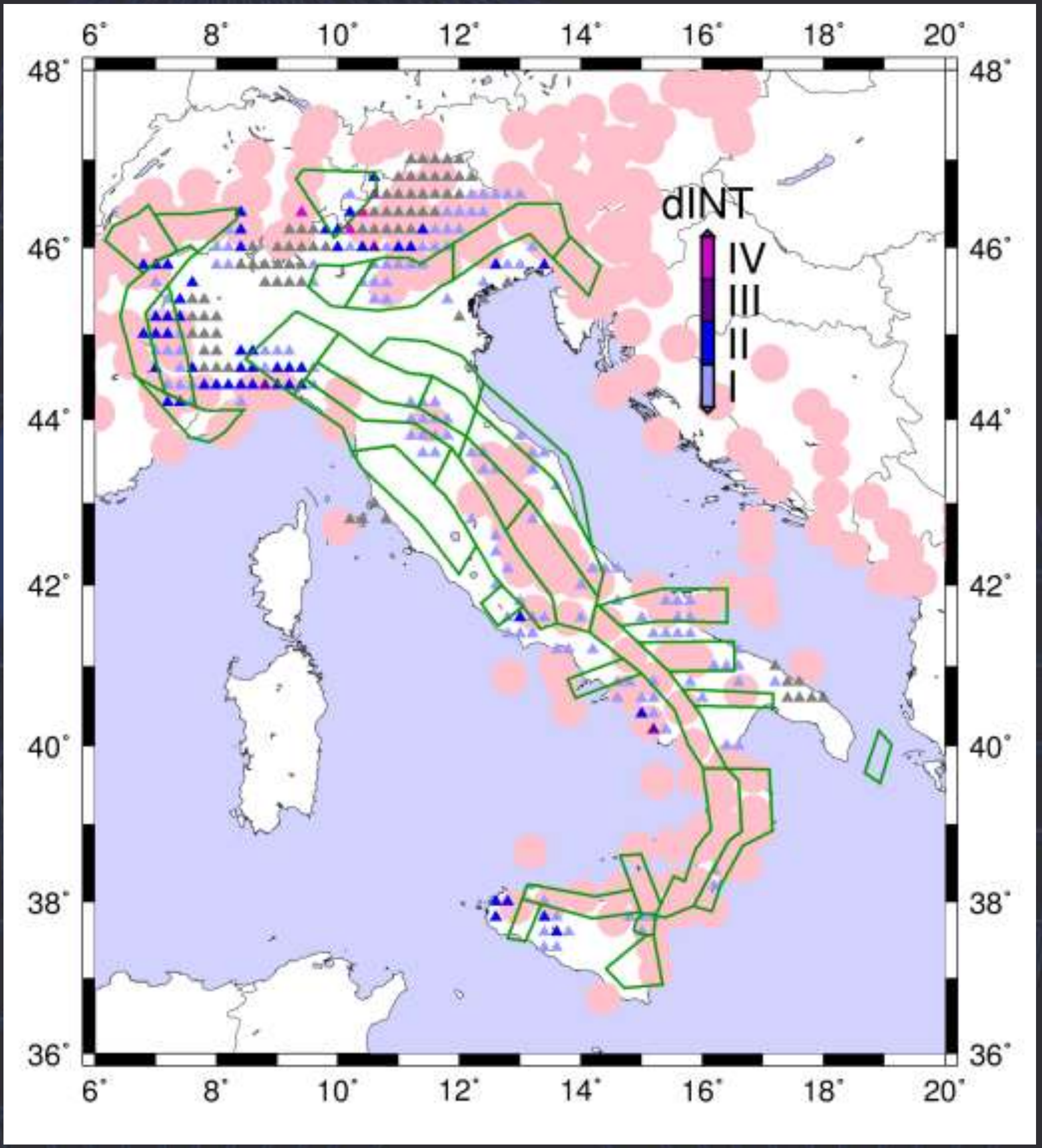
Courtesy by A.Gorshkov

Neo-deterministic seismic hazard assessment - NDSHA

Max(DGA)=0.556 g
Max (DGA_{nodes})=0.563 g

but…

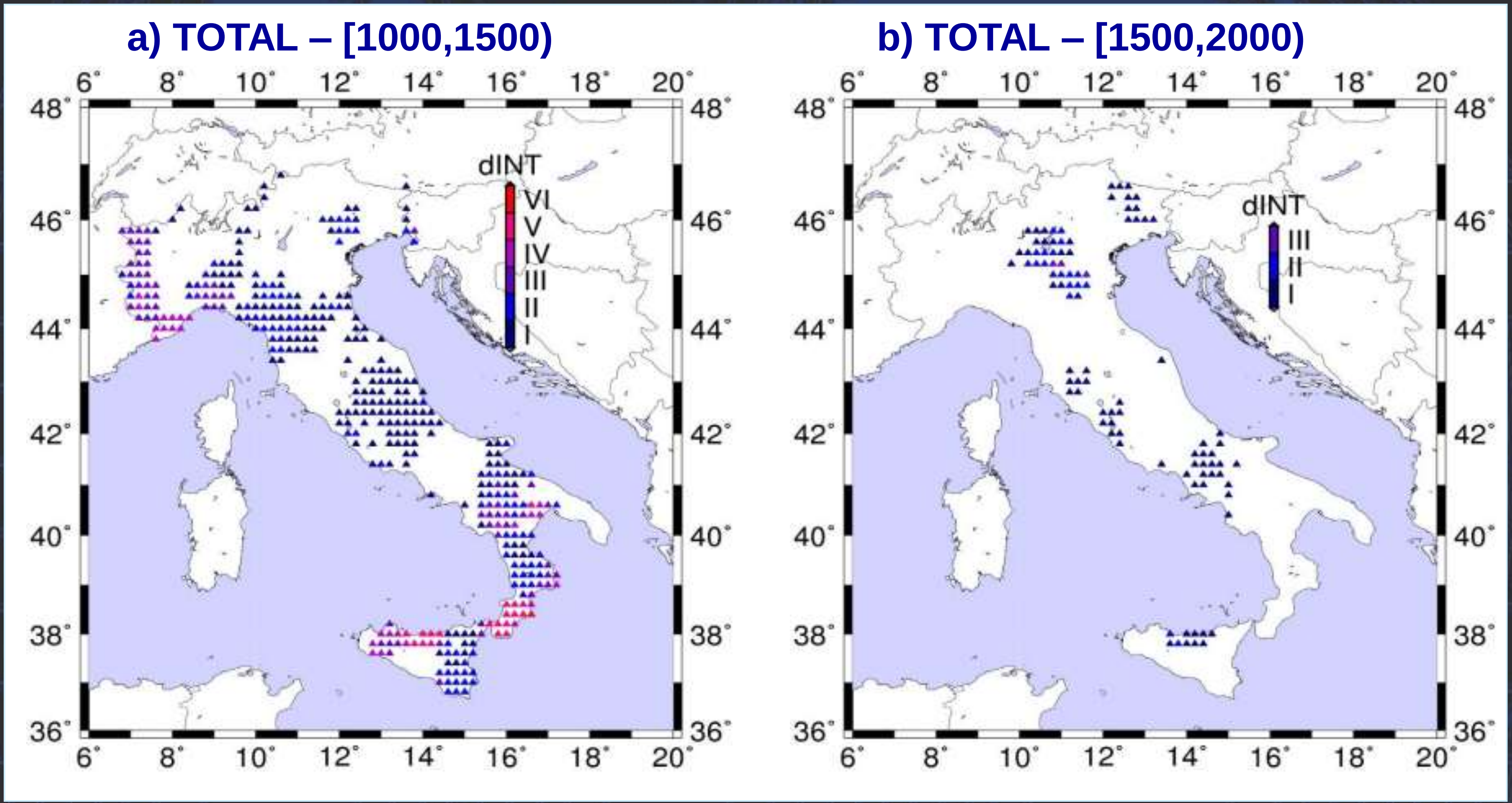
- Positive differences (upward triangles)
- Negative differences (downward triangles)
- Sites for which no value is given, when not considering seismogenic nodes (grey triangles)
- Seismogenic zones ZS9 (Meletti and Valensise, 2004) – polygons
- Seismogenic nodes identified for M≥6.0 and M≥6.5 (Gorshkov et al., 2002, 2004) - circles



Differences in intensity between the NDSHA maps computed with and without seismogenic nodes

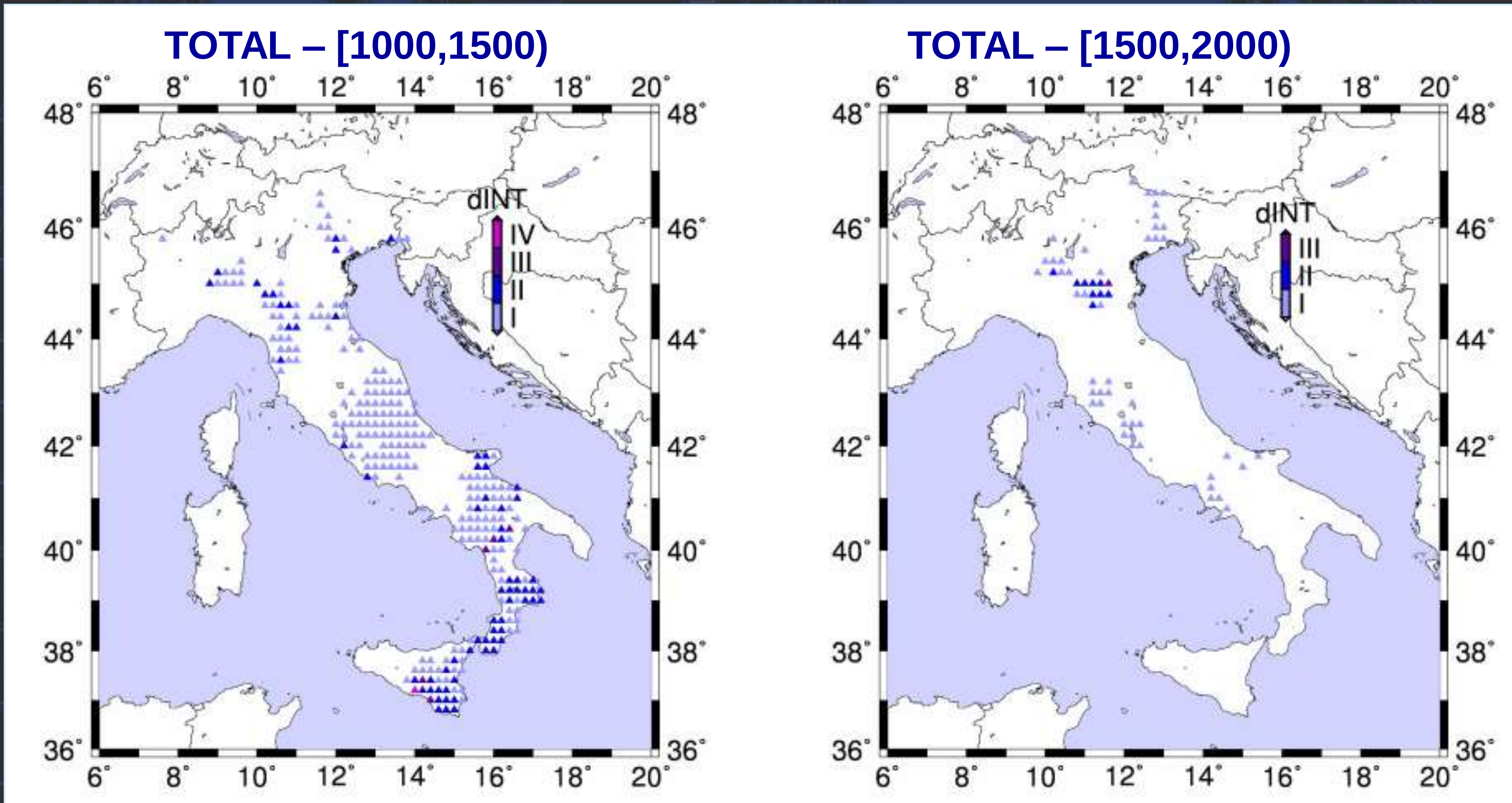
(Zuccolo et al., Pageoph., Vol.168. 2011)

NDSHA - Stability analysis:
the time span of the earthquake catalog



Intensity differences between the NDSHA map obtained considering the entire catalog (TOTAL) and the maps obtained for the following time intervals (500 years catalog): a) [1000,1500) e b) [1500, 2000)

Stability analysis:
the time span of the earthquake catalog (with nodes)



Intensity differences between the NDSHA map obtained for the entire catalog (TOTAL) and the maps obtained, considering the seismogenic nodes, for the time intervals: a) [1000,1500) e b) [1500, 2000)

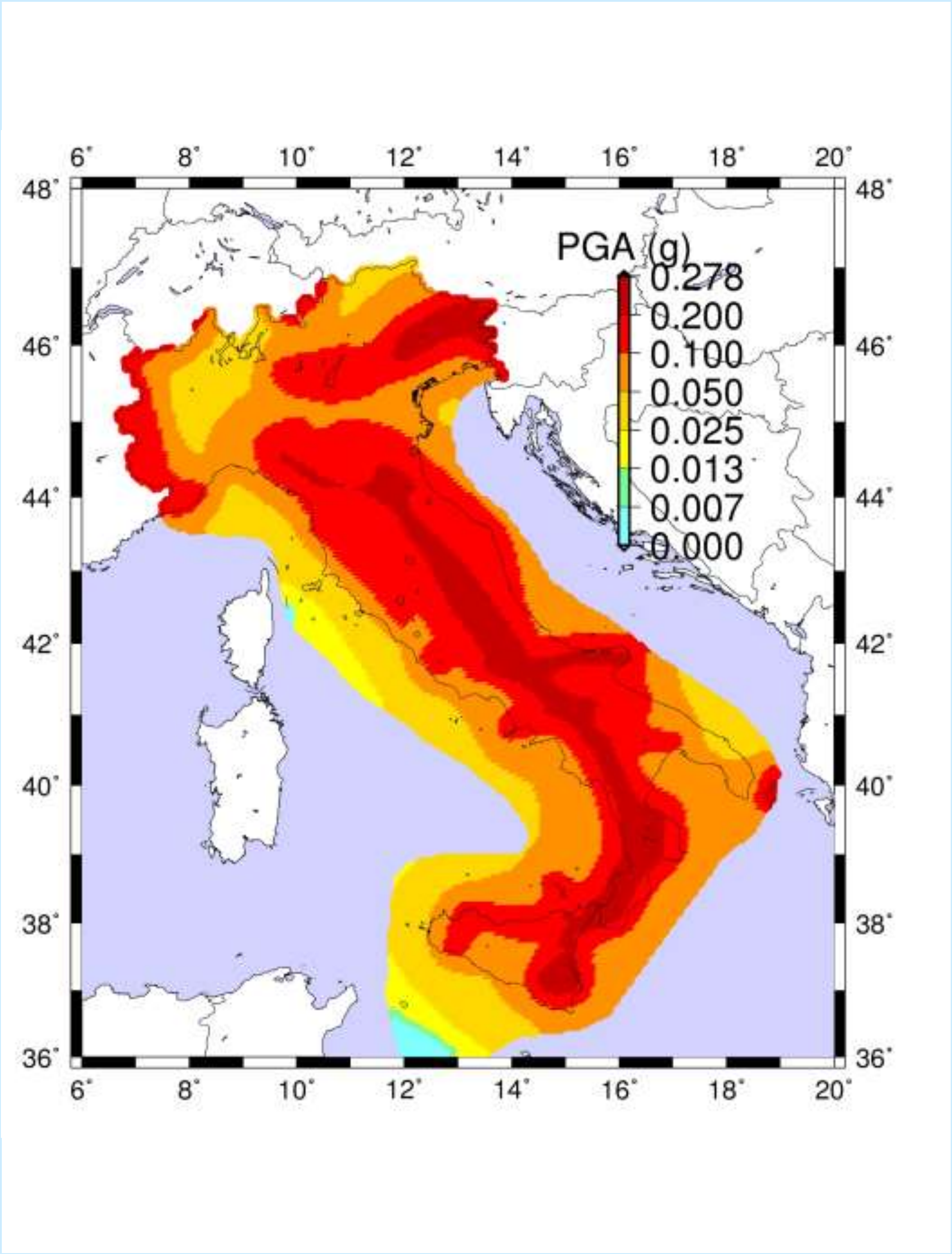
Stability analysis

- The stability analysis, testing the influence of the time span of the input catalog on NDSHA maps, shows that the seismicity level defined by earthquakes with M≥5.0, increased in the last 500 years with respect to that of the period [1000,1500).

- This observation suggests that the available information from past events may well not be representative of future earthquakes and that the use of independent indicators of the seismogenic potential of a given area is needed.

- The flexibility of the neo-deterministic method permits to incorporate the additional information about the possible location of strong earthquakes provided by the morphostructural analysis. This is impossible with PSHA!

PSHA vs NDSHA comparative analysis



Probabilistic seismic hazard map of Italy expressed in terms of expected PGA (g) with a probability of exceedance of 10% in 50 years (return period 475 years): http://zonesismiche.mi.ingv.it/mappa_ps_apr04/italia.html

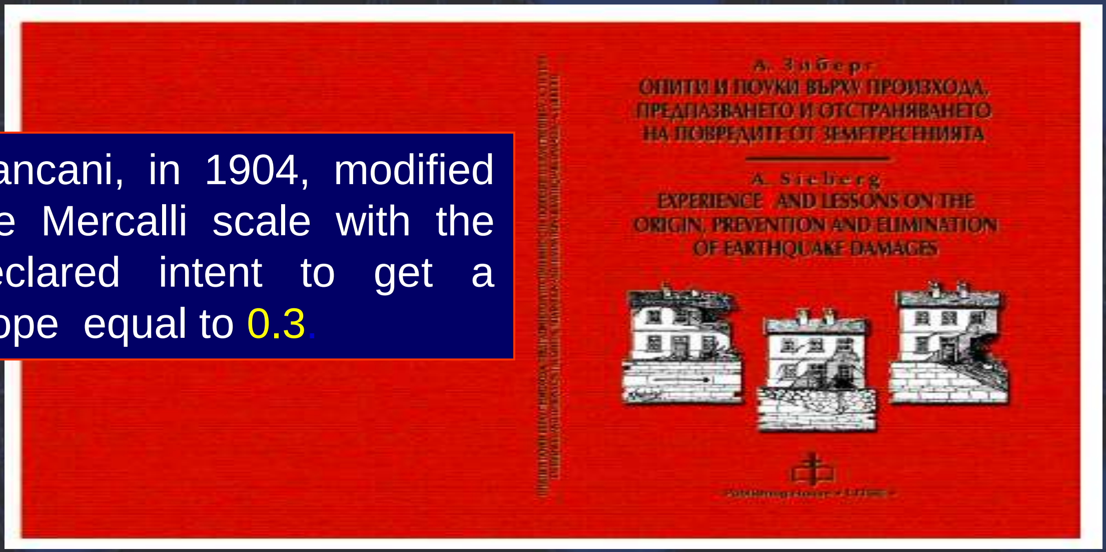
The colour palette is the same used for the neo-deterministic maps: each interval corresponds to one degree of Intensity (MCS).

Macroseismic Intensities

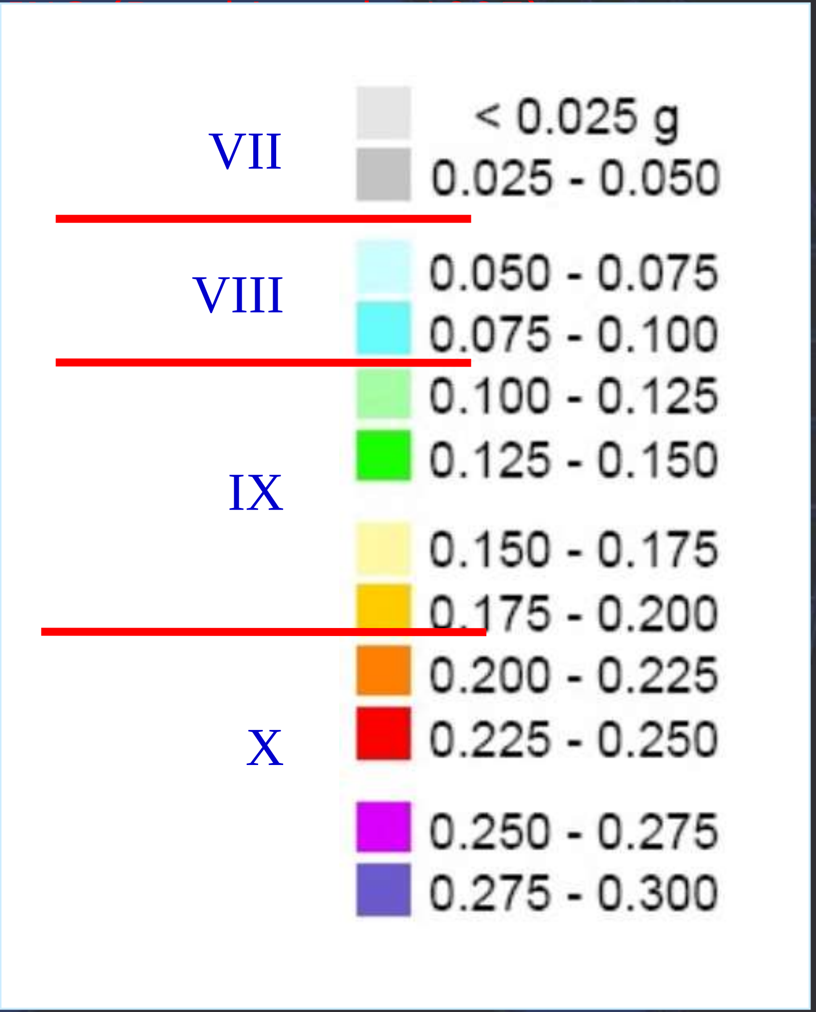
Peak value (I)/Peak value (I-1)~2

One degree of intensity corresponds to a factor 2 in the values of ground motion

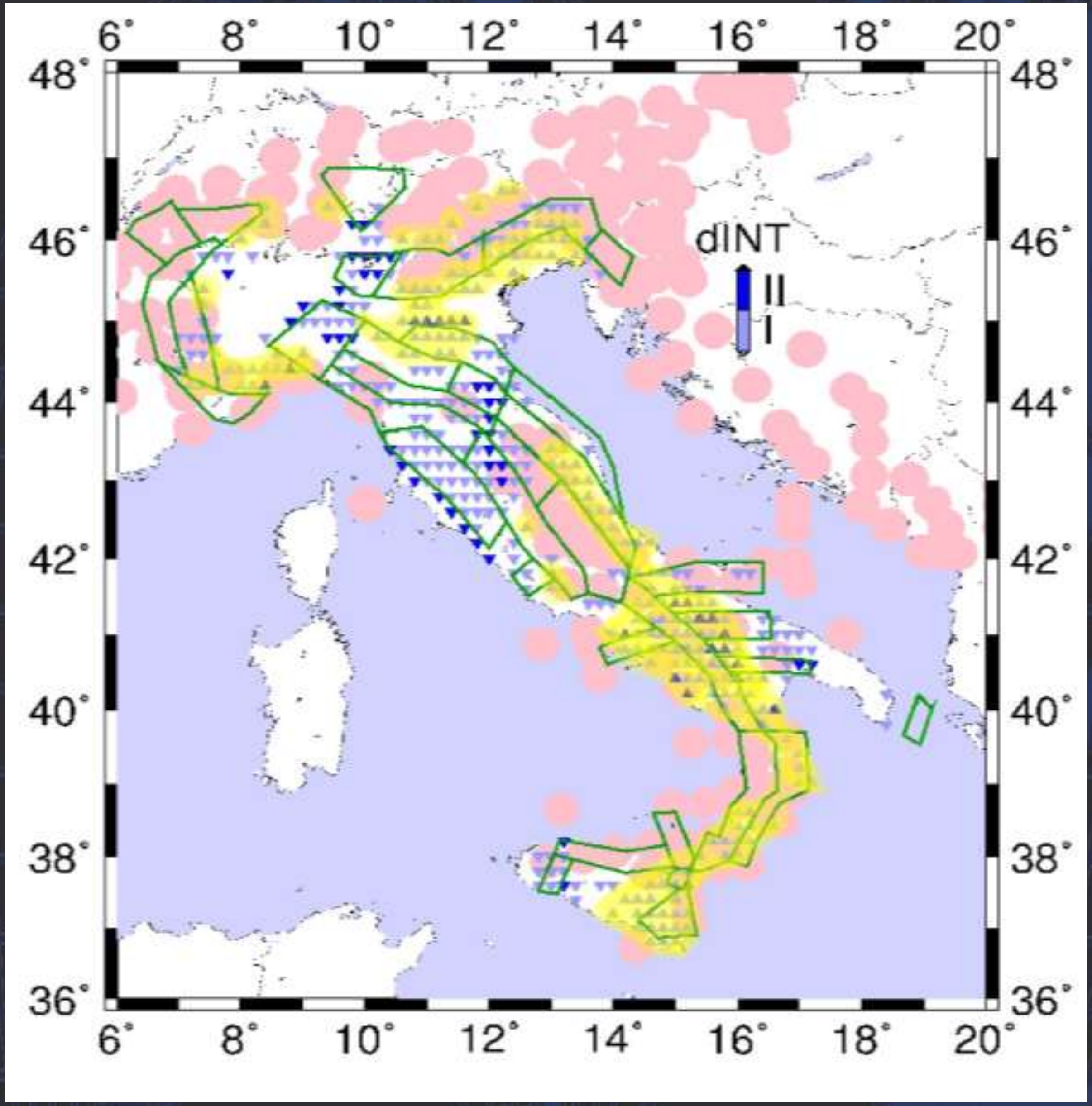
The log-linear regression between maximum observed macroseismic intensity, I (MCS), and computed peak values of ground motion (A), considering historical events, has a slope ≈ 0.3



Cancani, in 1904, modified the Mercalli scale with the declared intent to get a slope equal to 0.3.



NDSHA (standard maps) – PSHA



Zuccolo, Vaccari, Peresan, Panza (2011), Pageoph, vol. 168

Comparison PSHA - NDSHA

Intensity differences

- **NDSHA > PSHA**
in high-seismicity areas and in areas identified as prone to large earthquakes, but where no strong earthquake has been recorded in the last 1000 years.

- **NDSHA < PSHA**
in low-seismicity areas

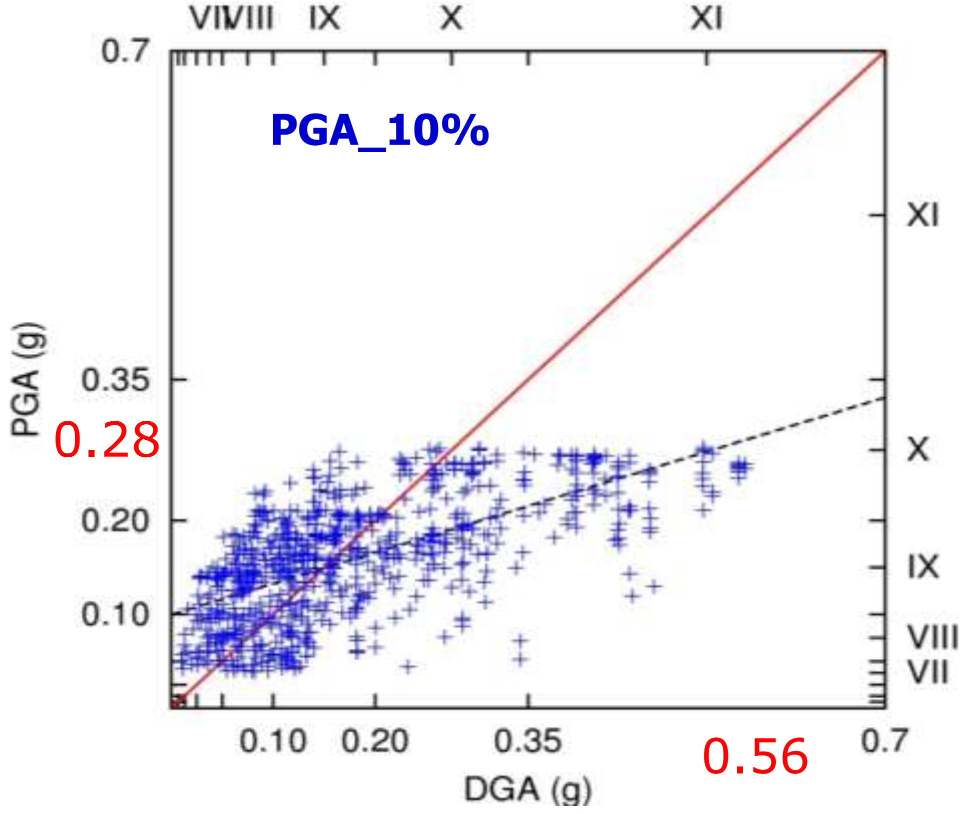
Comparison PSHA - NDSHA

- The comparison of maps produced for Italy by the PSHA and NDSHA approaches shows that, as a rule, NDSHA provides values larger than those given by the PSHA in high-seismicity areas and in areas identified as prone to large earthquakes, but where no strong earthquake has been recorded in the last 1000 years.

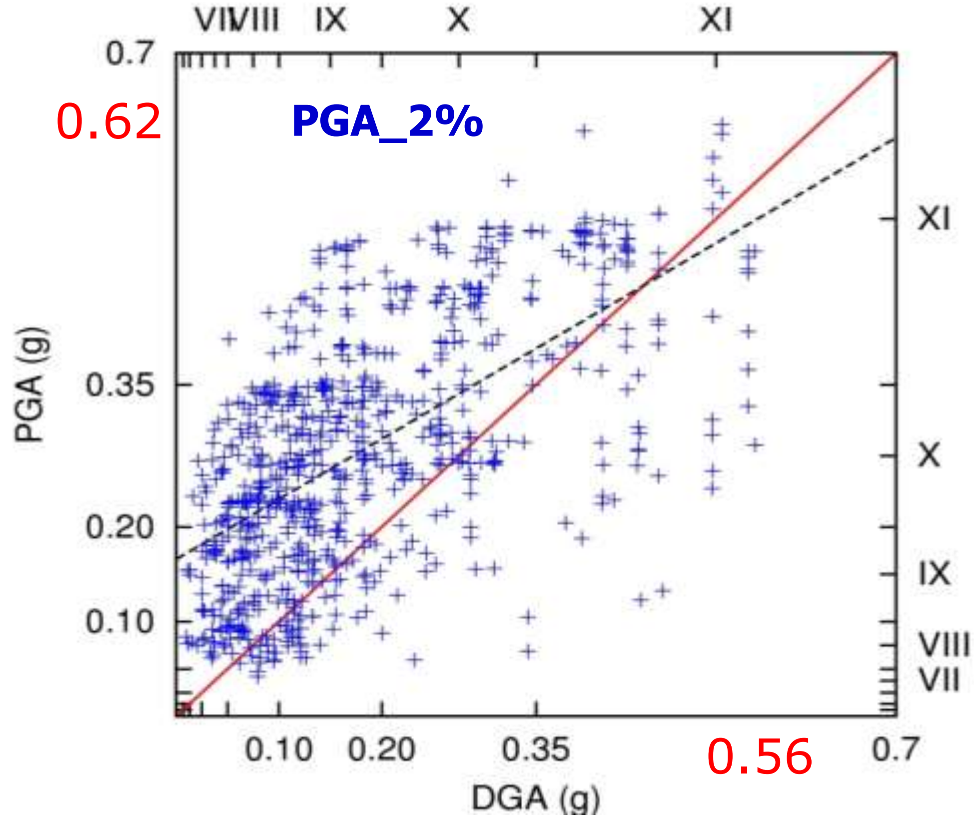
- Comparatively smaller values are obtained in low-seismicity areas.

Comparison PSHA – NDSHA
Italian territory

PGA vs DGA



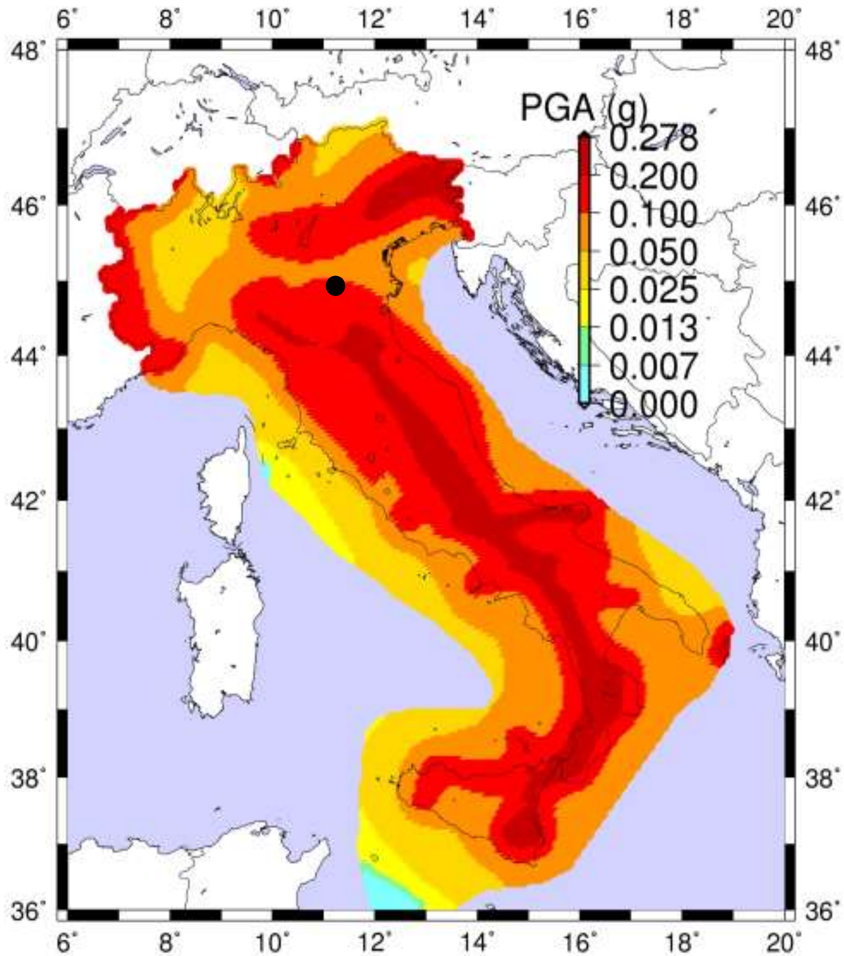
10% Probability of exceedance
in 50 years (T = 475 years)



2% Probability of exceedance
in 50 years (T = 2475 years)

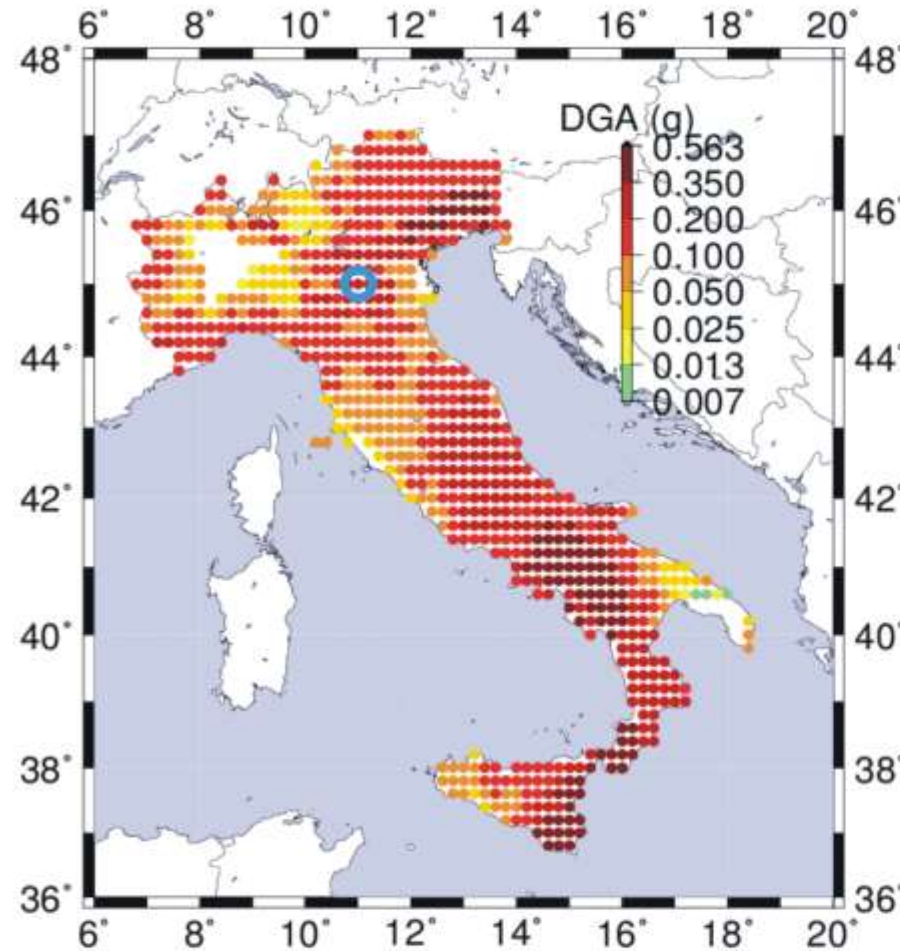
Zuccolo, Vaccari, Peresan, Panza (2011), Pageoph, vol. 168

The Emilia earthquake, 20th May 2012 (M6.1)



PSHA: 0.100 - 0.200 g

NDSHA



PSHA: 0.125 - 0.150 g

NDSHA: 0.200 – 0.350 g

Observed: ~ 0.25 g

Peresan & Panza (EOS, Vol.93, n. 51 – December 2012)

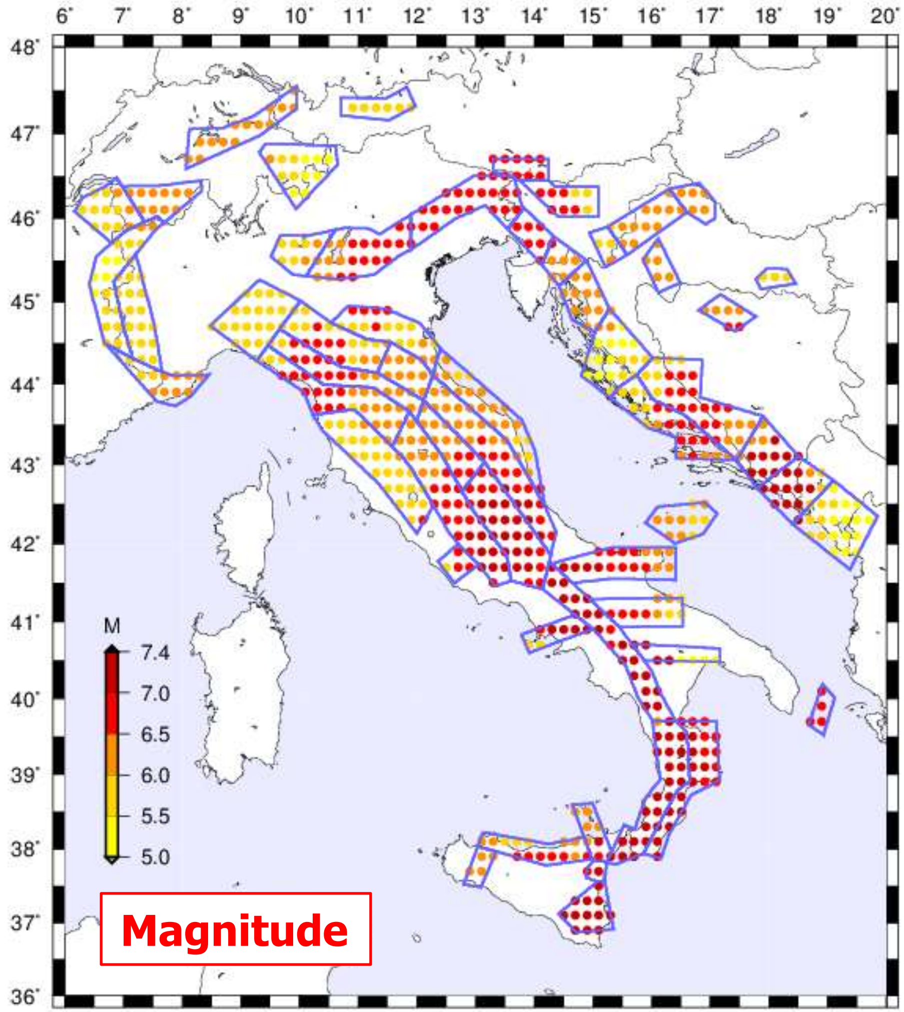
Improving Earthquake Hazard Assessments in Italy: An Alternative to "Texas Sharpshooting"

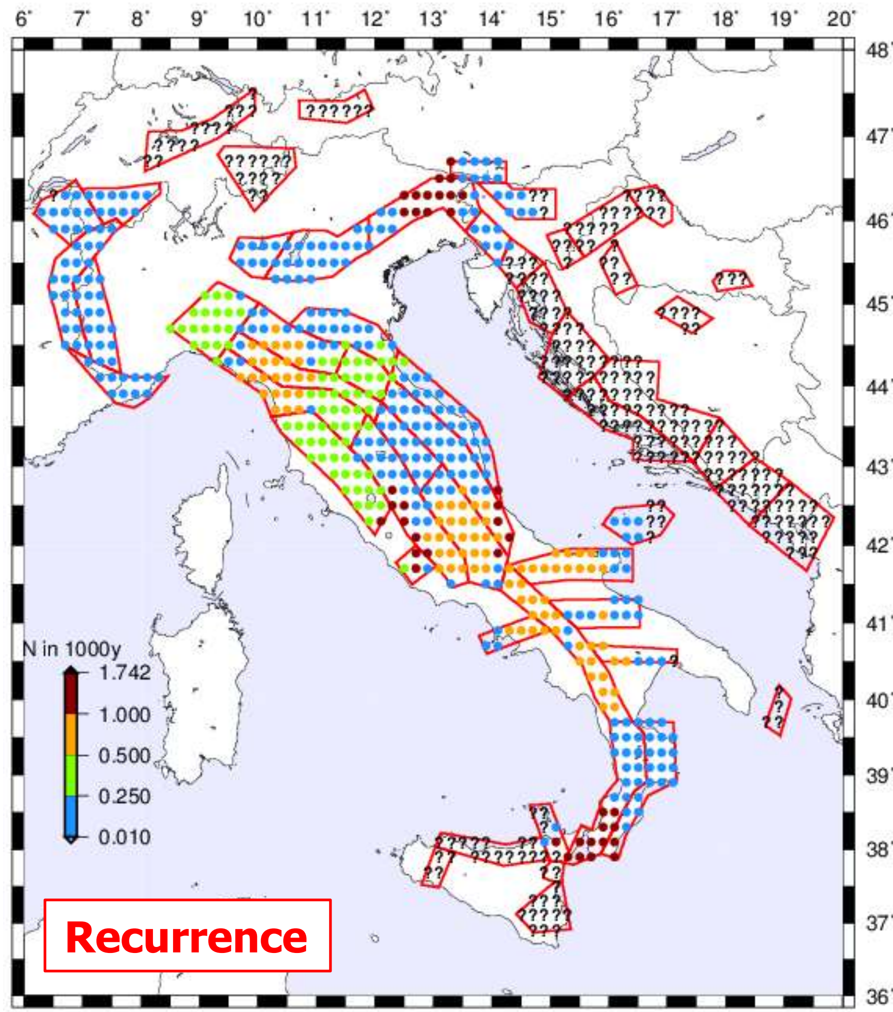
NDSHA
and earthquake recurrence

Regional ground shaking scenarios associated with earthquakes recurrence

(ground motion at bedrock)

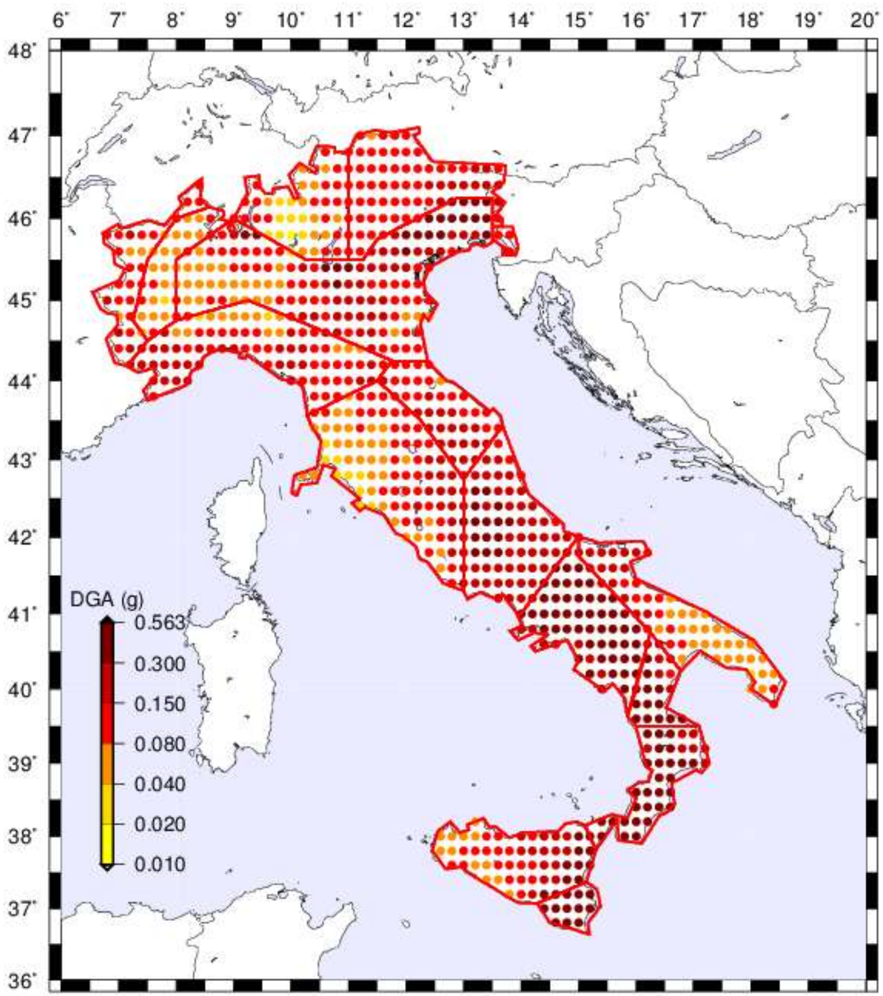
NDSHA maps of Ground Shaking: Seismic sources and recurrence





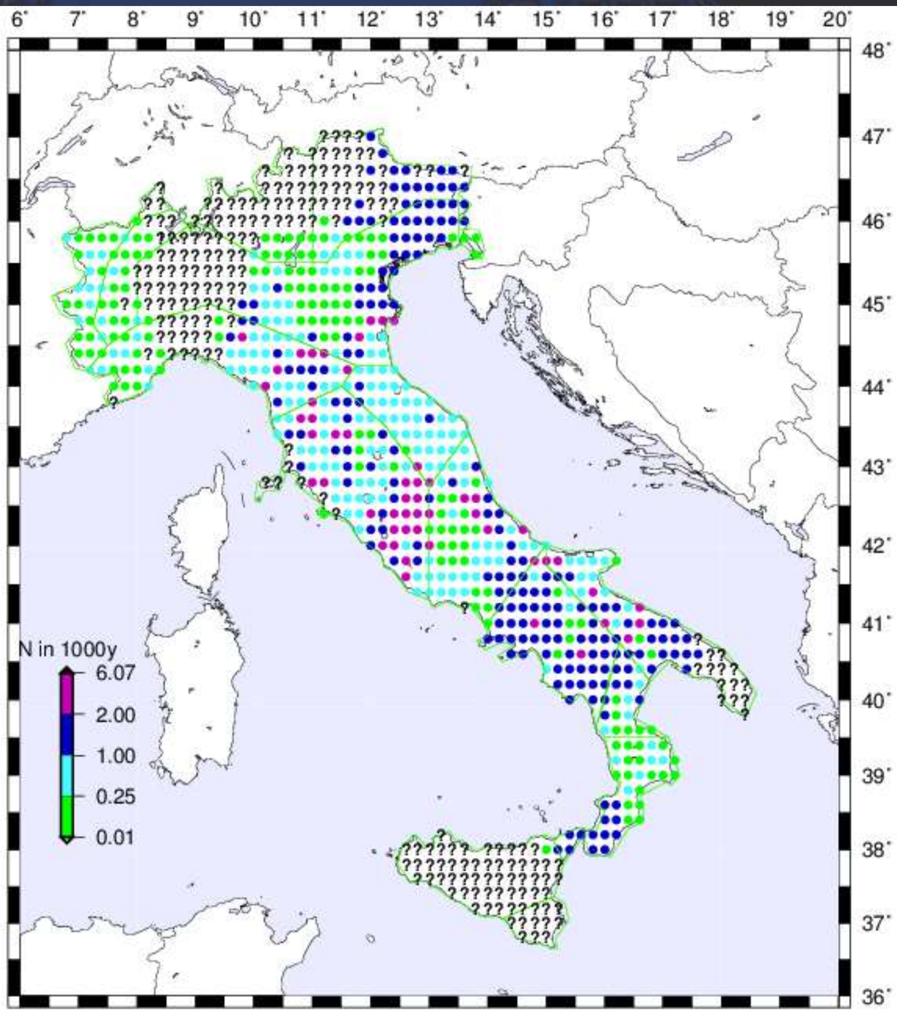
Seismic sources are characterized based on: maximum observed magnitude, earthquakes recurrence and FPS from seismogenic zones

NDSHA maps of Ground Shaking: DGA and Recurrence estimates



Ground shaking scenario: DGA

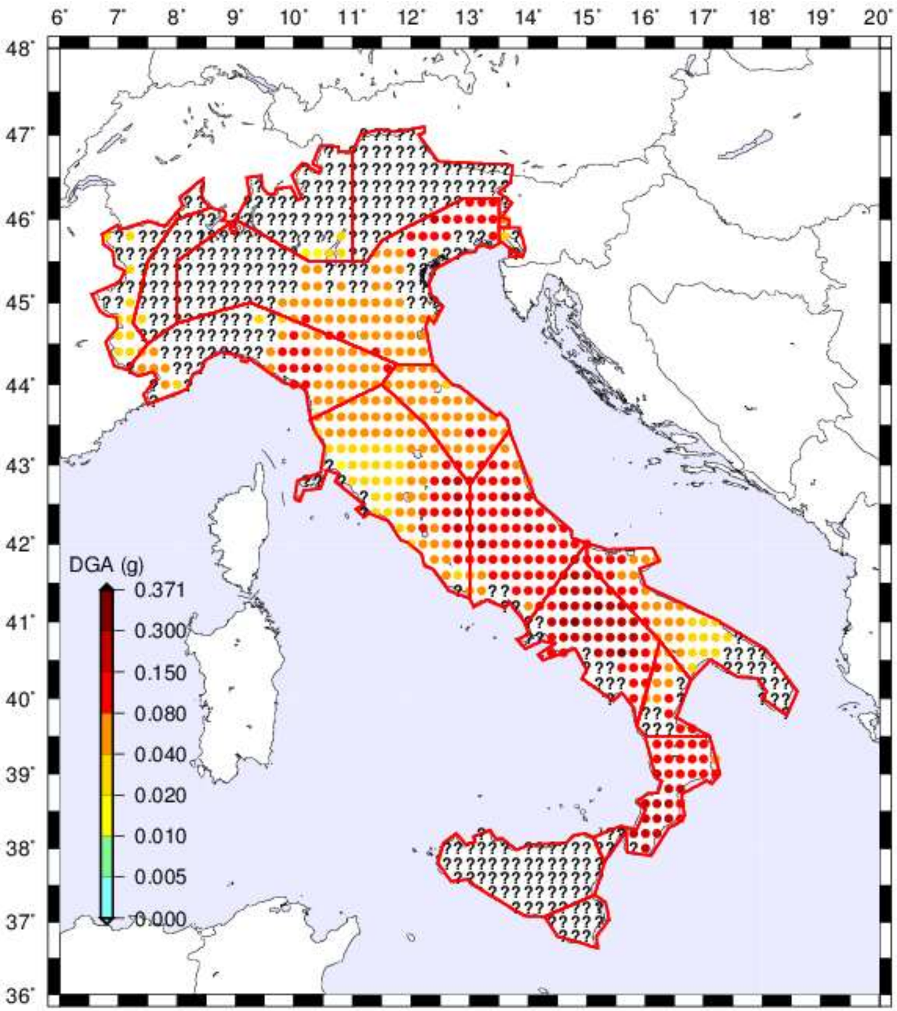
Design ground acceleration for all the possible sources within the seismogenic zones and nodes



Ground shaking scenario: recurrence

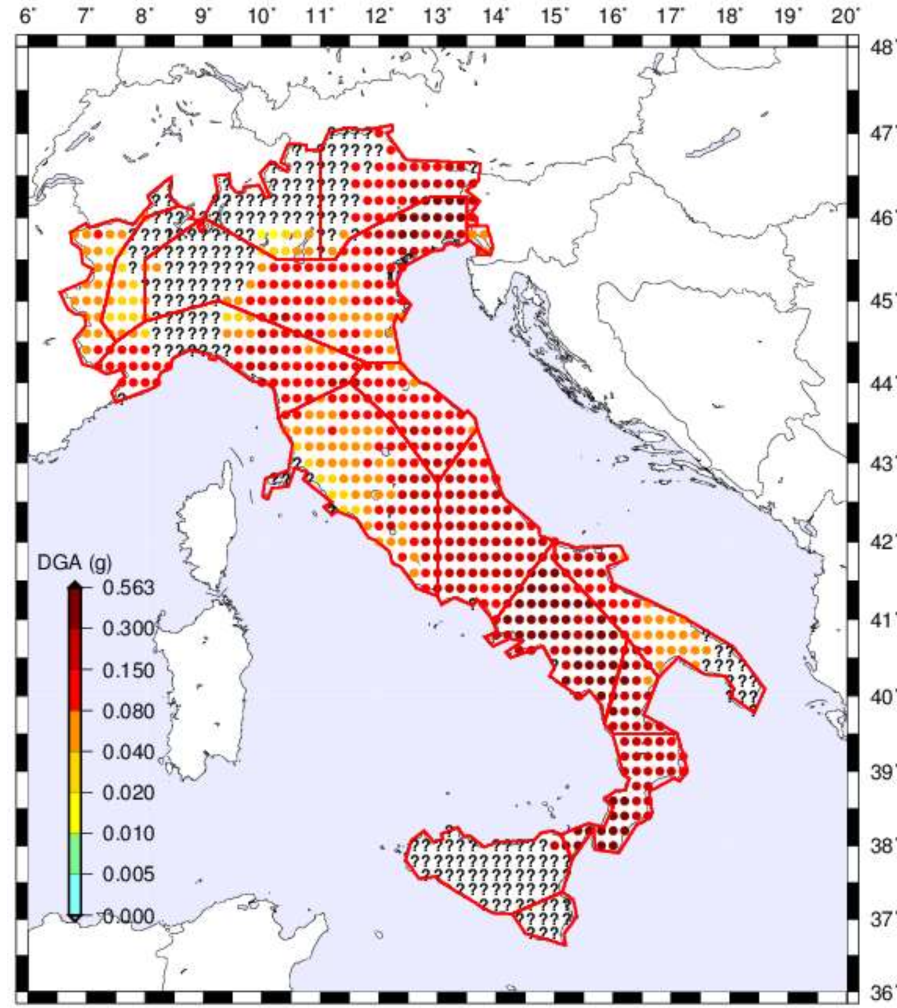
Recurrence estimates associated to the ground motion values of the DGA map

NDSHA maps of Ground Shaking at Fixed Return Period



Ground shaking scenario: DGA_10%

Return Period T = 475 years



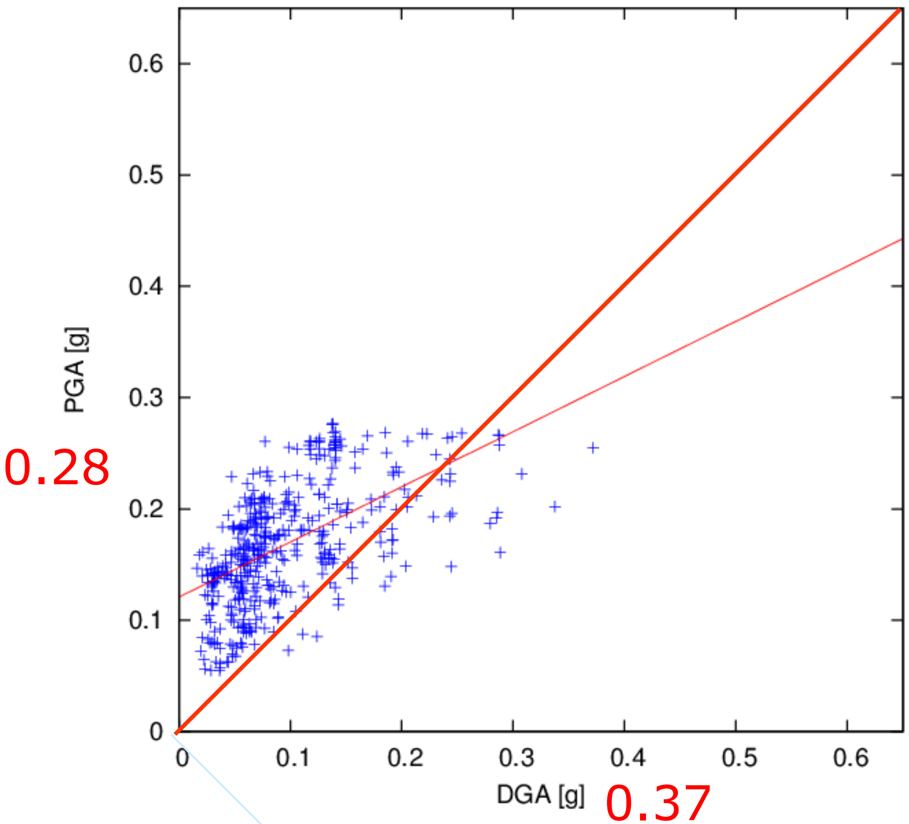
Ground shaking scenario: DGA_2%

Return period T = 2475 years

Comparison PSHA – NDSHA
Italian territory

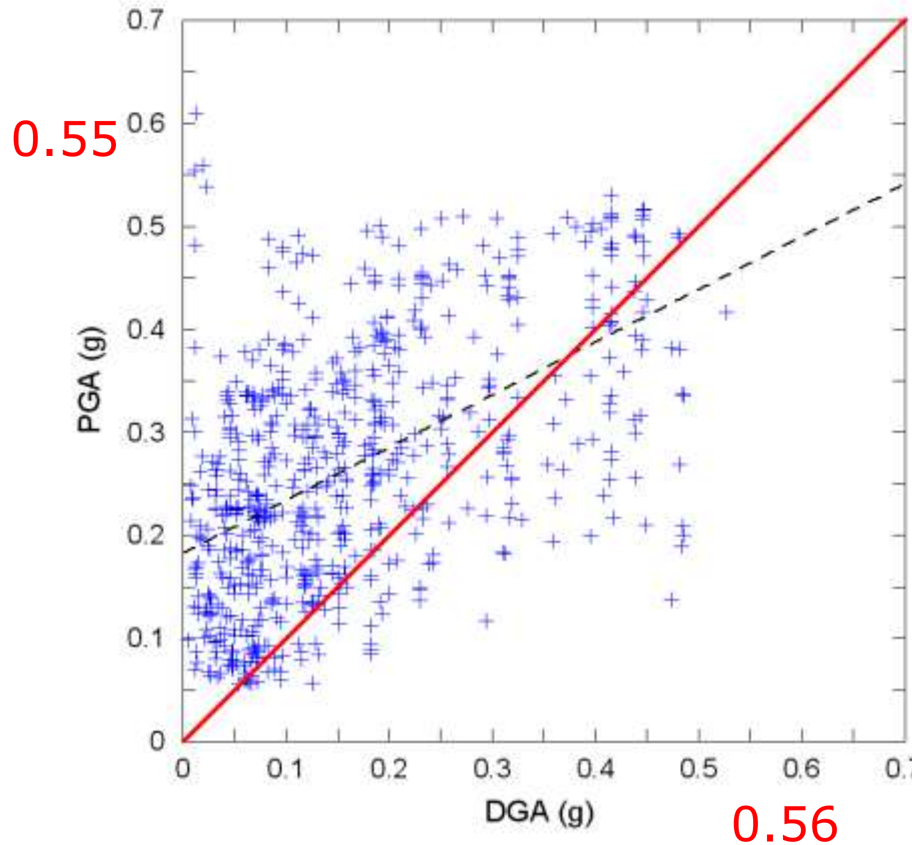
PGA vs DGA

10% Probability of exceedance
in 50 years (T = 475 years)



PGA_10% vs DGA_10%

2% Probability of exceedance
in 50 years (T = 2475 years)



PGA_2% vs DGA_2%

Conclusions

- The neo-deterministic seismic hazard procedure, NDSHA, makes it possible to incorporate geological and geophysical data sets, and permits to account for earthquake recurrence.

- NDSHA is especially useful as a mean of prevention in areas where historical and instrumental information is scarce, since it allows considering a wide set of scenarios and parametric analyses, without waiting for the strong earthquakes to occur.

- The reliability of hazard assessment by NDSHA is not severely limited by earthquake recurrence properties and by the short length of earthquake catalogues. This is particularly relevant for NPP and industrial plants, for which with PSHA very long return periods must be considered.

Conclusions

- Traditional PSHA maps strongly depend on assumptions about recurrence of large earthquakes that have large uncertainties and often turn out incorrect.

- Accounting for the lower probability of earthquakes with long recurrence times is an attractive feature in formulating cost-effective policies - but underpredicts the shaking if the strong earthquakes occur.

Italian Parliament Resolution 8/00124

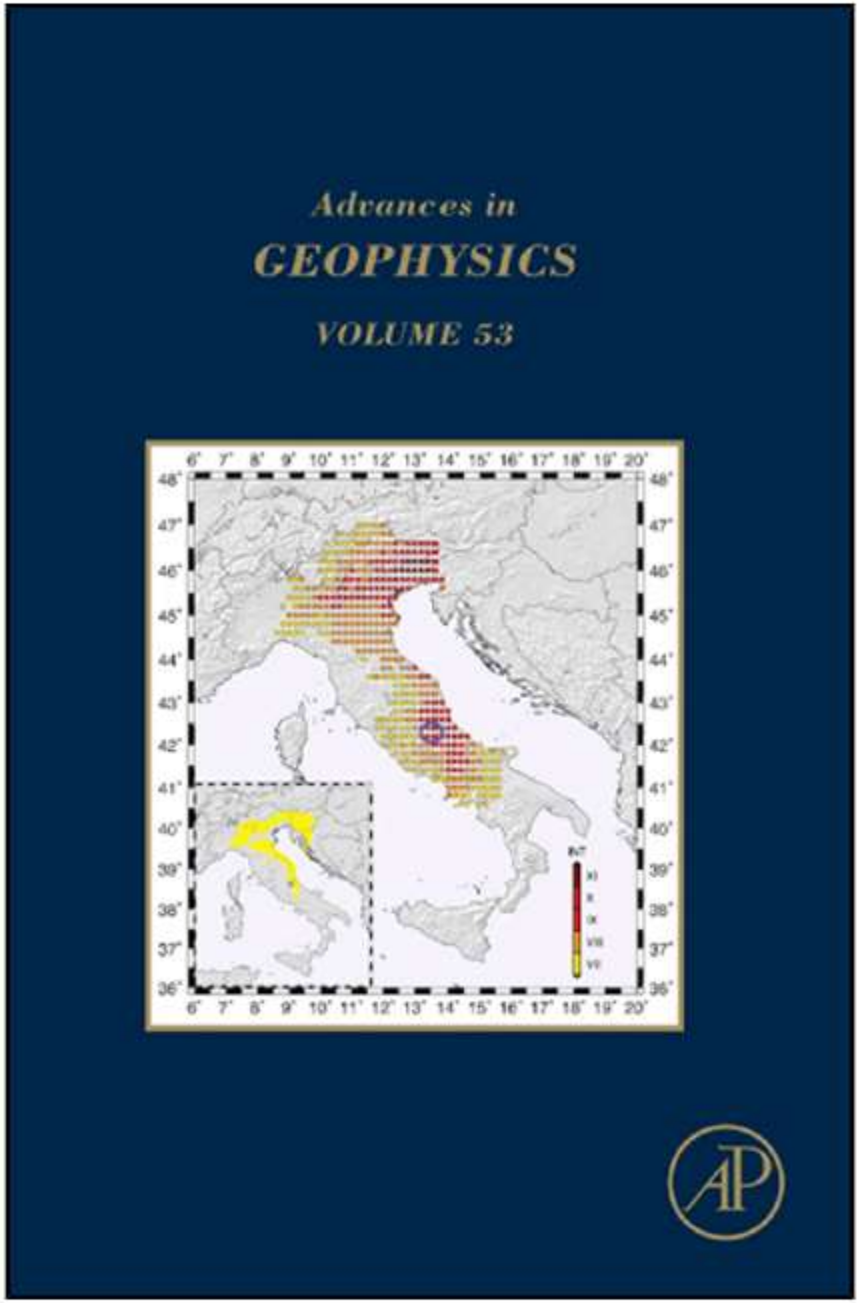
"Recommended modifications of the Italian design rules for seismically isolated structures". The resolution, approved on 8 June 2011 by the Italian Chamber of Deputies, explicitly mentions the need to resort to physically sound deterministic methods.

Conclusions

- From an anthropocentric perspective, buildings and other critical structures should be designed so as to resist future earthquakes.

- When an earthquake with a given magnitude M occurs, it causes a specific ground shaking that certainly does not take into account whether the event is rare or not => ground motion parameters for seismic design should not be scaled depending on earthquake recurrence.

- Therefore, when considering two sites A and B prone to earthquakes with the same magnitude, say M=7, given that all the remaining conditions are the same, the site where the recurrence is lower appears naturally preferable; nevertheless parameters for seismic design must be equal at the two sites, since the expected magnitude is the same (M=7).



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