Recent advances on assessing seismic hazard and earthquake probabilities in Italy

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Physical and Stochastic Modelling of Earthquake Occurrence and Forecasting

Erice, Italy

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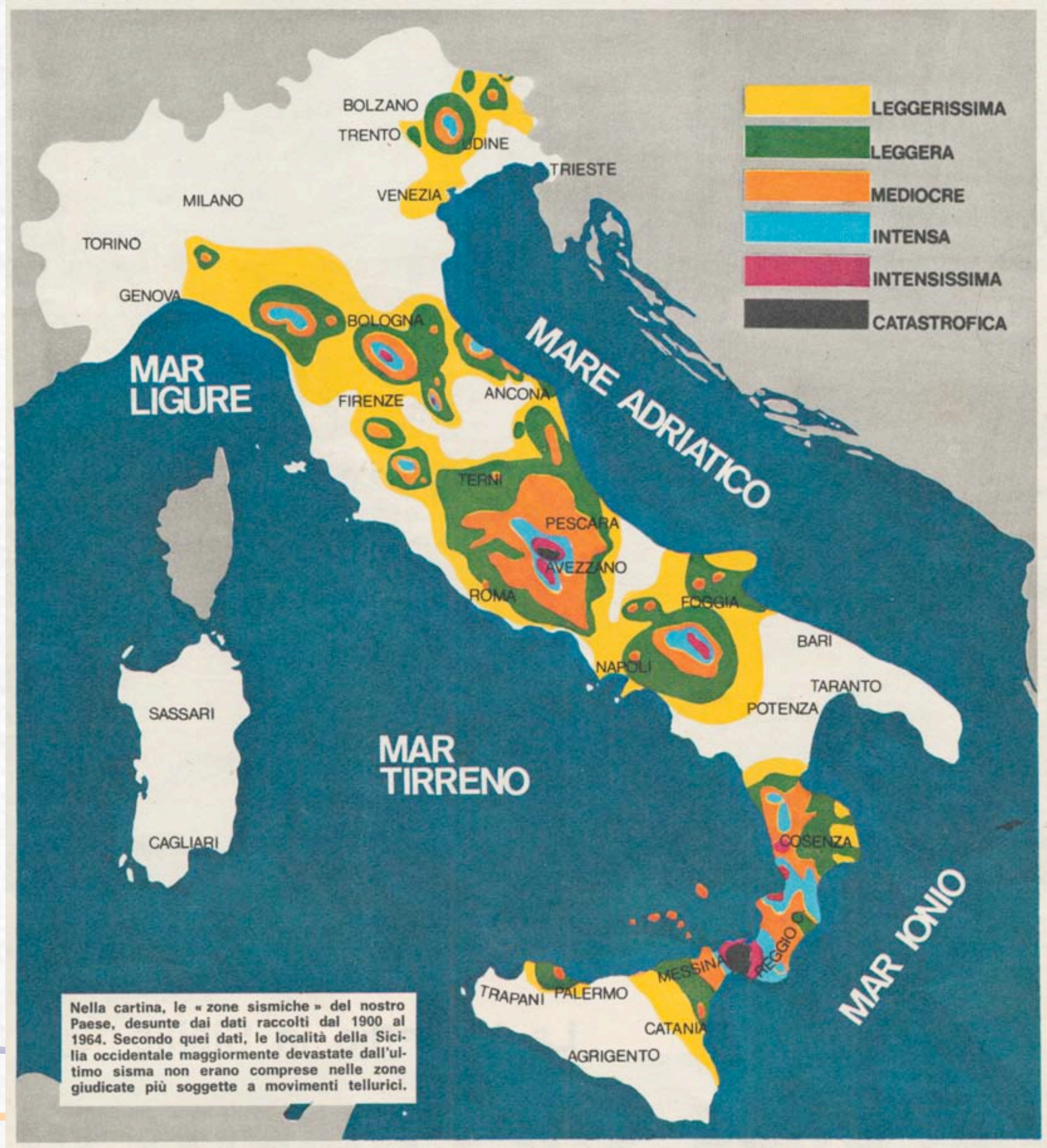
The 1st Italian “hazard” map (1968)

Seismic zones according to the 1900-1964 seismicity

from “La Domenica del Corriere”
(courtesy Franco Pettenati)



Generations of hazard maps

Yesterday: 1st Generation - Historical Determinism

Approaches

- Historical Determinism
- Historical Probabilism
- Seismotectonic Probabilism

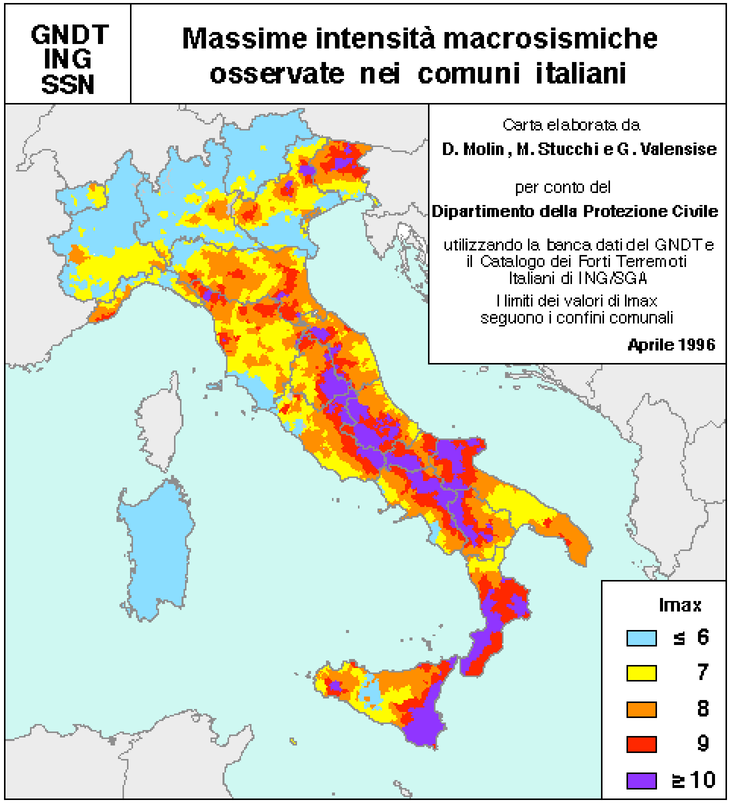
} yesterday

- Non-Poissonian Probabilism — today & tomorrow
- Earthquake Prediction — ?

(Muir-Wood, 1993)

Generations of hazard maps

Yesterday: 1st Generation - Historical Determinism



Approaches

- Historical Determinism
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- Earthquake Prediction — ?

(Muir-Wood, 1993)

Yesterday late 70’s: 2nd Generation - Historical Probabilism

The Gumbel approach

Given I_{max} = max X_i, with i=1, …, n and n large

Type 1: no upper limit of X_i

$$P[I_{\max} \geq i] = F_{\mathrm{Im}\,ax}(i) = \exp[-e^{-\alpha(i-u)}]$$

Type 3: upper limit of X_i

$$P[I_{\max} \geq i] = F_{\mathrm{Im}\,ax}(i) = \exp\{-[(w-i)/(w-u)]k\}$$

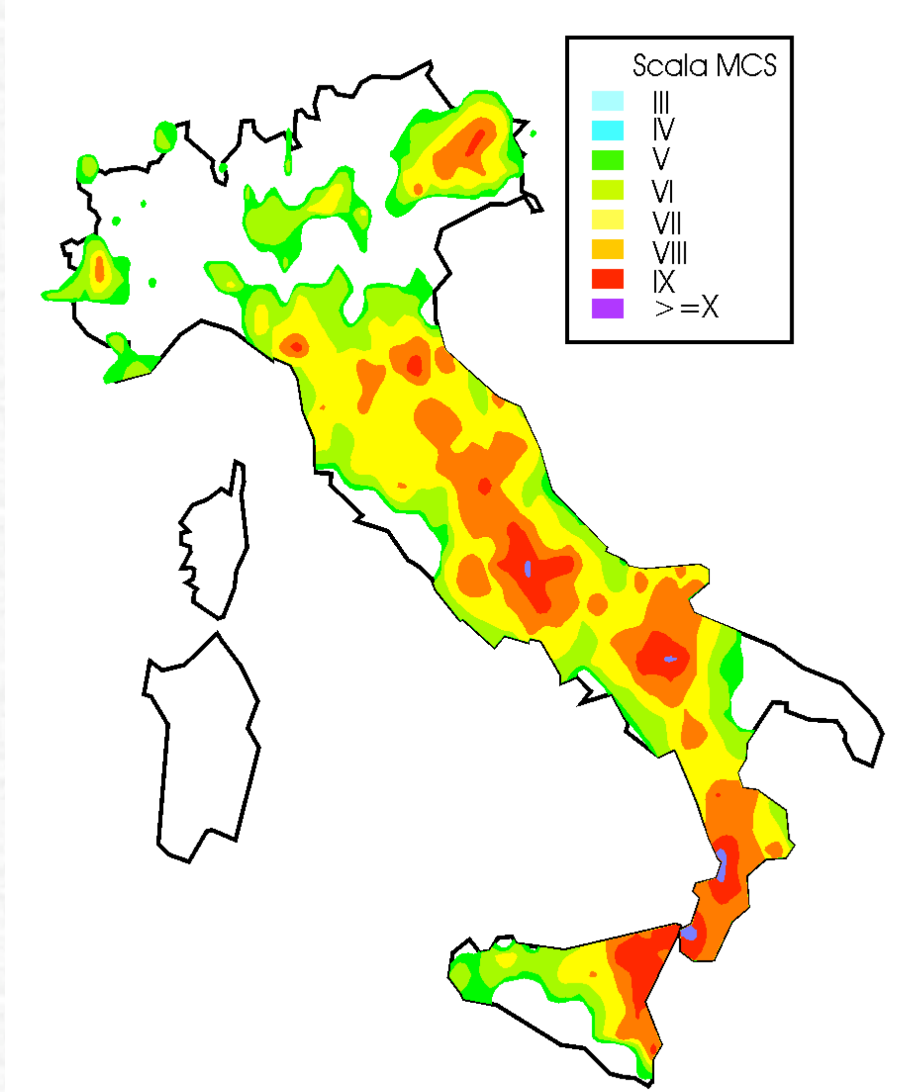
Application

Putting $F_X(x) = i/(n+1)$

Introducing the reduced variable

$$y_i = -\ln\{-\ln[F_X(x_i)]\}$$

$$y_i = \alpha(x_i - u)$$



Seismic hazard map (CNR, 1979) used as basis of the 1980 Italian seismic zonation

Yesterday: 3rd Generation - Seismotectonic Probabilism

The Cornell (1968) approach

The total probability theorem $P[E] = \int P\left[E \mid S\right] f_s(s)\,ds$

where $f_S(s) = \partial F_S(s) / \partial s$ is the PDF of S

and $F_S(s) = P[S < s]$ is the CDF of S

Application

$$\lambda_z = \sum_{i=1}^{N} \nu_i \int_{mo}^{mu} \int_{r=o}^{r=\infty} P(Z > z \mid m,r)\, f_i(m)\, f_i(r)\, dr\, dm$$

- λ_z: Mean annual rate of exceedence
- $\sum_{i=1}^{N}$: for all SZs
- ν_i: Mean annual rate of occurrence
- $P(Z > z \mid m,r)$: Attenuation model
- $f_i(m)$: GR distribution
- $f_i(r)$: SZ geometry

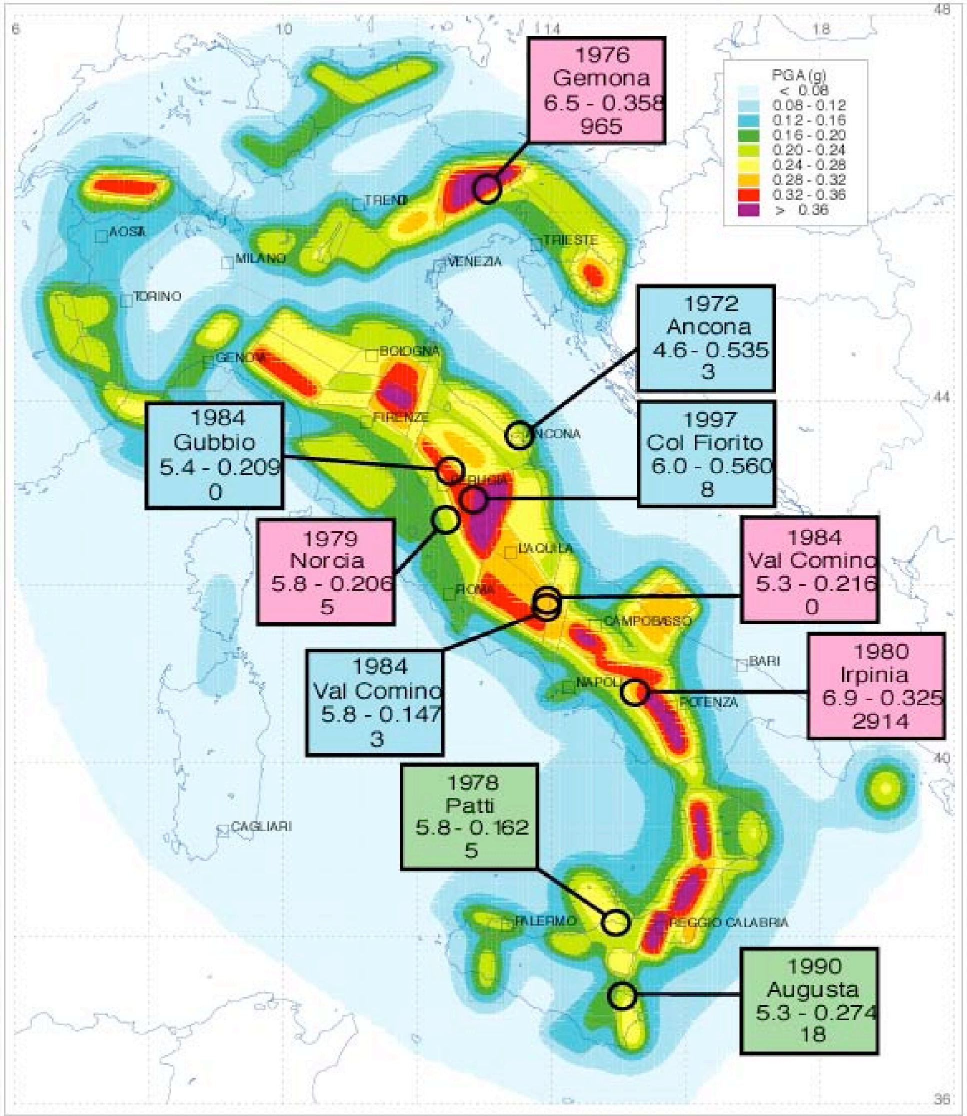
If it is a Poisson process (stationary, independent, non-multiple events)

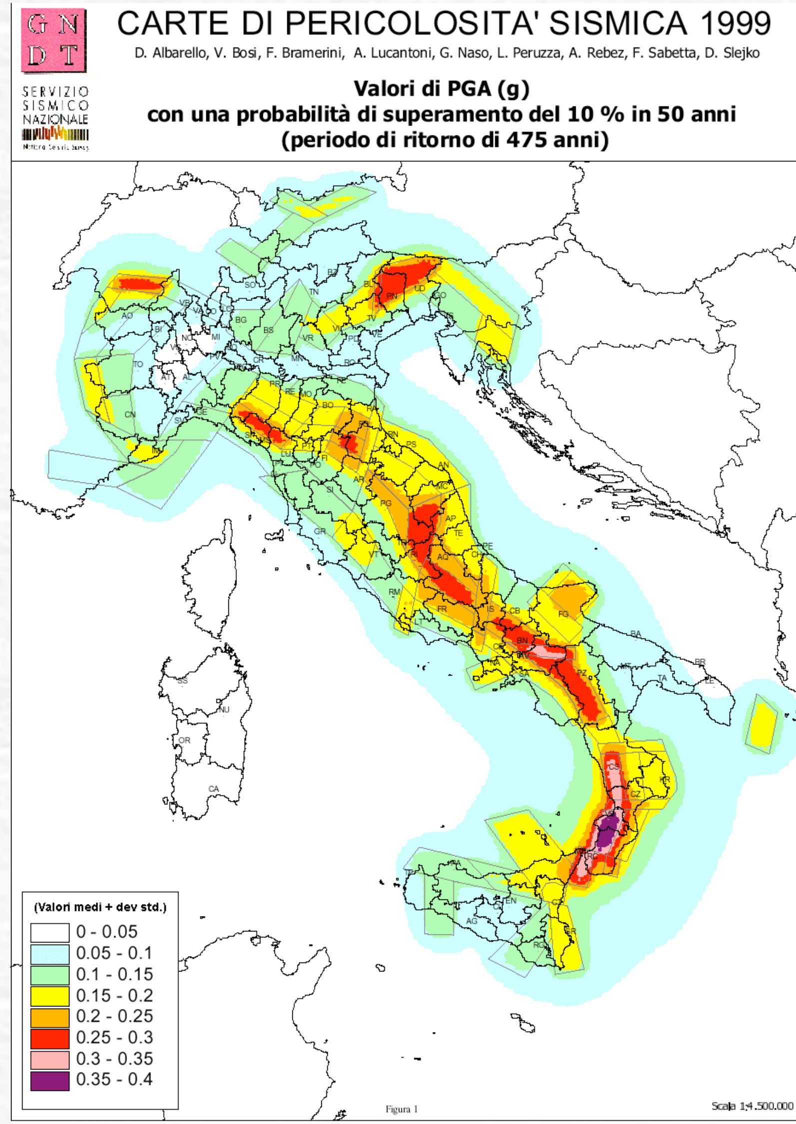
$$P\left[Z_T > z\right] = 1 - e^{-\lambda_z T}$$

$$T = -t / \ln(1 - P(Z_T > z))$$

where: T=return period;
t=period of analysis

Yesterday late 90’s: 3rd Generation - Seismotectonic Probabilism

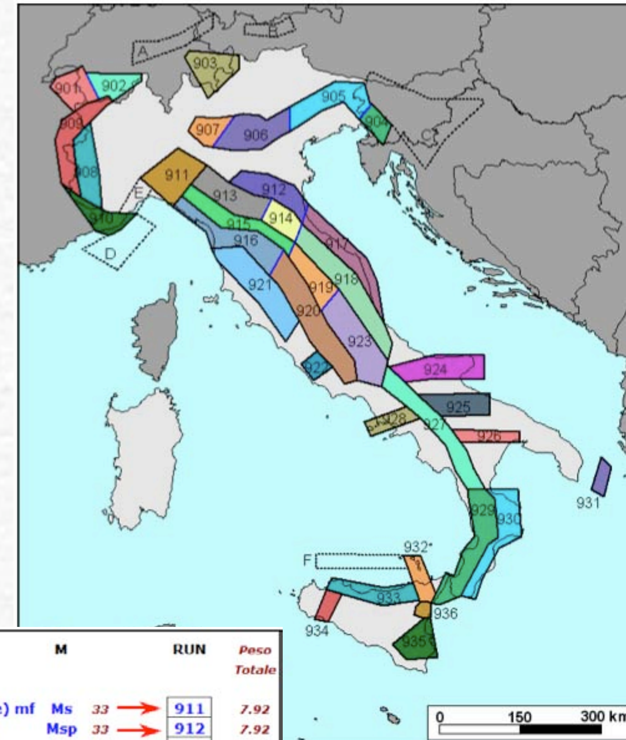


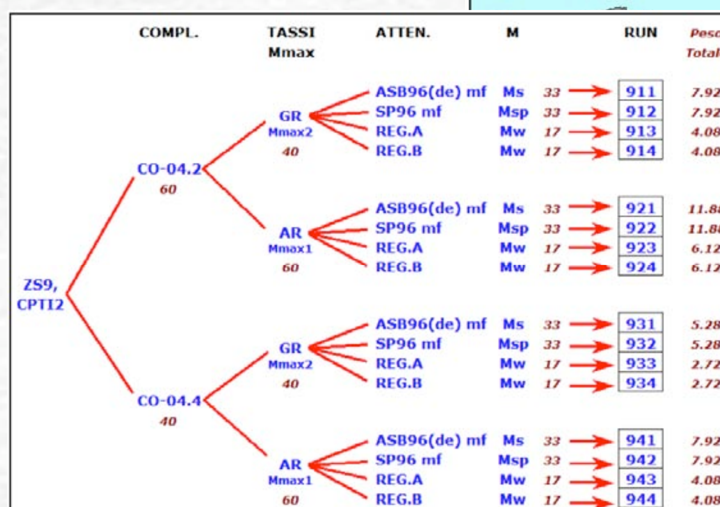


Seismic hazard maps (Slejko et al., 1998; Albarello et al., 1999) used as basis of the 2004 Italian seismic zonation

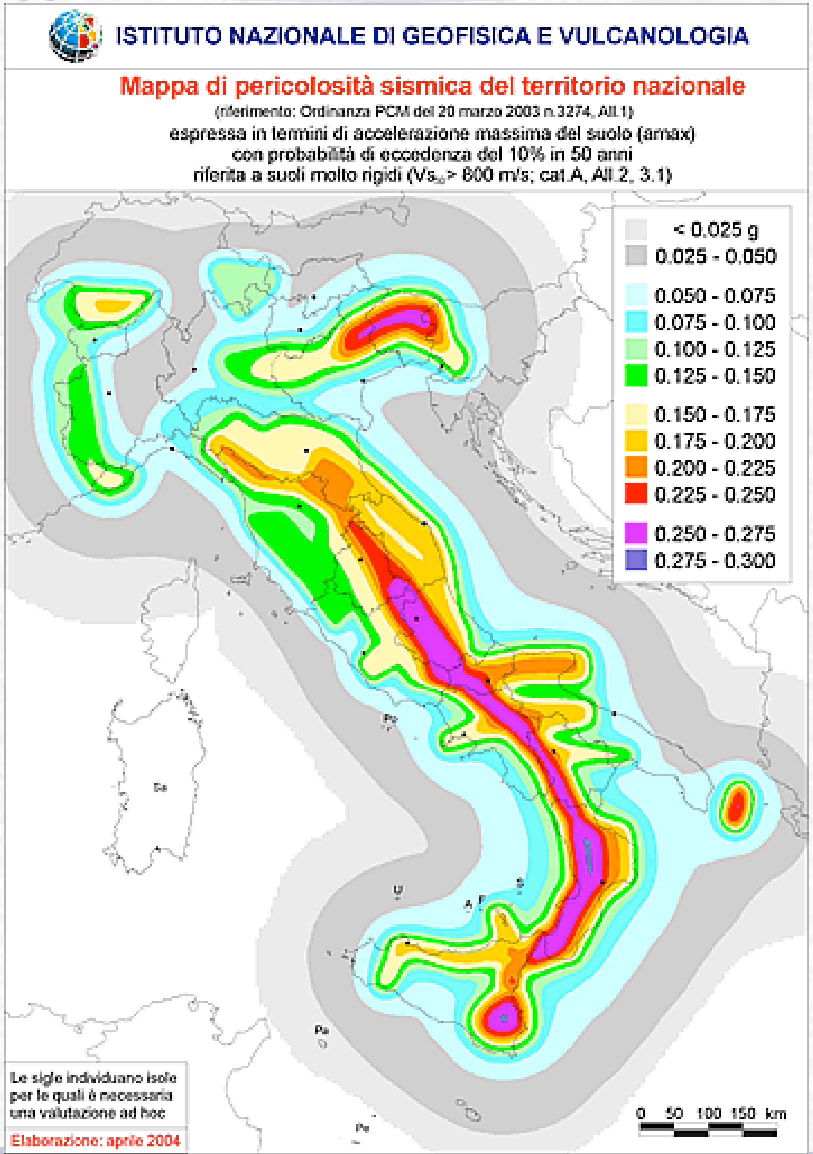
Yesterday 2004: 3rd Generation - Seismotectonic Probabilism

Seismic hazard map (Gruppo di Lavoro, 2004) used as basis of the present Italian seismic zonation





Yesterday 2004: 3rd Generation - Seismotectonic Probabilism



Seismic hazard map (Gruppo di Lavoro, 2004)
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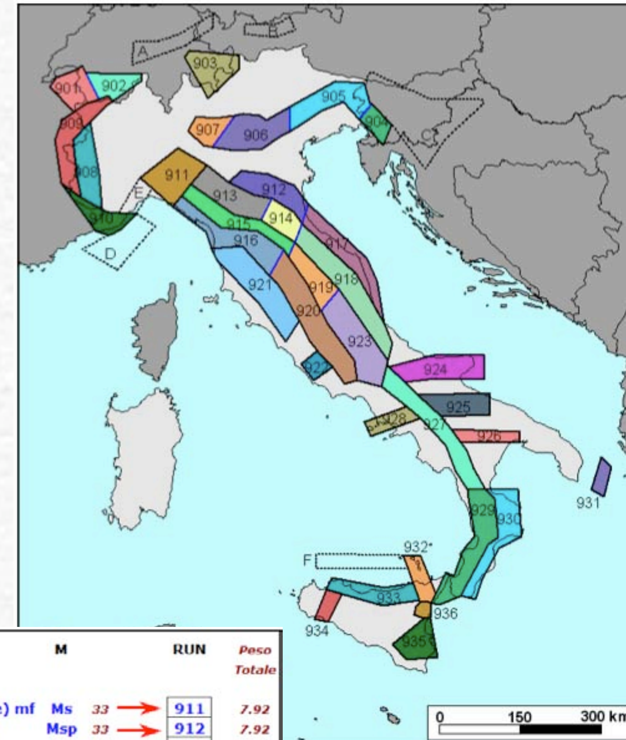
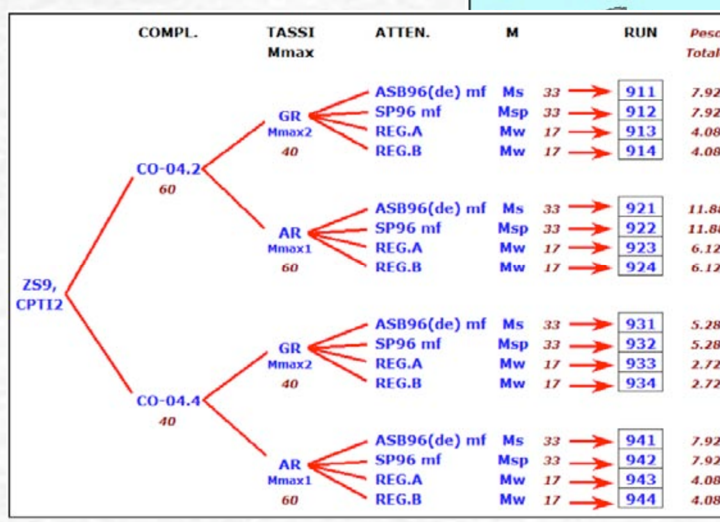
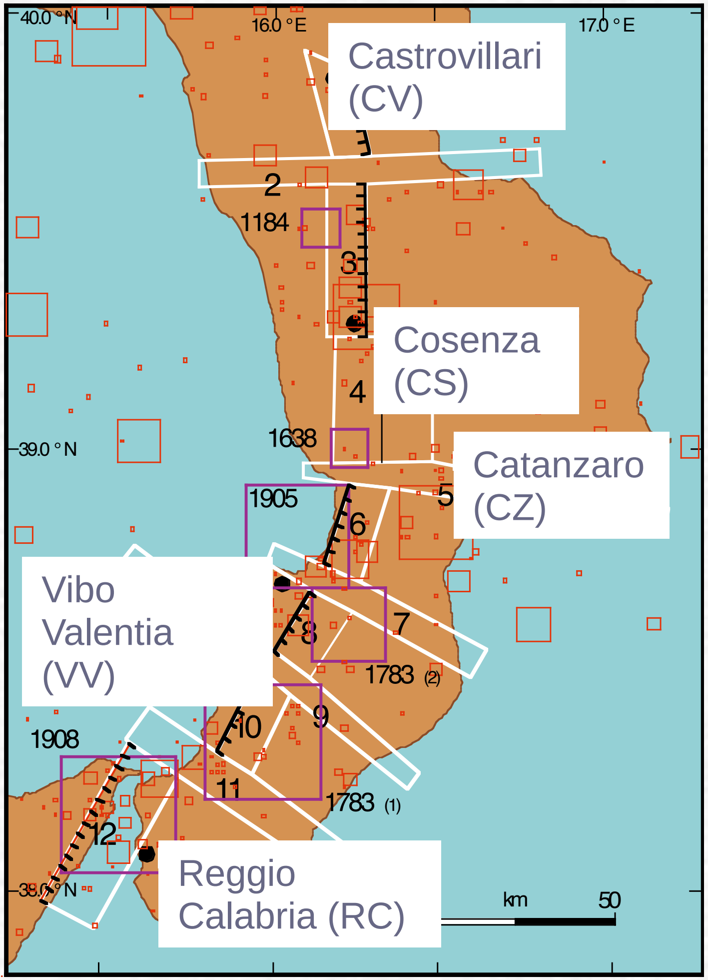


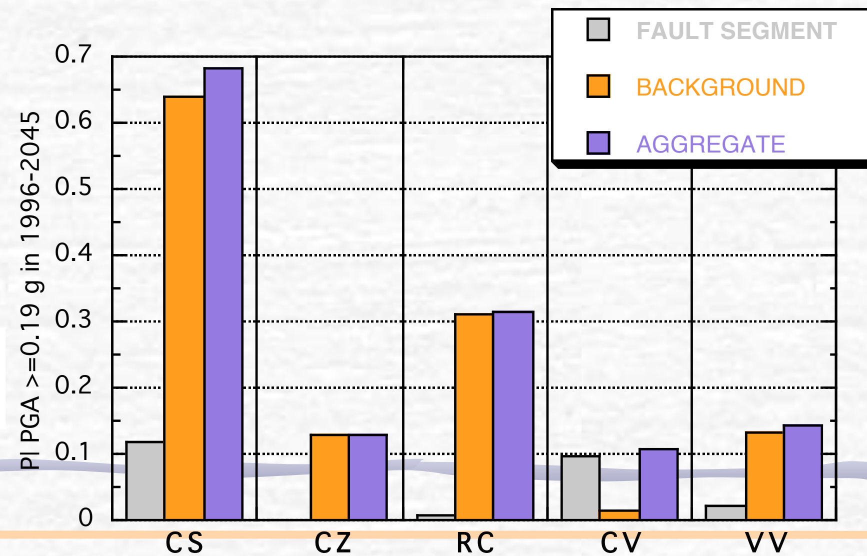


Today 1995: Hybrid approach for Calabria



First application for Italy of characteristic eqs on faults + background seismicity (from Peruzza et al., 1997)

Major faults + Main events => Non-Poissonian probabilism
Background seismicity => Gumbel statistics



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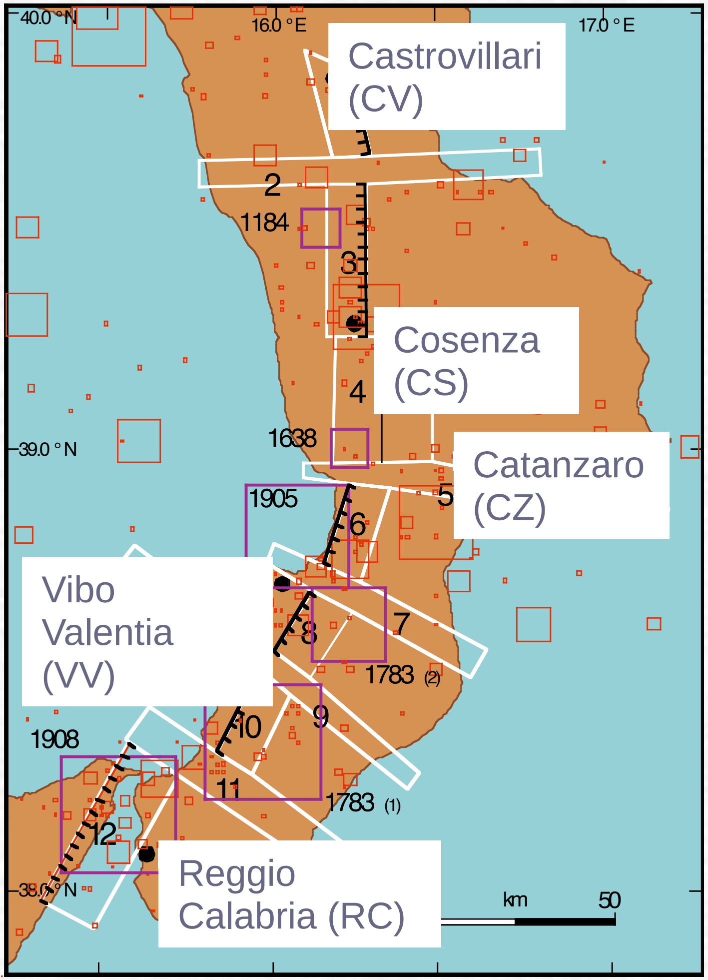

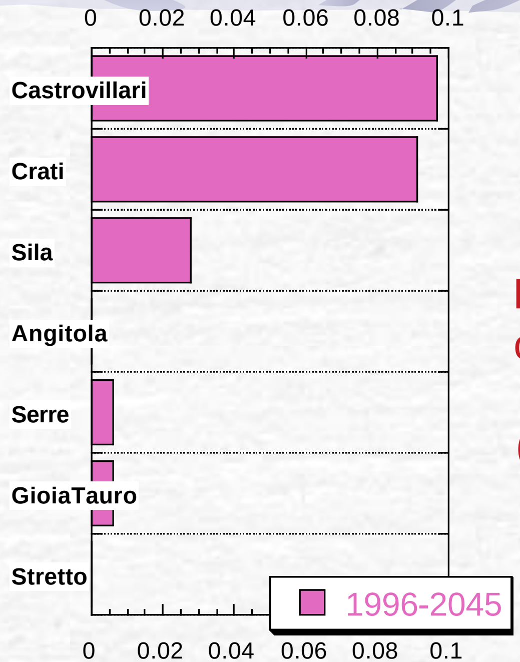

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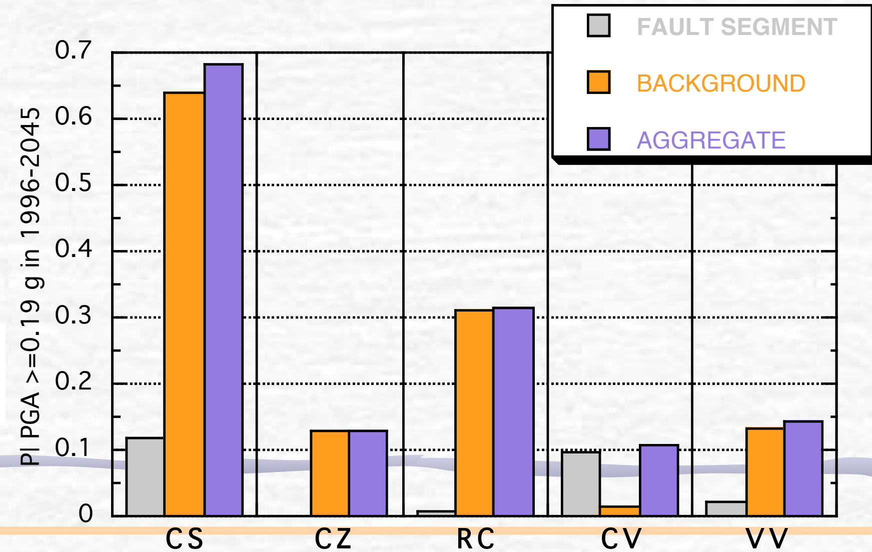
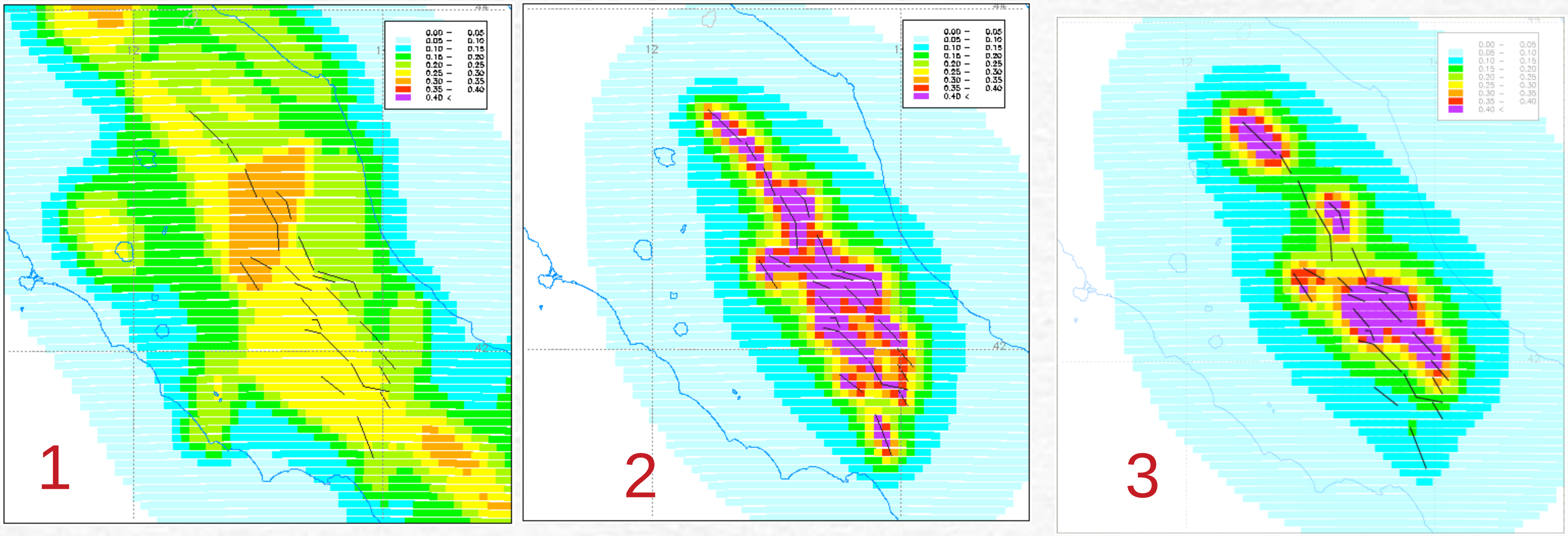


Major faults + Main events => Non-Poissonian probabilism
Background seismicity => Gumbel statistics

Today 1999: From the 3rd to the 4th generation

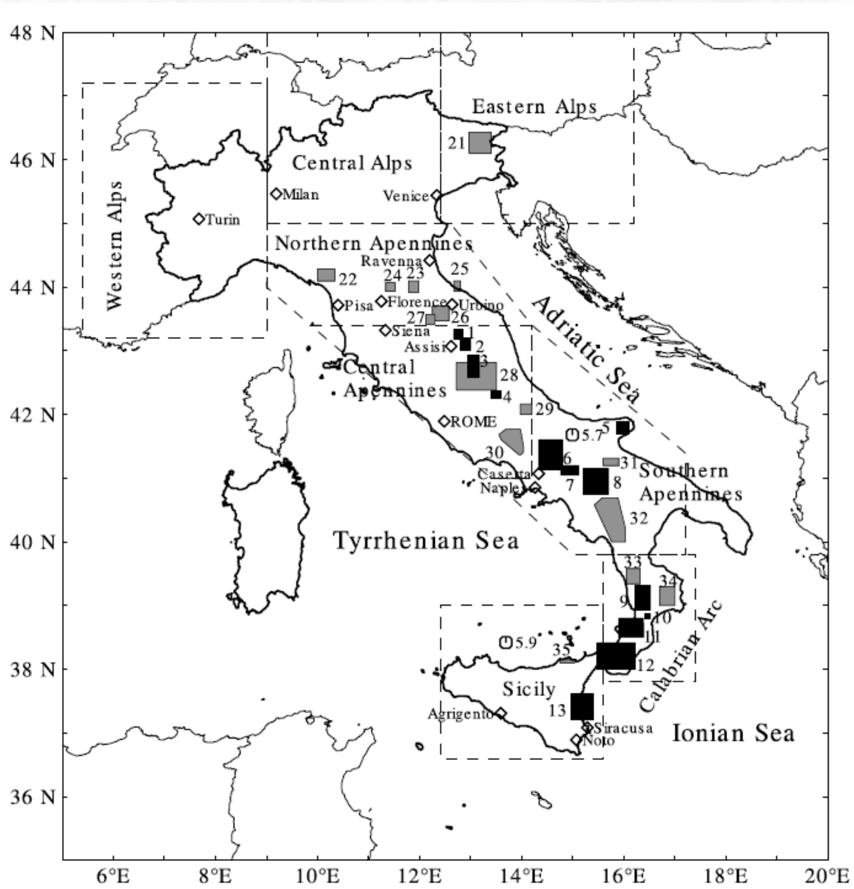


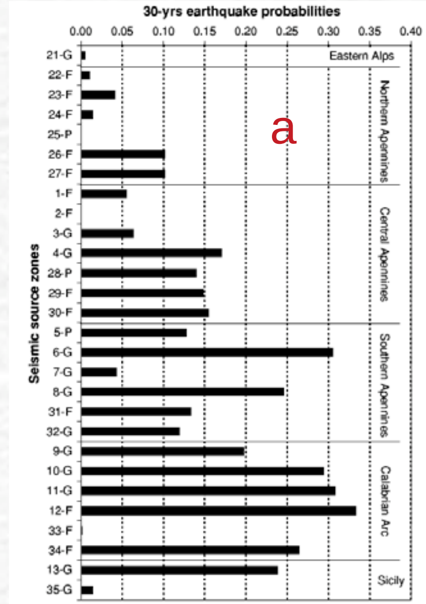
Seismic Hazard in Central Italy

475-yr return period PGA (Peruzza, 1999)

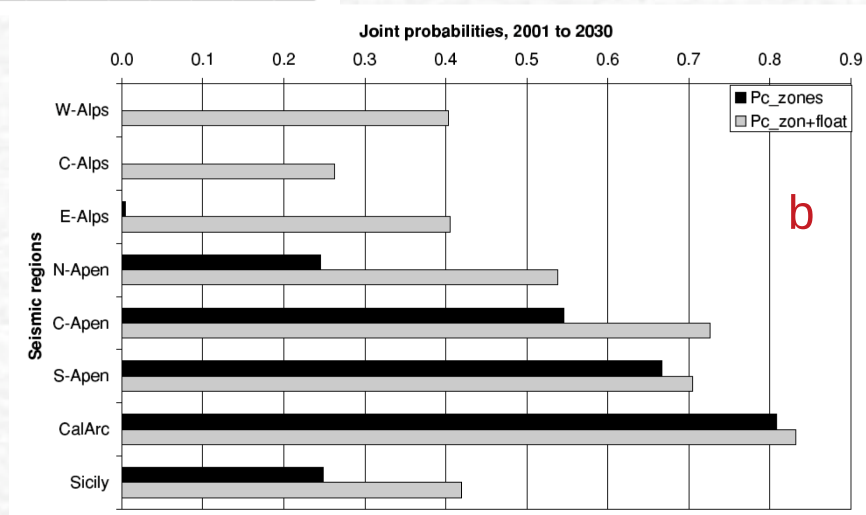
1 - Cornell approach with SZ's
2 - Cornell approach with faults
3 - characteristic time-dependent eq on faults

Today 2003: Earthquake Hazard in Italy, 2001–2030 (Romeo, 2003)

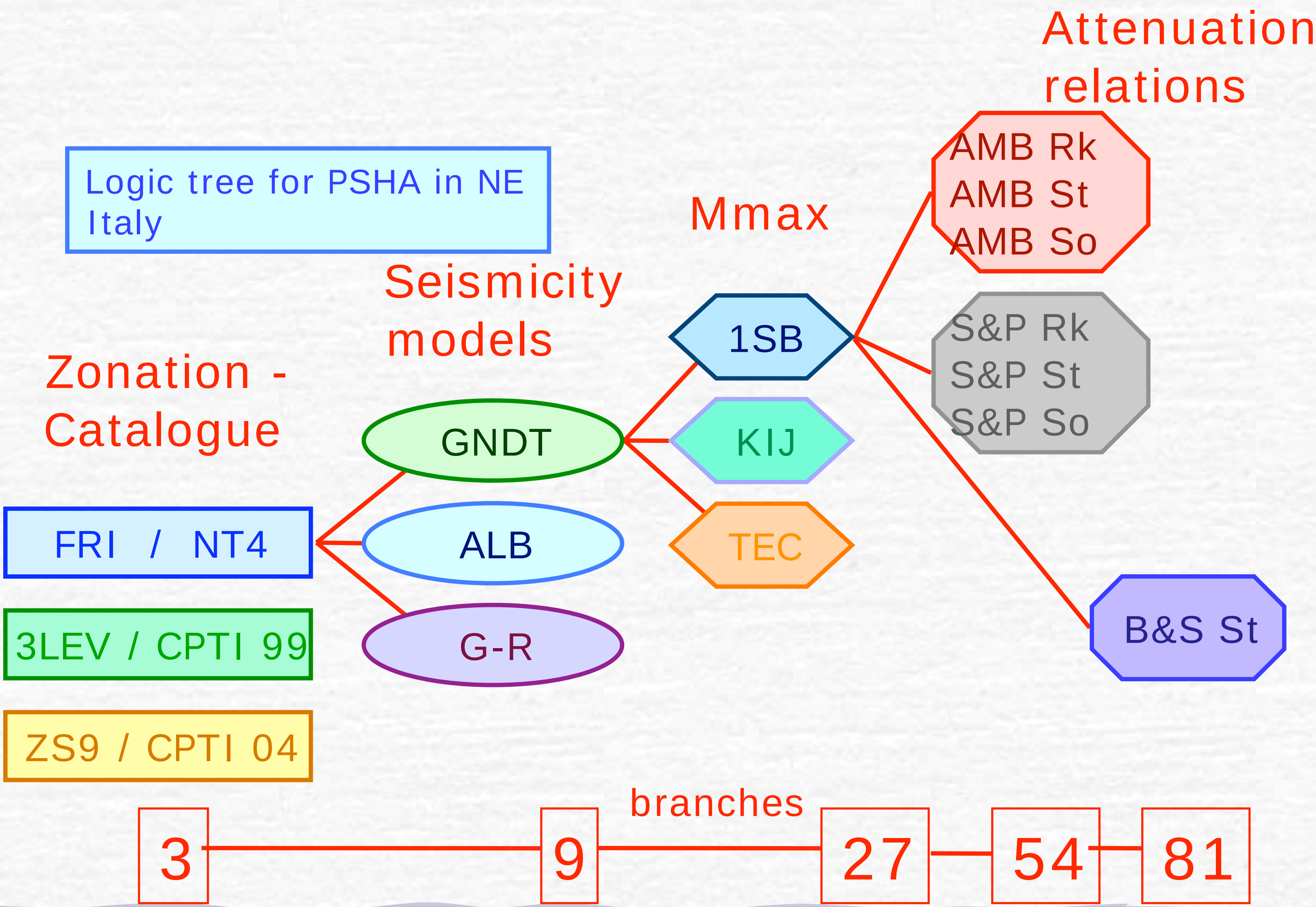




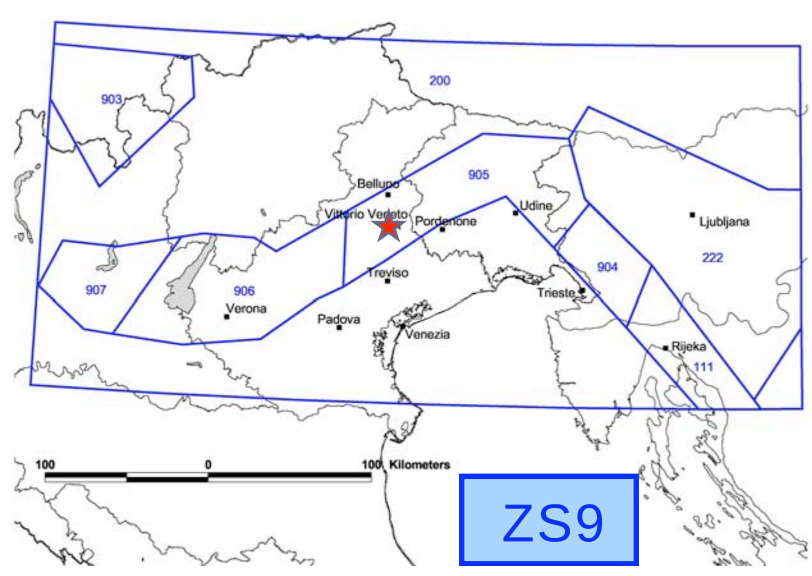
Eq probabilities for M6 + in the next 30 yrs since 2001 for: a) individual source zones, b) aggregated into the seismic regions.

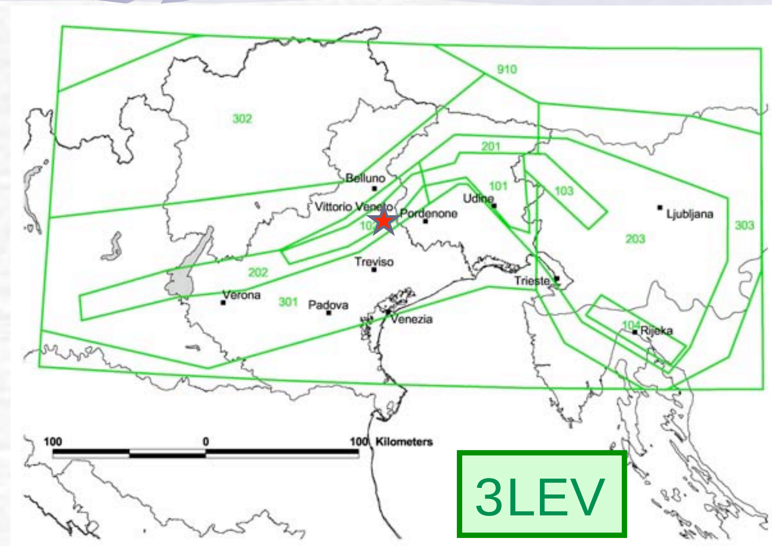


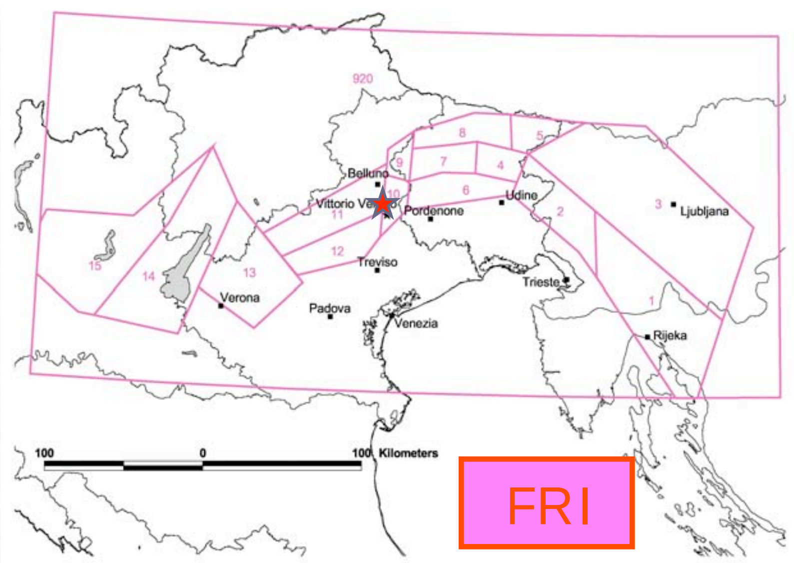
Today 2004: Soil seismic hazard for NE Italy (GNDT project Vittorio Veneto 2000-2004)



Today 2004: Seismogenic zonations for NE Italy

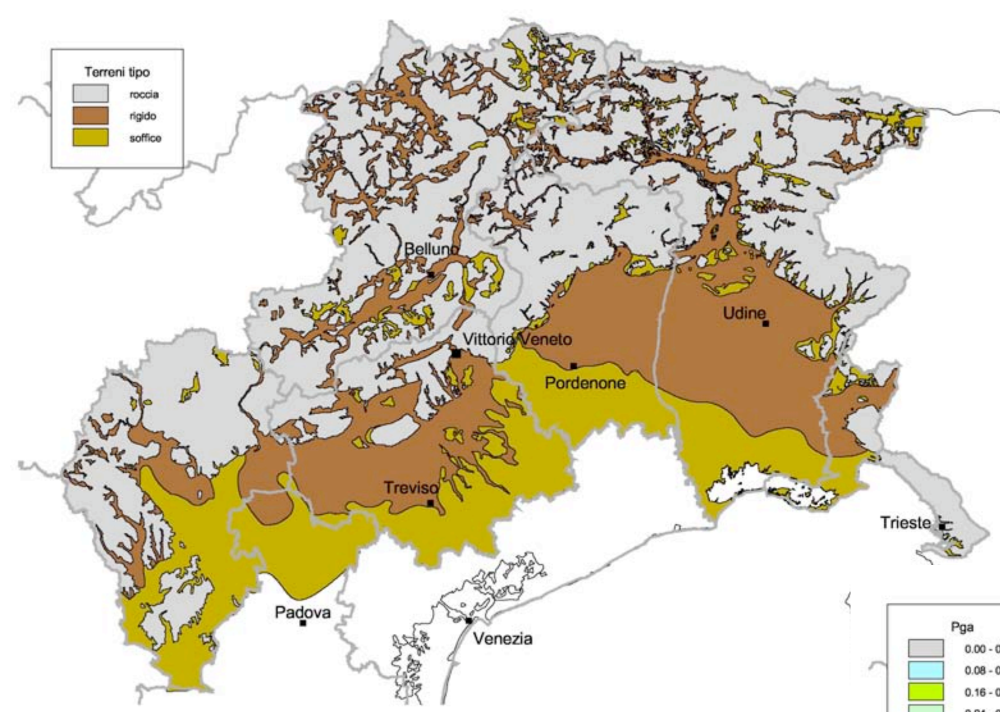






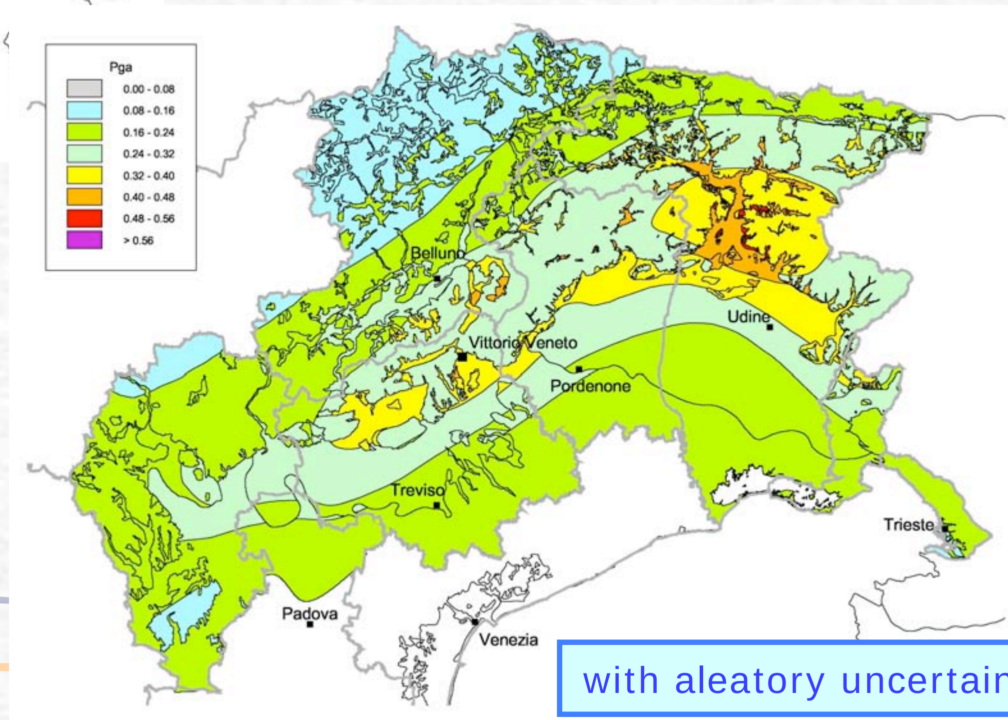
ZS9 = Gruppo di Lavoro (2004)
3LEV = Stucchi et al. (2002) + Galadini & Poli (2004)
FRI = Slejko & Rebez (2002)
(from Slejko et al., 2007)

Today 2004: Soil hazard for NE Italy



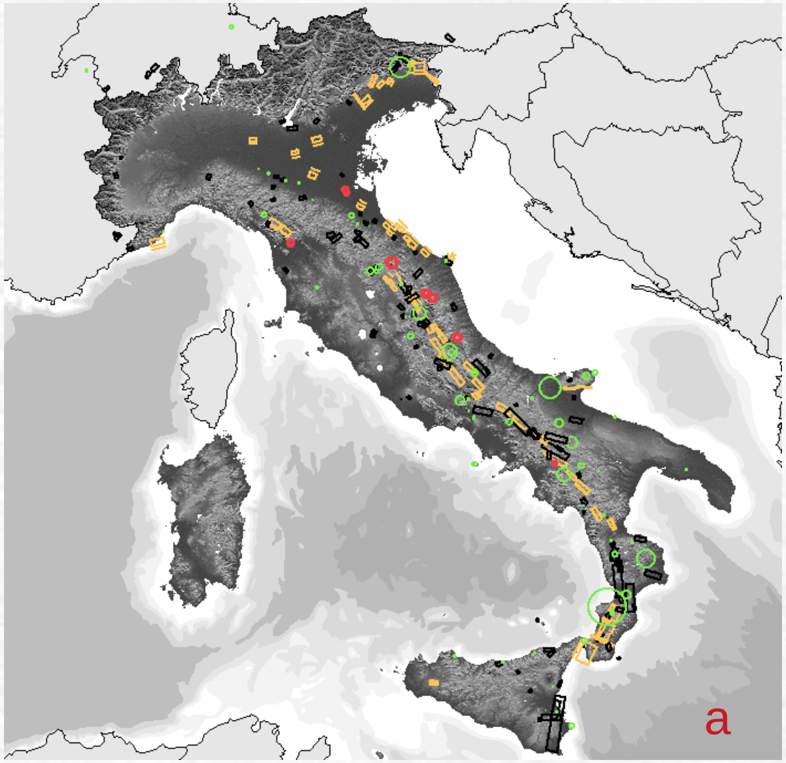
Aggregate PGA with a 475-yr return period (3 soil types: rock, stiff, and soft soil)

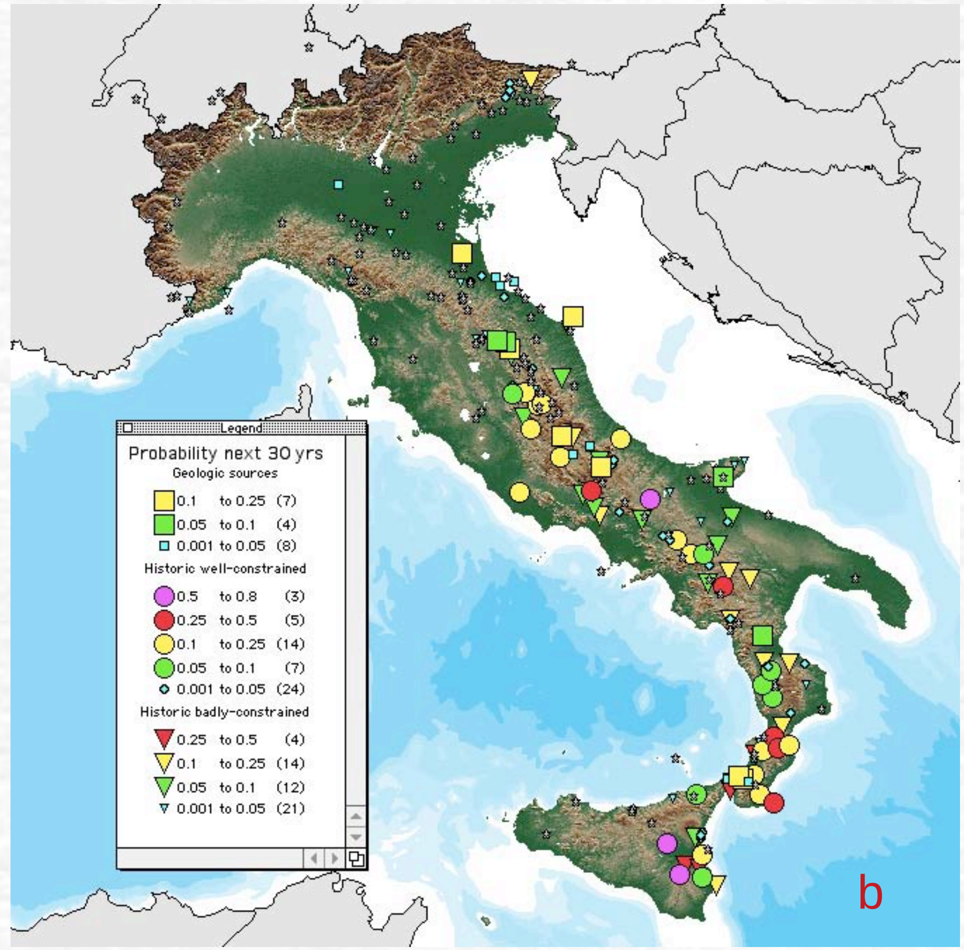
(from Slejko et al., 2007)



with aleatory uncertainty

Today 2004: The GNDT/Amato Project (2000-2004)

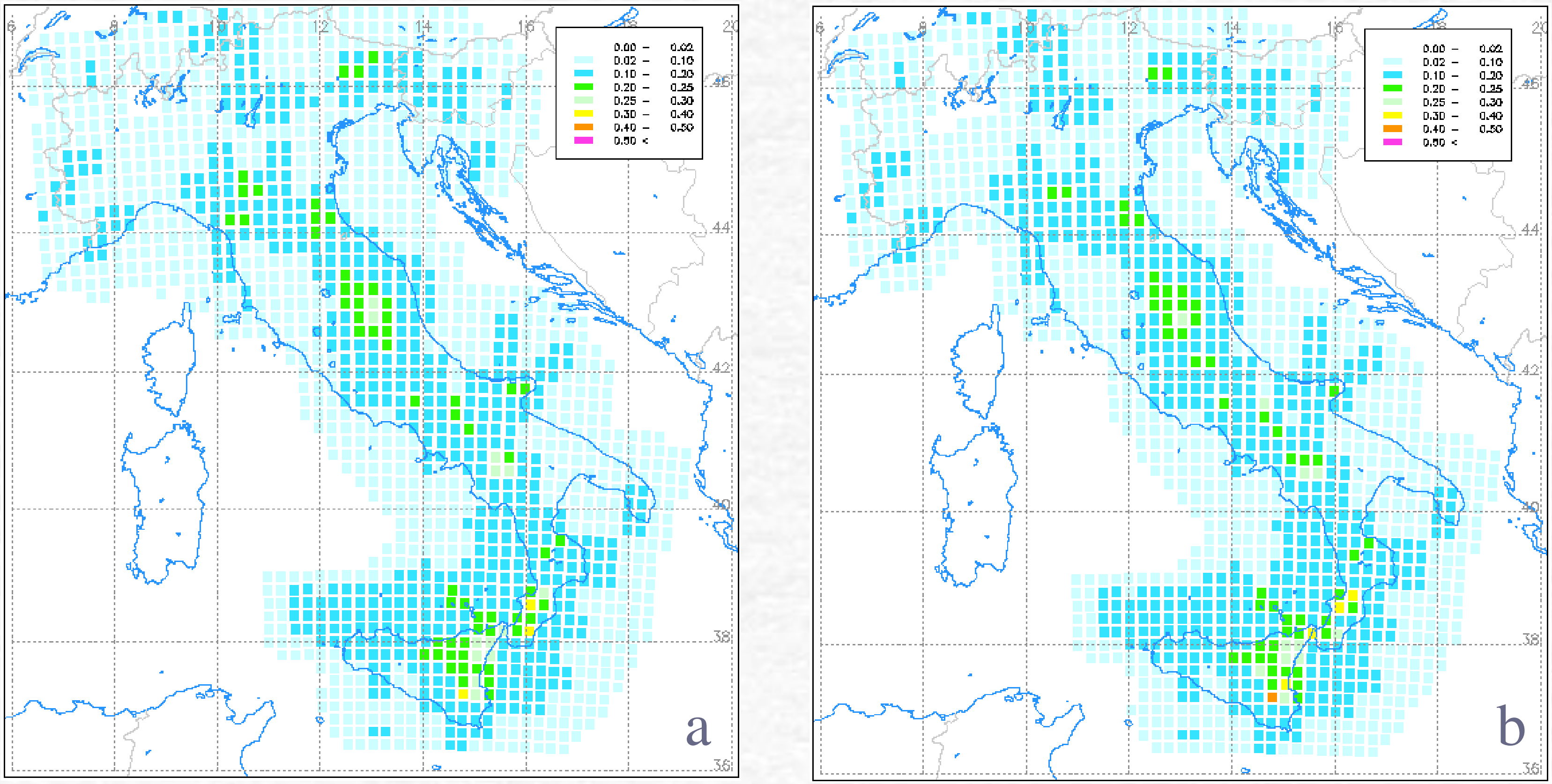




a) Seismogenic sources (Valensise and Pantosti, 2001)

b) Occurrence probability of the characteristic eq on the seismogenic sources (from Peruzza, 2006)

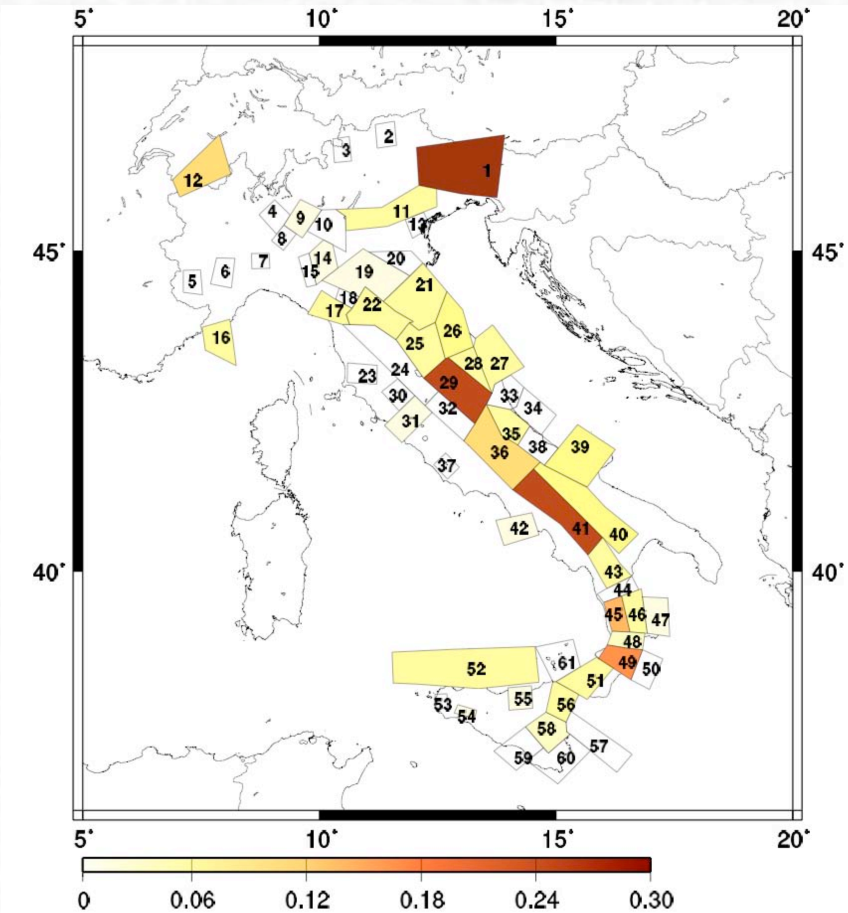
Today 2004: The GNDT/Amato Project (2000-2004)

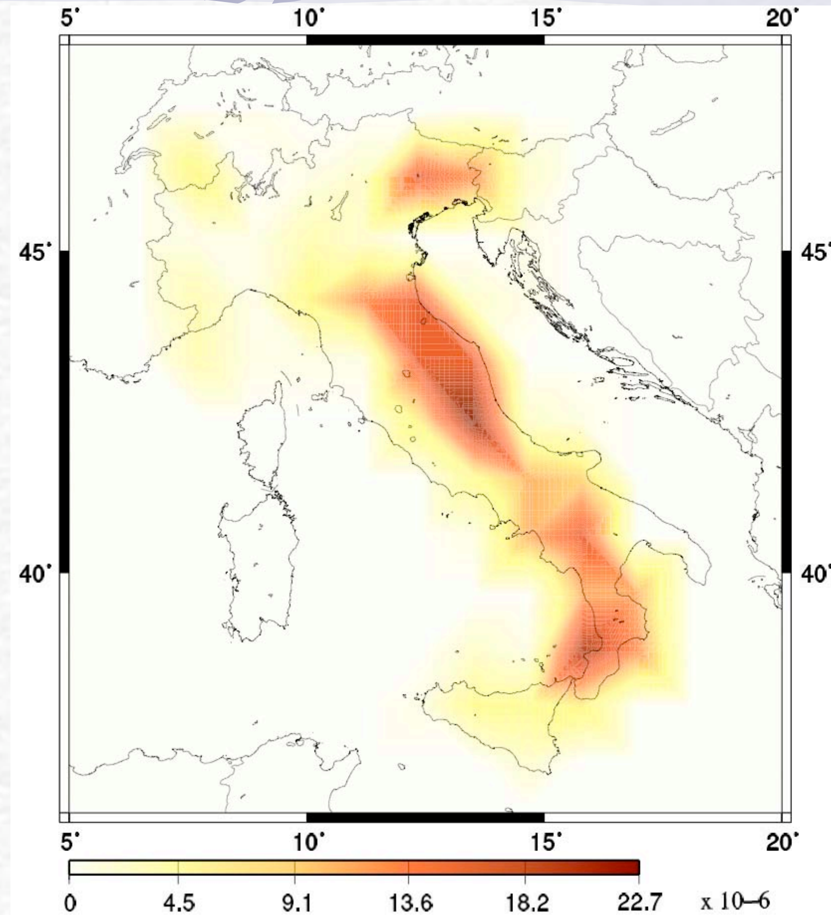


PGA with a 90% probability of exceedence in the period 2003-2033:
a) Poisson model; b) time-dependent model (Peruzza, 2006)

Today 2007: Occurrence probability of next M 5.5+ eq for the next 10 yrs

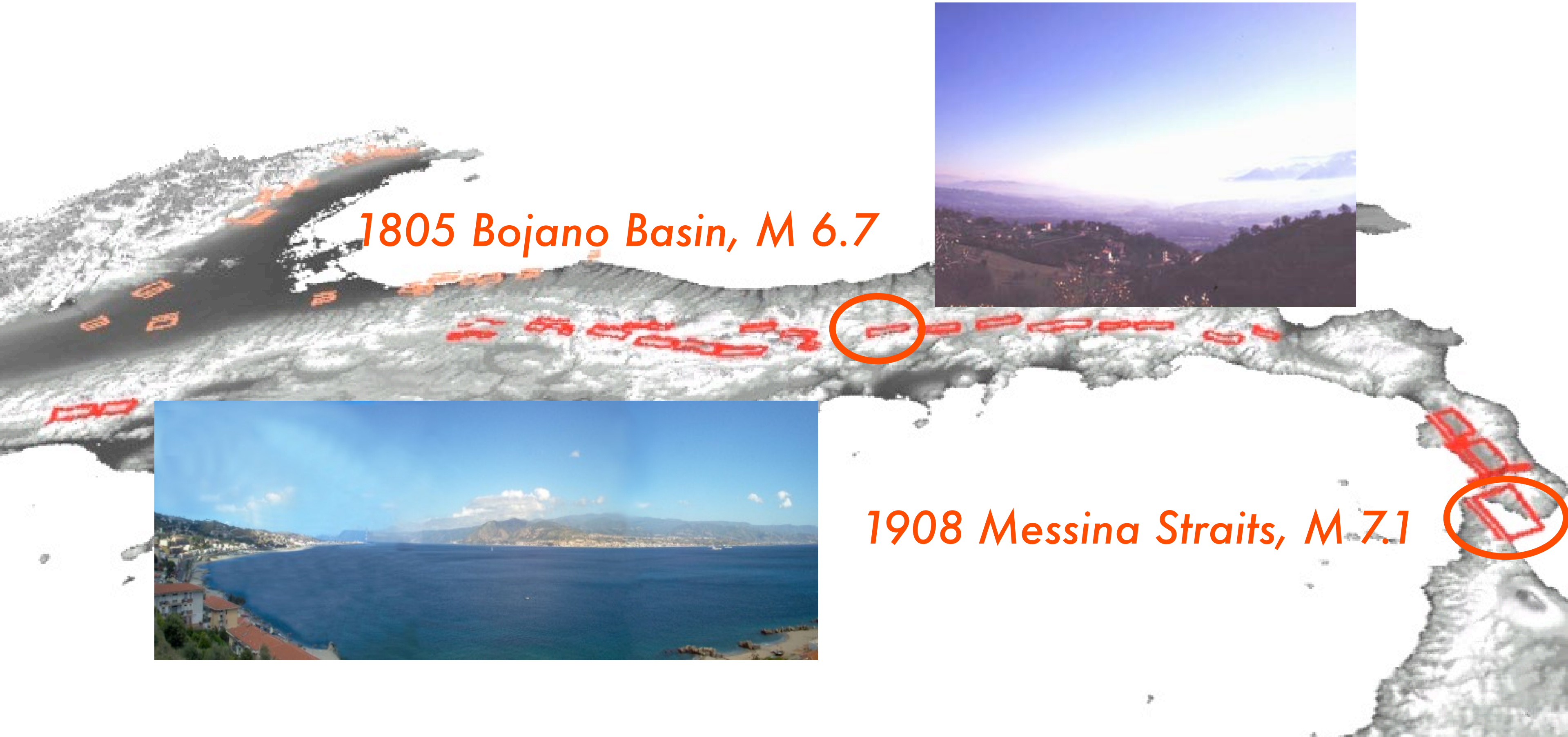
www.bo.ingv.it/~earthquake/ITALY/forecasting/M5.5+/





The two maps are calculated by using the same statistical procedure (Faenza et al., 2003; Cinti et al., 2004) applied to a seismotectonic zonation (a) and to a regular grid (b). The probability maps are updated every 1st of January and after the occurrence of a new target eq.

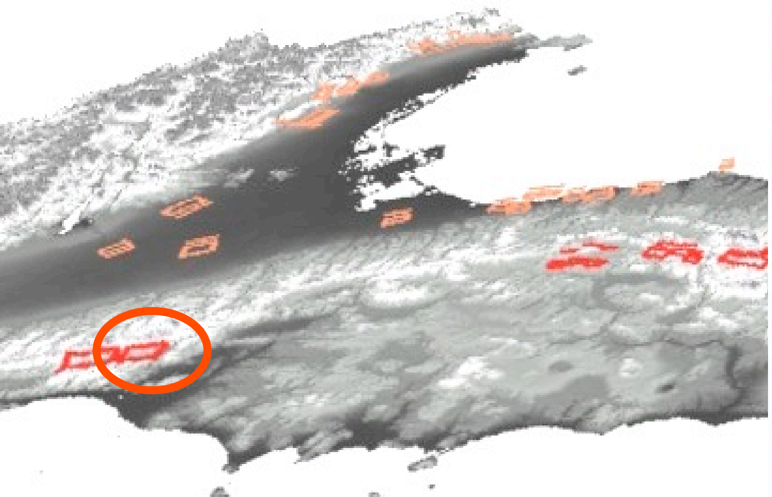
Do characteristic eqs exist? (1)

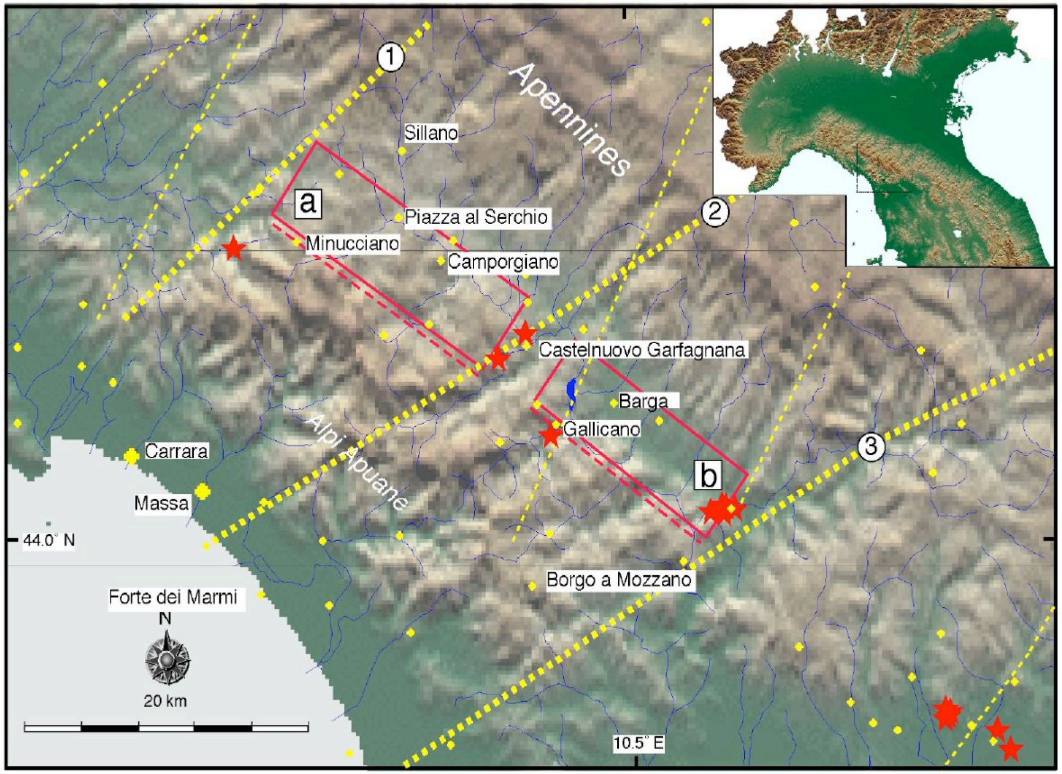


Evidence from significant (M=> 6) dip-slip Italian eqs suggests that:

- ✓ *earthquake ruptures tend to mimic geological domains and large landscape features*

Do characteristic eqs exist? (2)



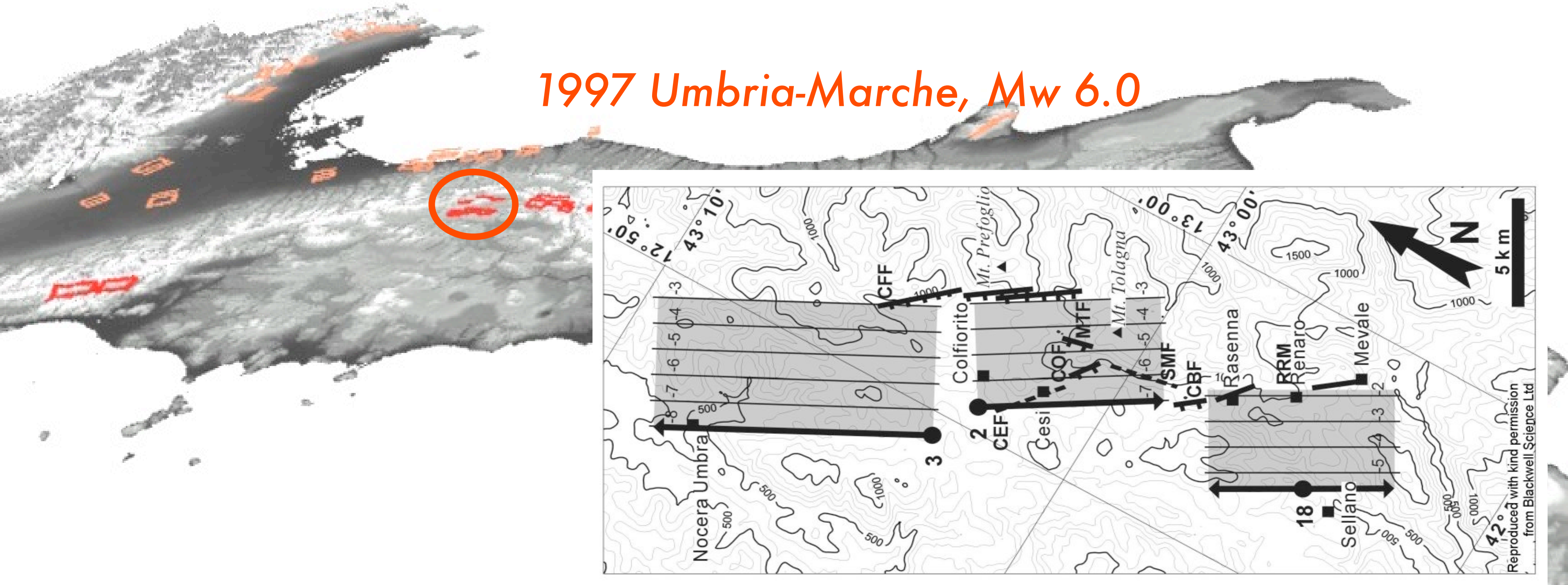


1920 Garfagnana, M 6.5

Evidence from significant (M=> 6) dip-slip Italian eqs suggests that:

✓ *earthquake ruptures tend to coincide with singularities of the tectonic fabric*

Do characteristic eqs exist? (3)



Evidence from significant (M=> 6) dip-slip Italian eqs suggests that:

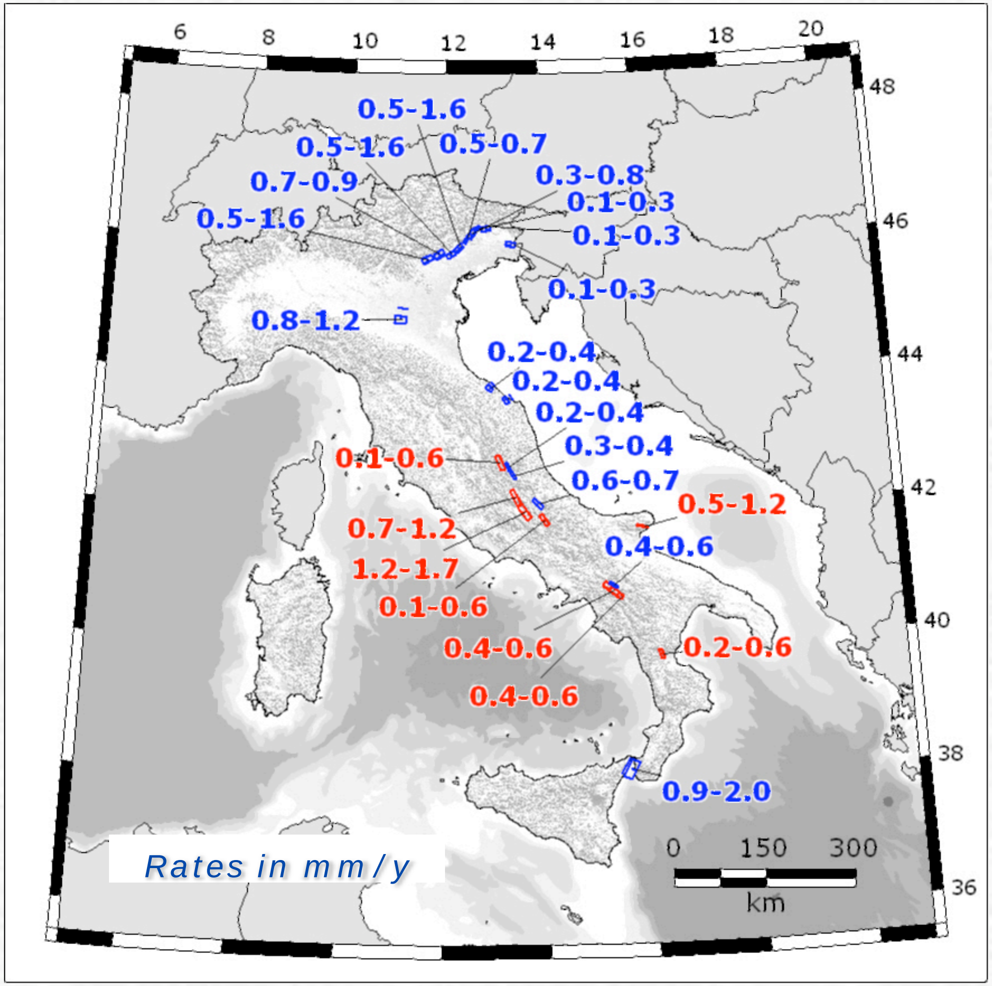
✓ *eq ruptures tend to be juxtaposed but never overlap*

Do characteristic eqs exist? (4)

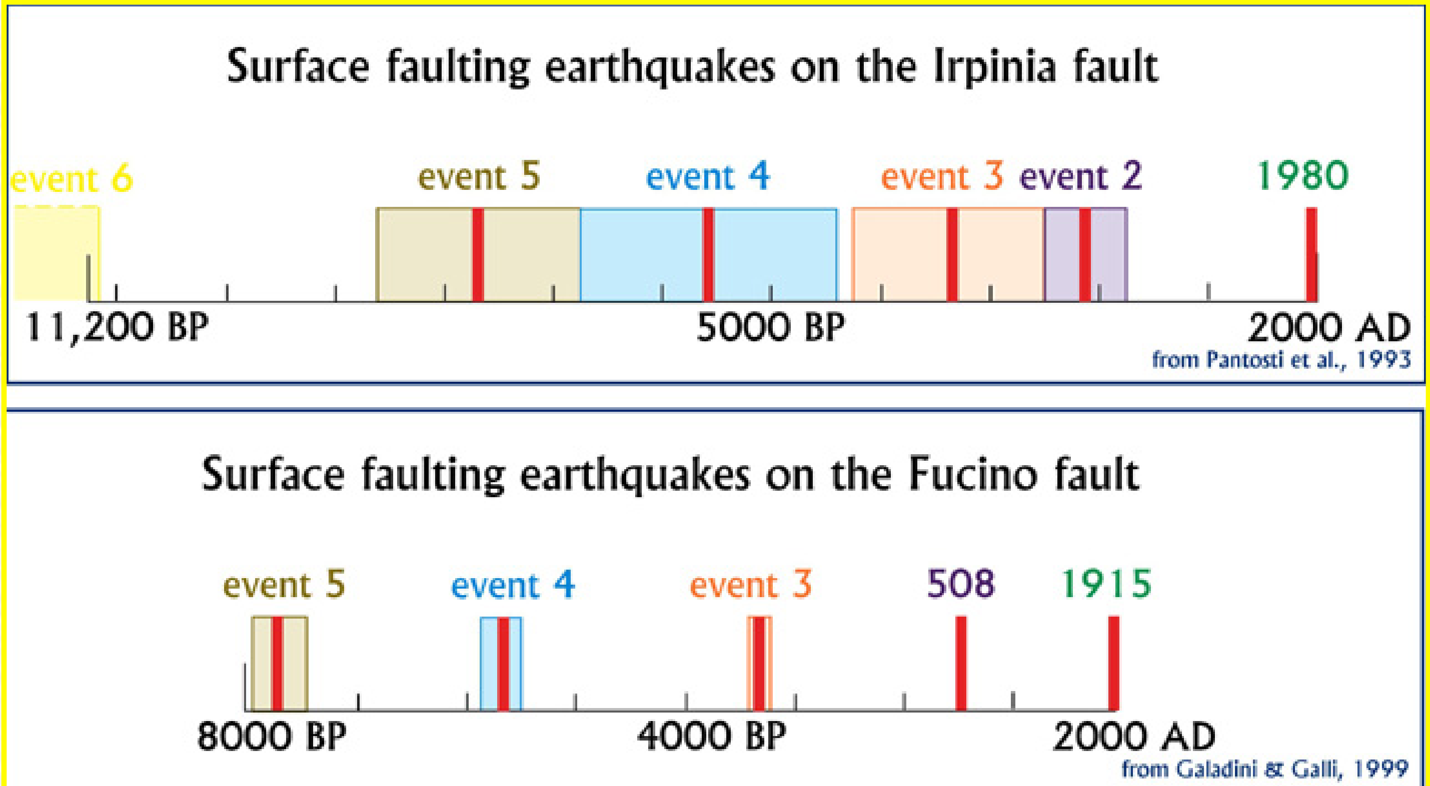
- ✓ Growing geological evidence shows that the rupture length of Italian dip-slip eqs - and hence their M - coincides with the characteristic length of large-scale geological structures.
- ✓ The existing geologic fabric exerts a strong control over the fragmentation of active deformation/fault zones, effectively putting a (predictable) upper bound to the M_{max} of individual rupture episodes.
- ✓ Rupture complexity due to fault interaction may make things appear more random than they are. To further confuse then issue, growing historical and instrumental evidence is suggesting that the majority of Italian eqs are complex in one way or the other.
- ✓ Large-scale geological evidence obviously does not control, nor contain any information on, the timing of subsequent eqs.
- ✓ The debate on characteristic eqs is dominated by evidence from strike-slip faults and subduction zones. Dip-slip faulting follows different rules.

Recurrence of Italian earthquakes - Slip rates

Most Italian faults are blind and hence hard to investigate. Direct observations of slip rate (e.g. trenching, in red) exist for about 10 faults. 15-20 additional estimates were obtained through indirect observations (deformation of recent geologic horizons, of marine and fluvial terraces, subsurface data, in blue)



Recurrence of Italian earthquakes - Interevent times



Interevent times exist only for very few faults. The causative faults of the 1980 Irpinia (top) and 1915 Avezzano (bottom) eqs yield the most complete records available countrywide. Typical recurrence intervals for the other faults is longer than several centuries (often>1,000 years), in agreement with historical record.

Progetto S2: Valutazione del potenziale sismogenetico e probabilità dei forti terremoti in Italia

Project S2: Evaluation of the seismogenic potential and occurrence probability of large

Task 1. Construction of a database for the seismogenesis (DISS).
Task 2. Spatial definition of the main seismogenic structures.
Task 3. Geophysical characterization of the main seismogenic structures.
Task 4. Seismic characterization of the main seismogenic structures and assessment of eq occurrence probability.

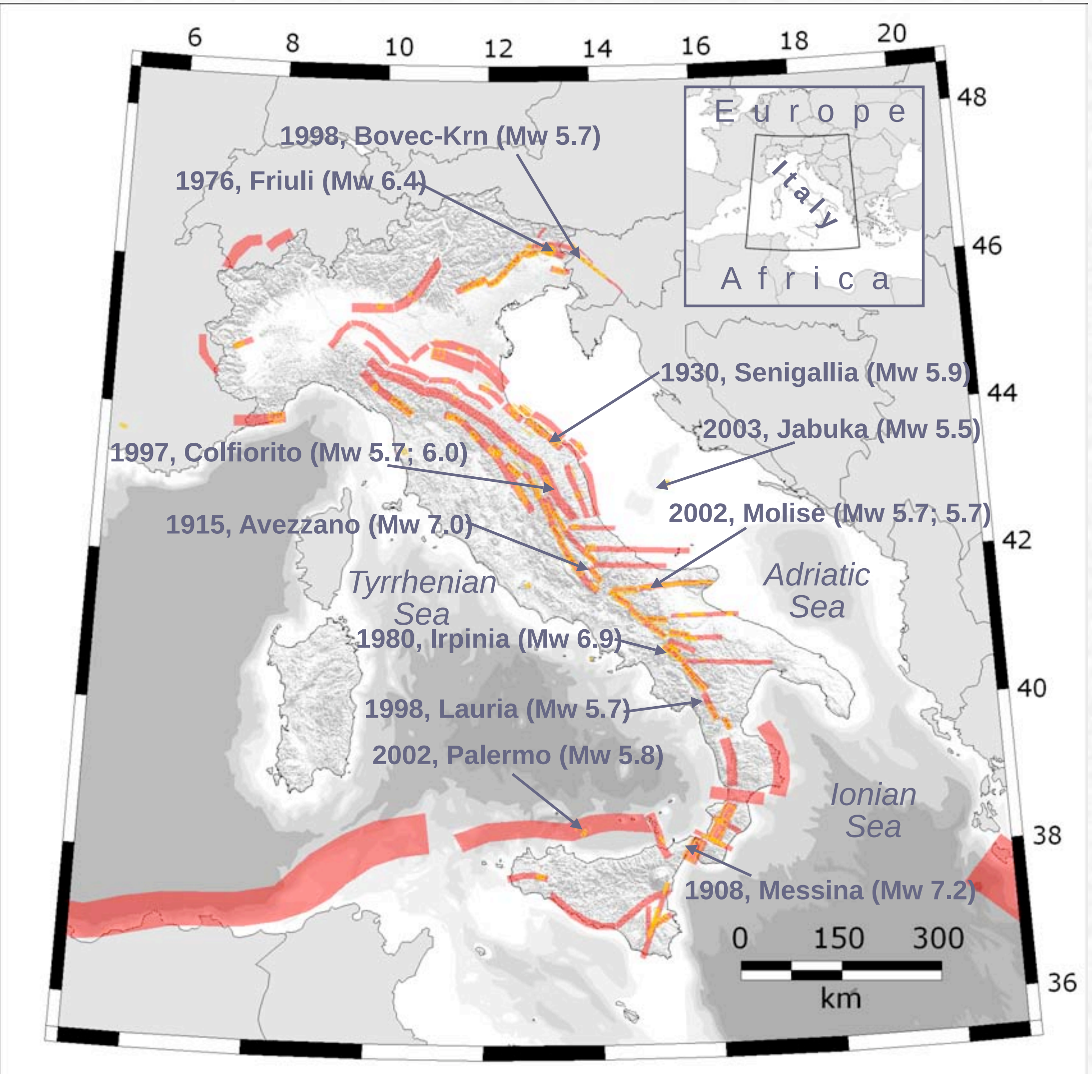
Deliverables for application

1) Database of the Italian M5.5+ seismogenic sources (SSs and SAs) with all geological and seismological information (DISS);
2) Map of the seismogenic sources with Mmax and, when possible, with recurrence interval;
3) Maps of tsunami wave heigh along the Italian coasts.

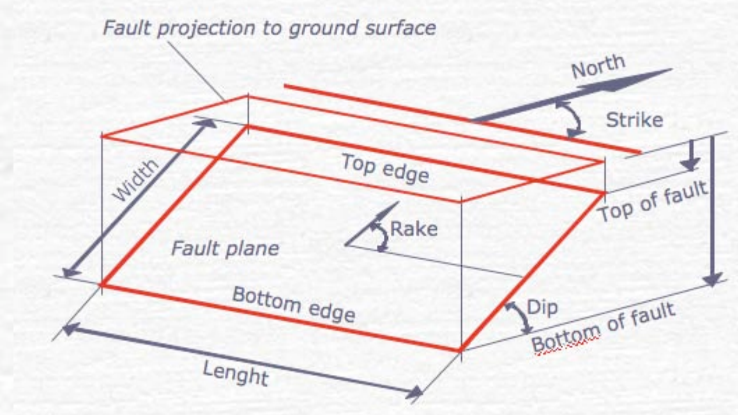
Research Deliverables

- Monographs of the SSs and SAs;
- Code Boxer (for treatment of macroseismic data);
- Database EMMA of focal mechanisms of the Mediterranean region;
- Maps of velocity and strain-rate from GPS data;
- Maps of velocity and strain-rate from 3D numerical modelling.

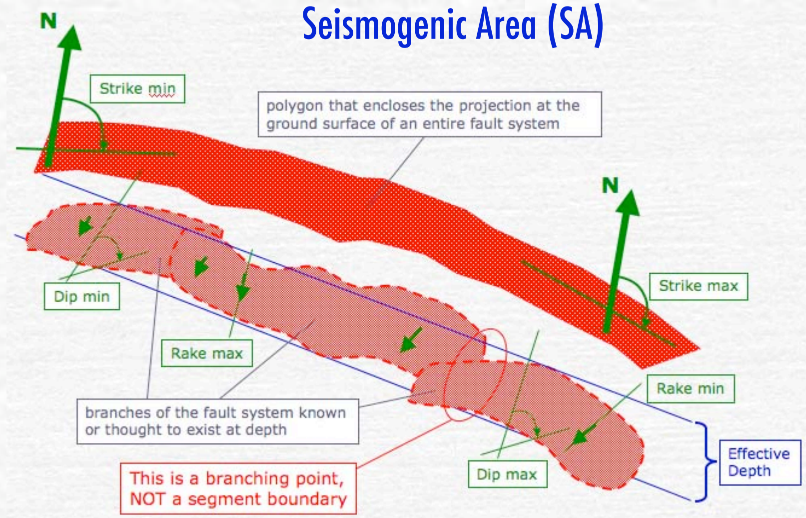
Tomorrow: Task 1 & 2 - the DISS database



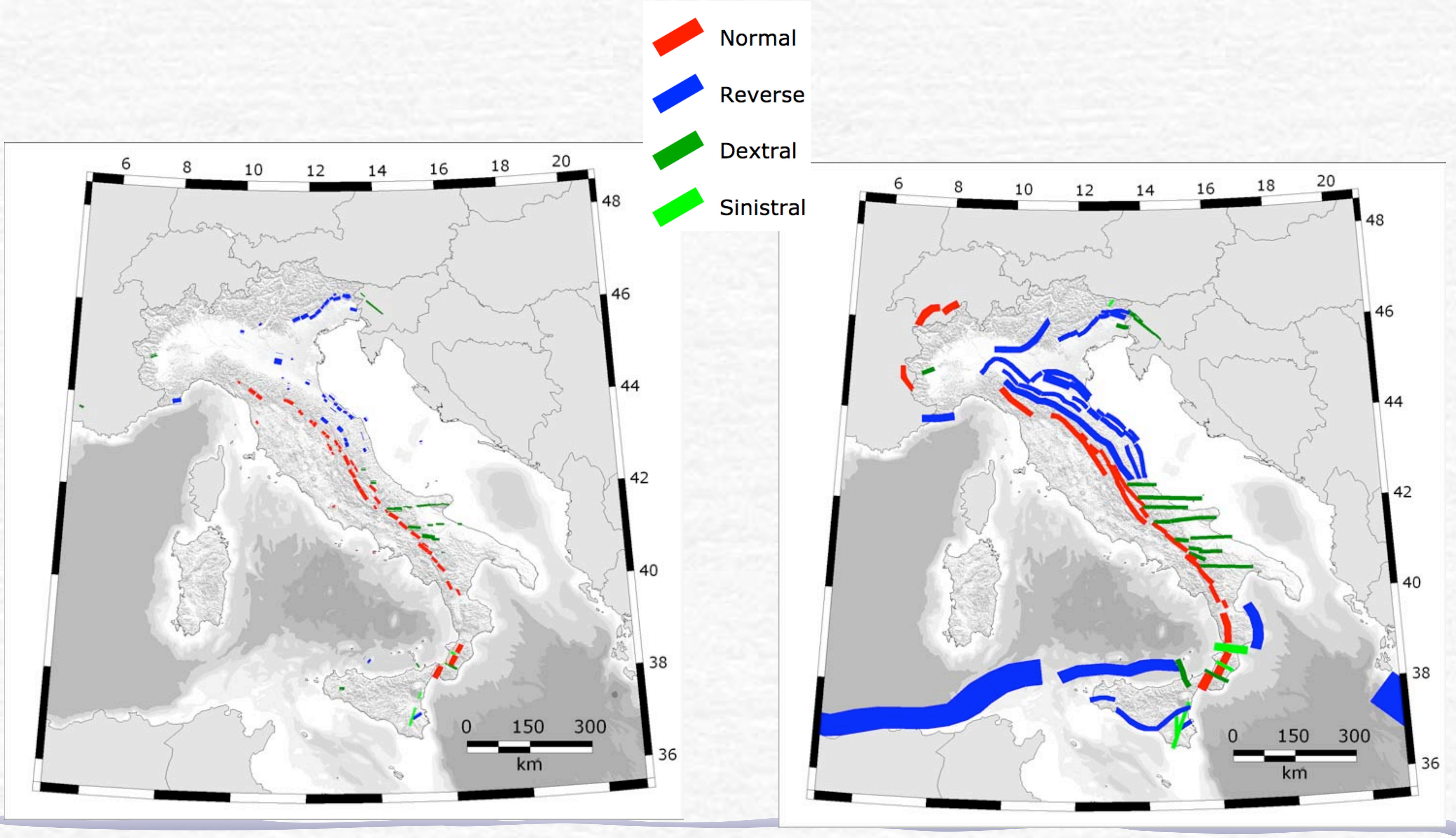
Individual Seismogenic Source (SS)



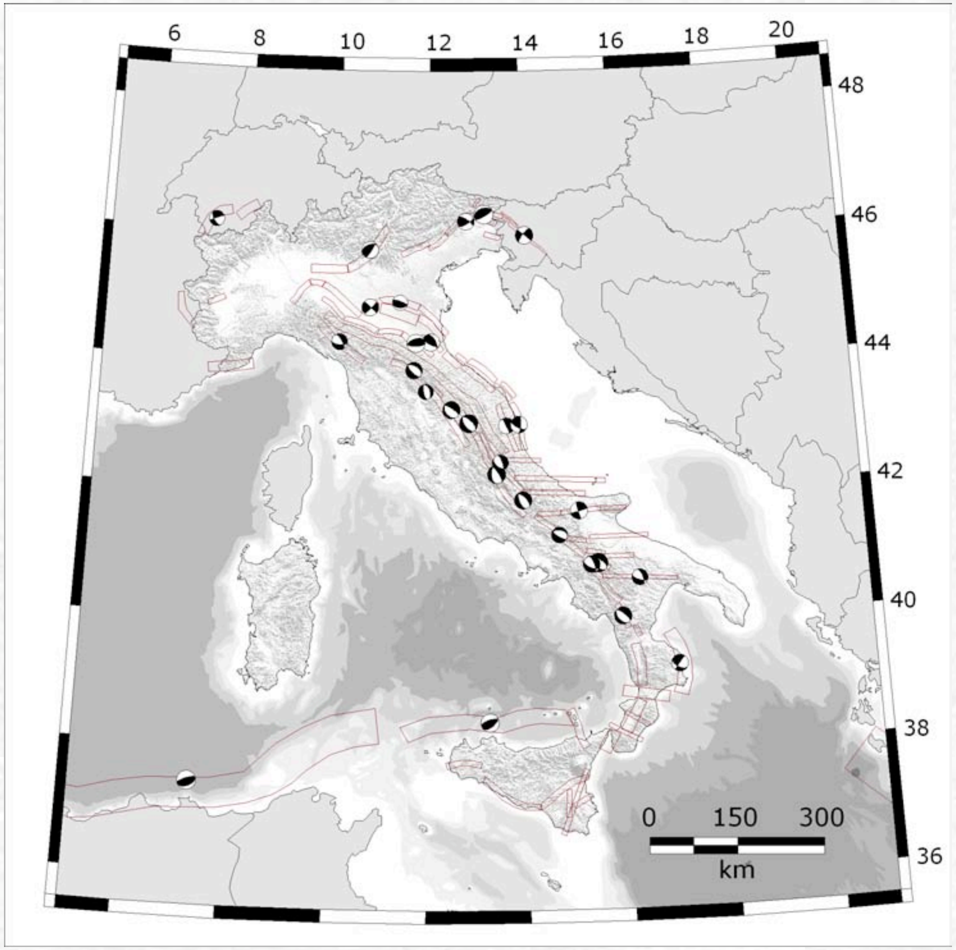
Seismogenic Area (SA)



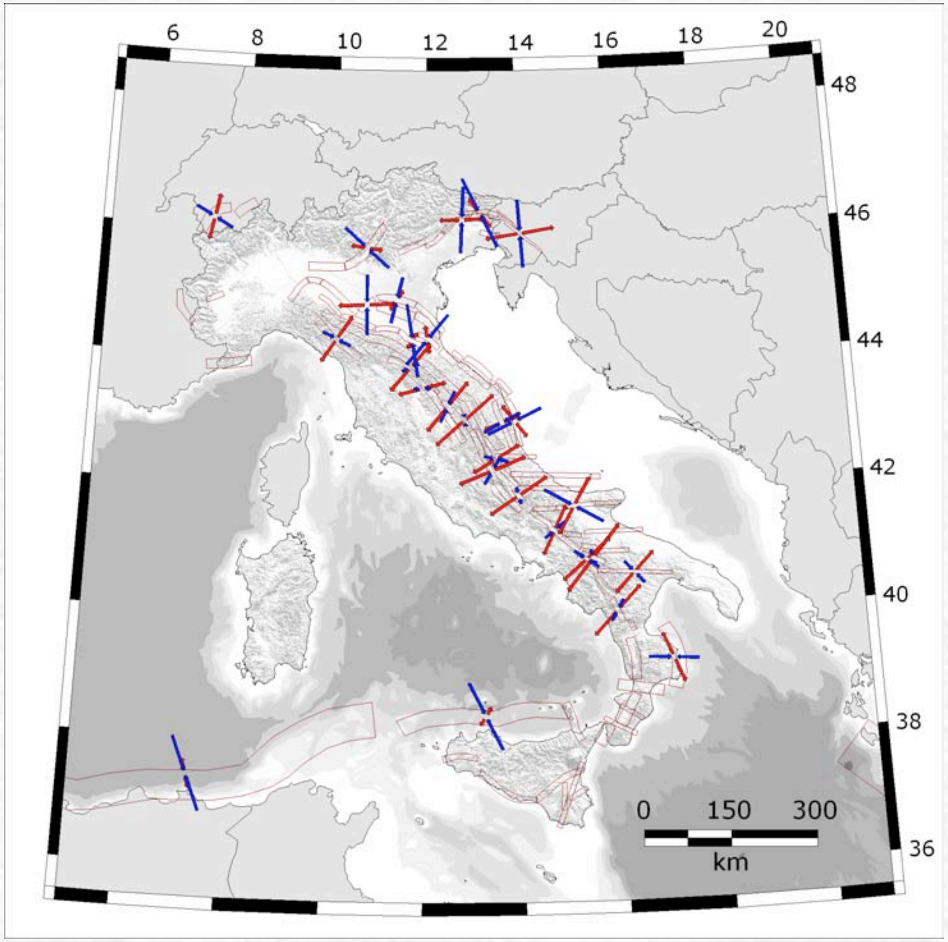
Tomorrow: The DISS database
Faulting mechanisms of the seismogenic sources and areas



Tomorrow: The DISS database
Average focal mechanisms in the SAs

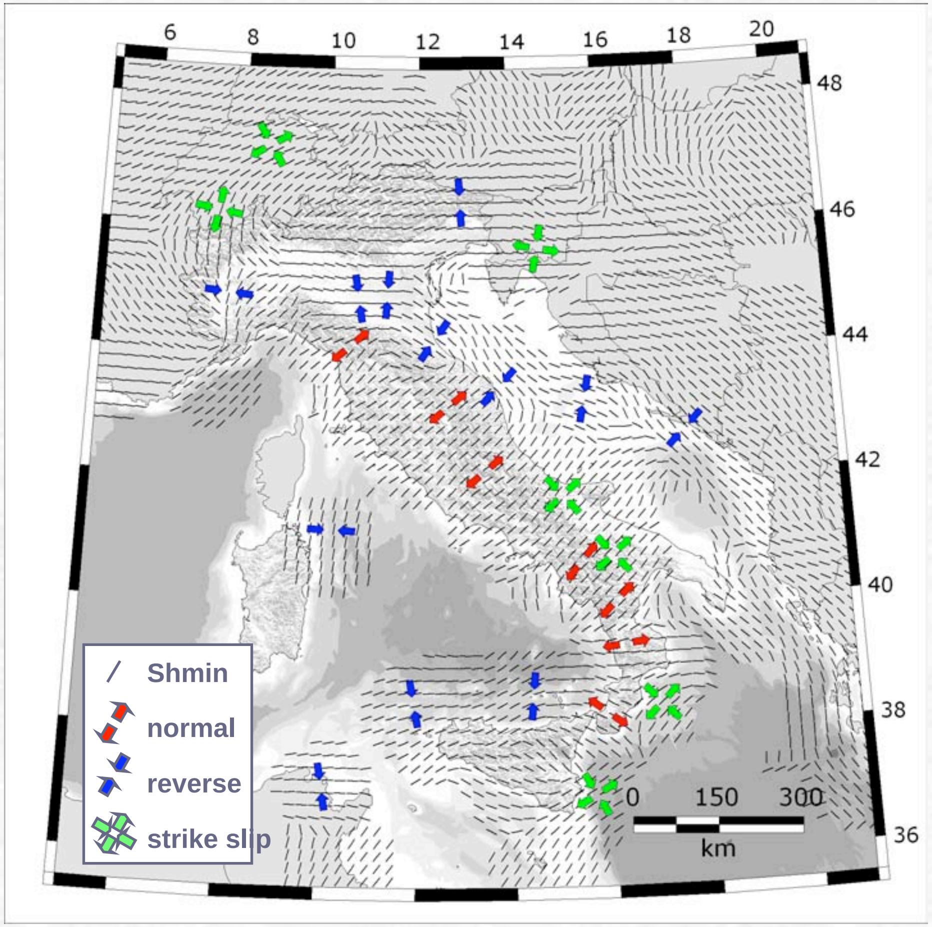


Average focal mechanism in the SA

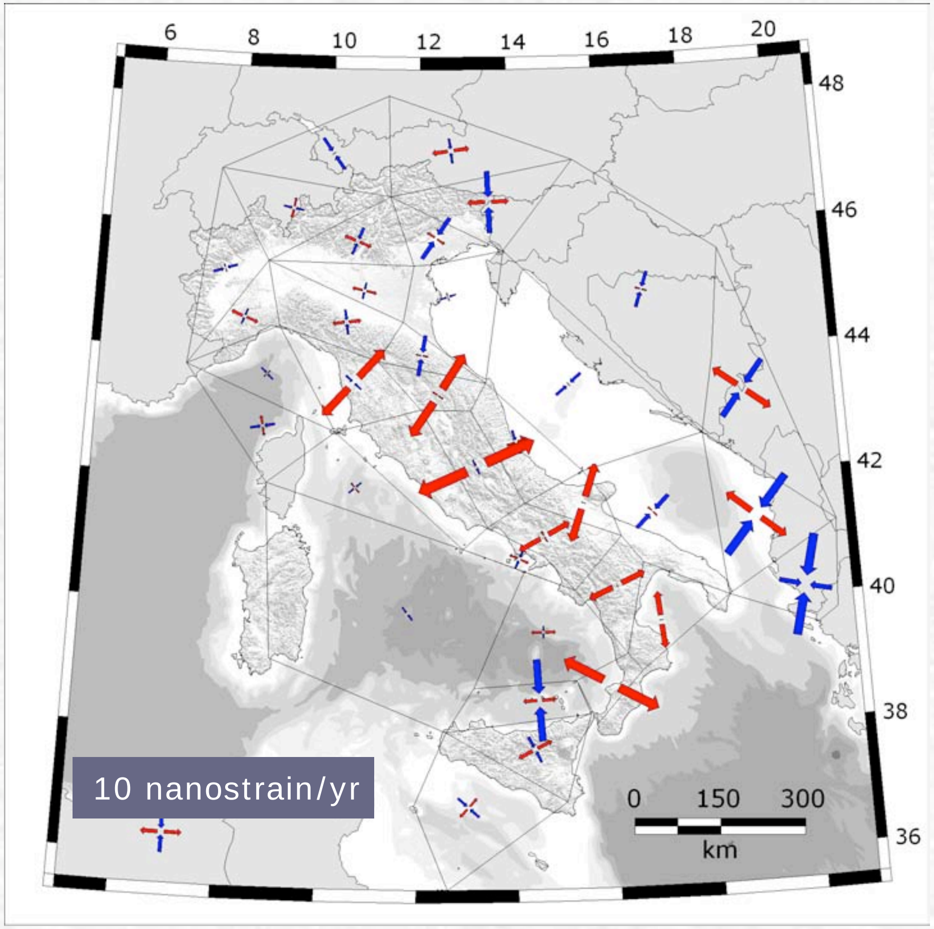


P and T axes from moment tensor summation of eqs in the SA

Tomorrow: The DISS database
Stress and strain regime in the SAs



Smoothed Shmin orientation and stress regime



Horizontal strain rates

Tomorrow: Task 3

Obtaining strain rates for all Italian fault zones

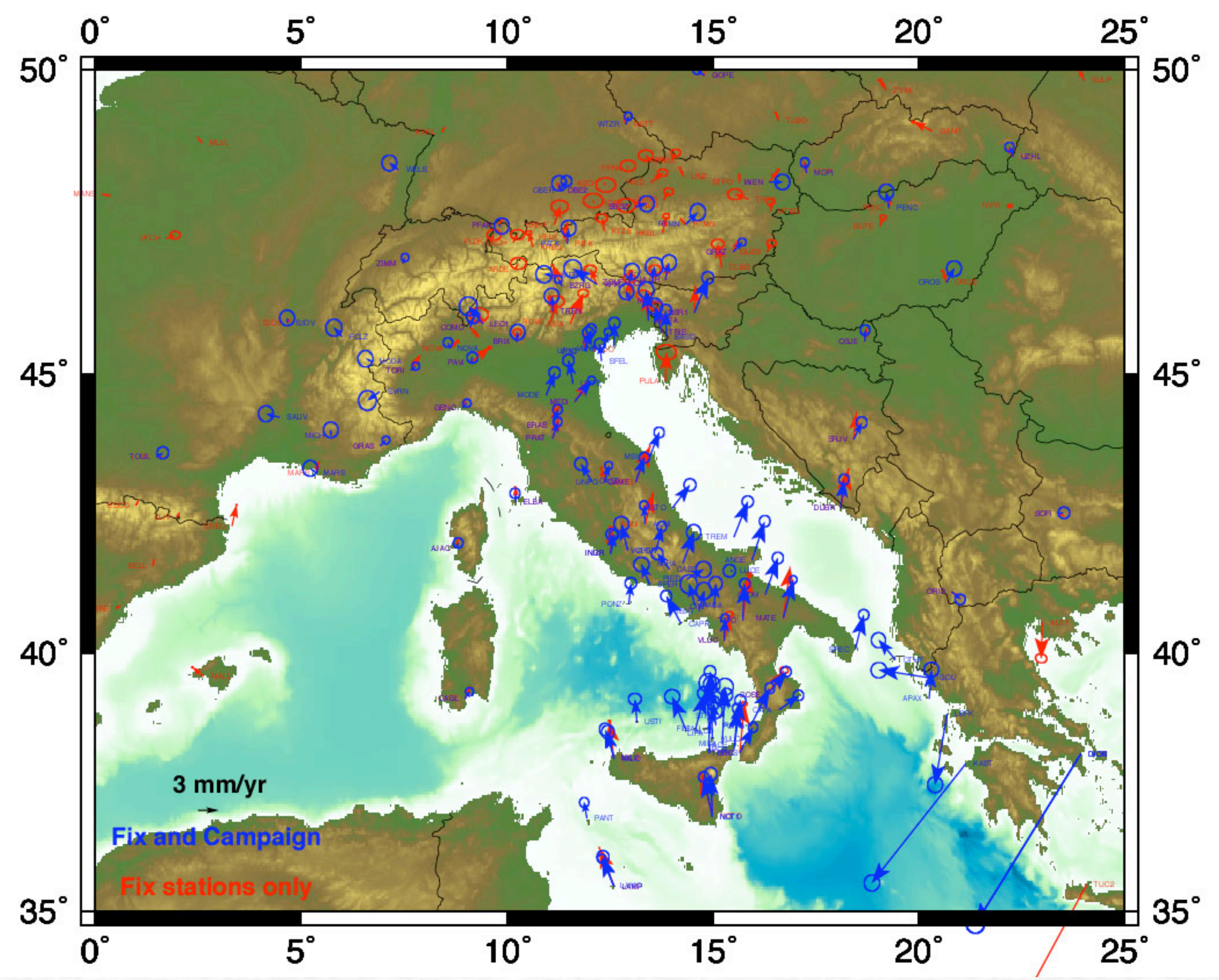
Tomorrow: Task 3
Obtaining strain rates for all Italian fault zones

Three strategies:
1) regional measurements;
2) national strain map;
3) geodynamic modelling.

Main result:
Estimation of the strain rate for all sources (SSs or SAs) in the Italian peninsula

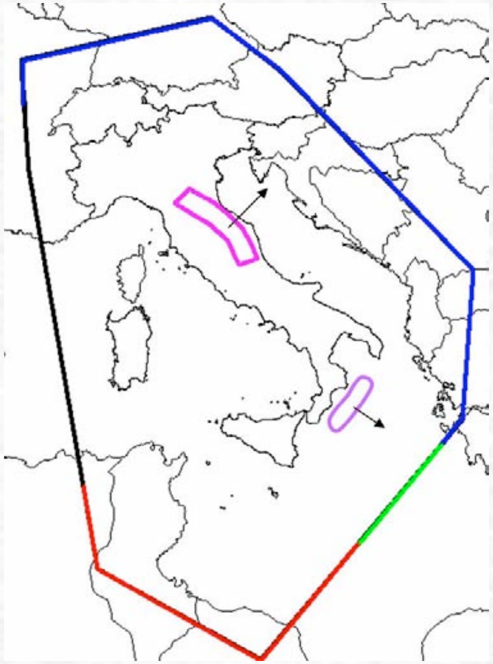
Tomorrow: Task 3

National strain map



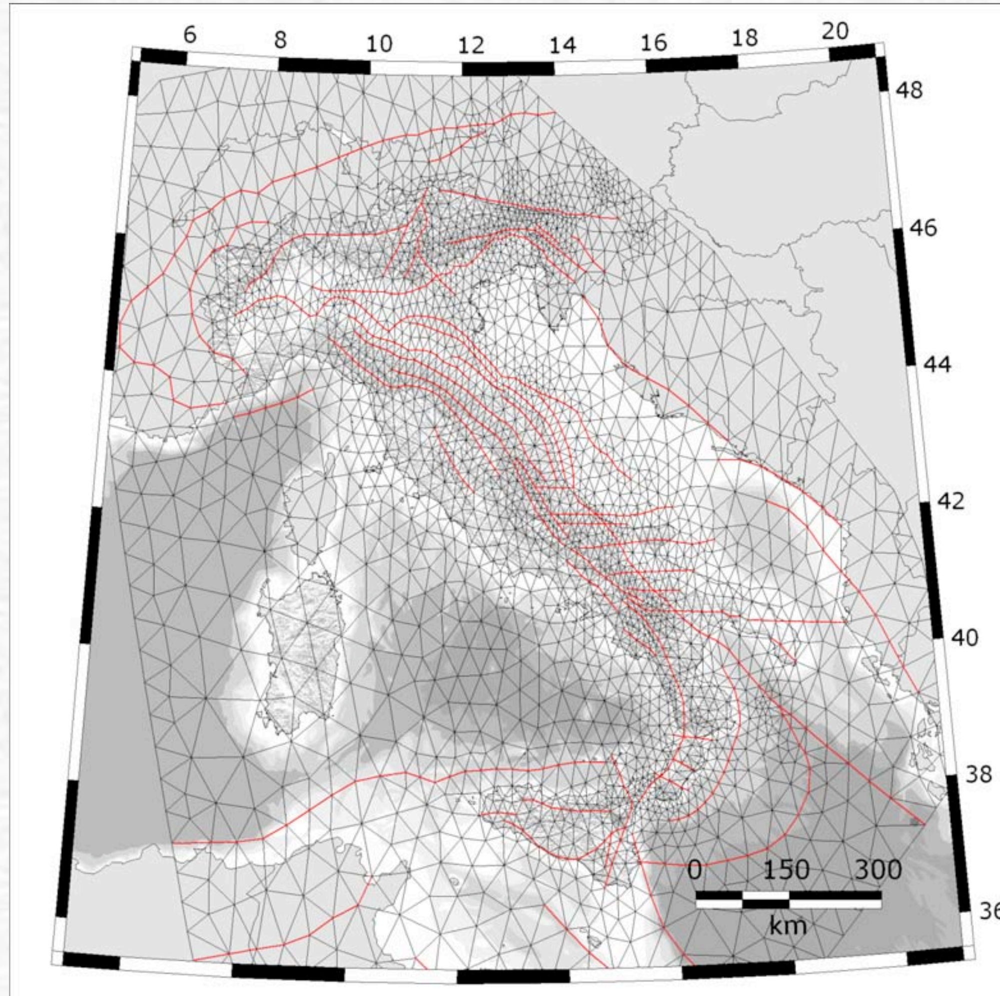
Velocities measured by permanent and additional stations

Tomorrow: Task 3
Geodynamic modelling



The best fitting model has been selected using:
- GPS displacements;
- SHmin orientation from break-out and eqs;
- tectonic regime in DISS SAs

Finite elements numerical modelling
Software SHELLS (Bird, 1999)
Boundary conditions:
blue = Adria rotation;
red = Africa compression;
violet = basal tractions
black = fixed



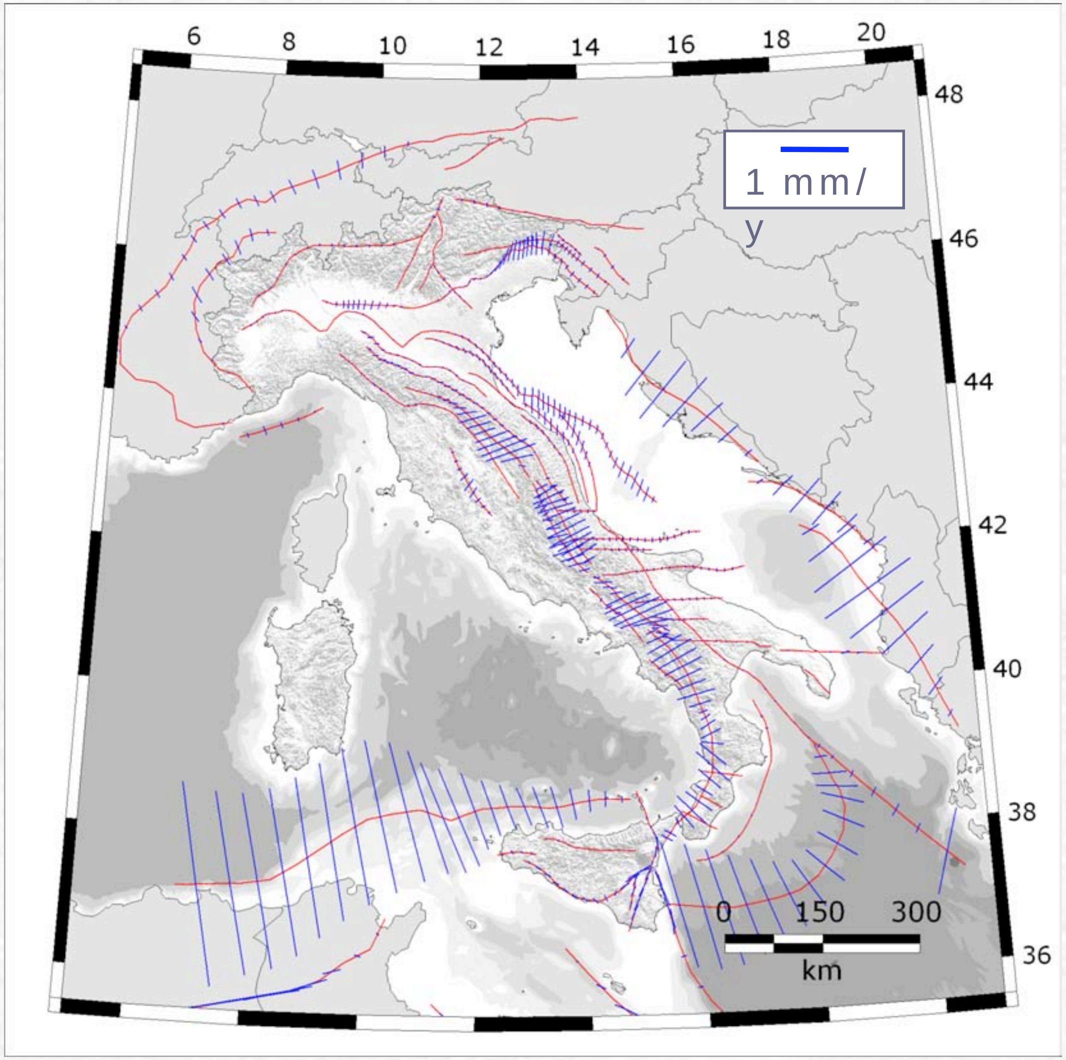
Triangular grid (black) and faults (red) of the physical model

Geodynamic modelling
Slip rates predicted along model discontinuities

With this model, anelastic slip rates and moment rates are computed.

The behaviour of areas that do not include large faults or where M<5.5 eqs dominate must be derived from the strain-rate directly.

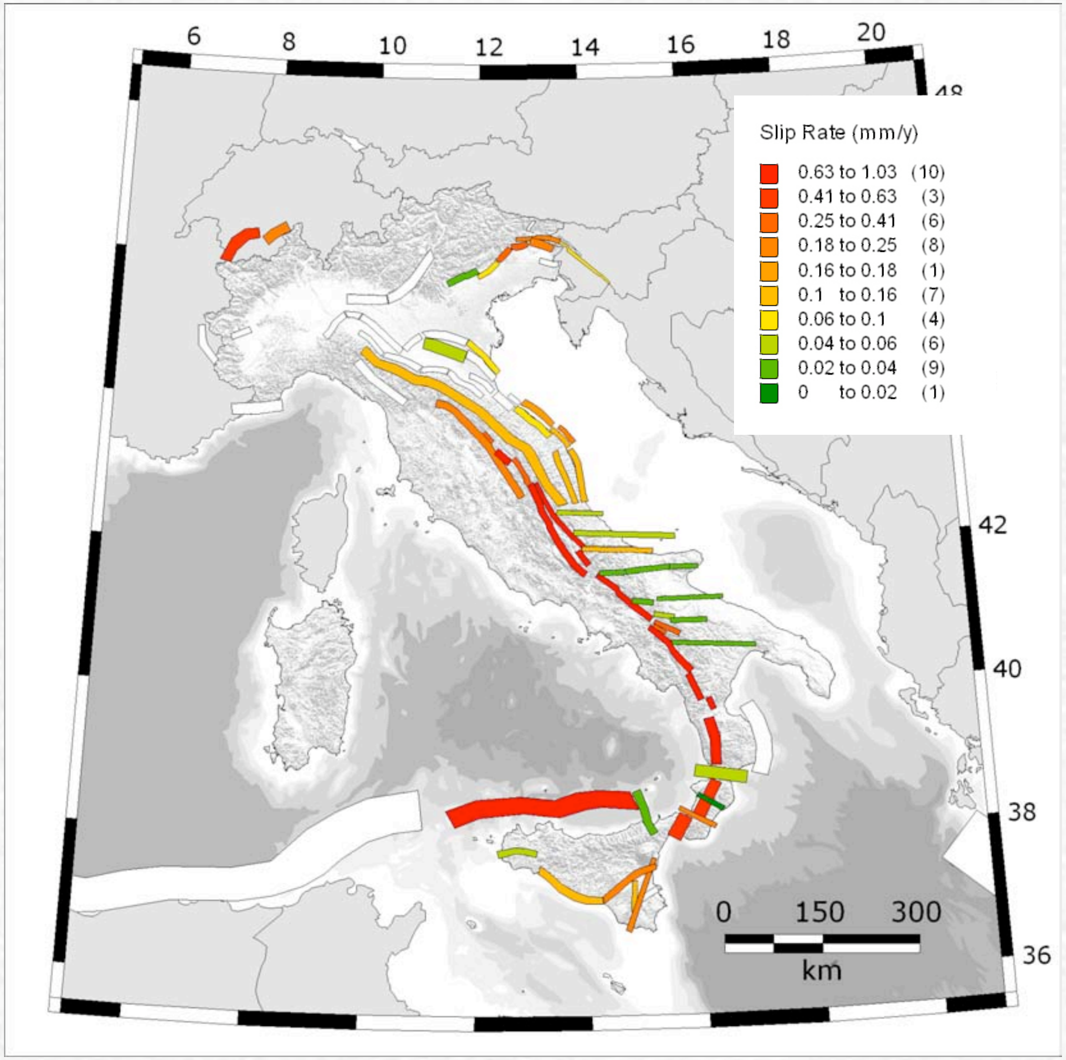
Anelastic slip rates can be compared with observed (geological) slip rates.



Geodynamic modelling

Predicted slip rates spread over the SAs

Anelastic slip rates are averaged within the SAs in order to gain stability. This first-order picture can ideally be checked against patterns of occurrence of large earthquakes. White areas are not determined



Tomorrow: Task 4

Seismic characterization of the main seismogenic structures and assessment of eq occurrence probability

1) Probability of an imminent earthquake using instrumental data-sets of events

2) Occurrence probabilities supported by physical model

3a) Probabilities of main events based on inter-times derived from areas

3b) Probabilities of main events based on fault data

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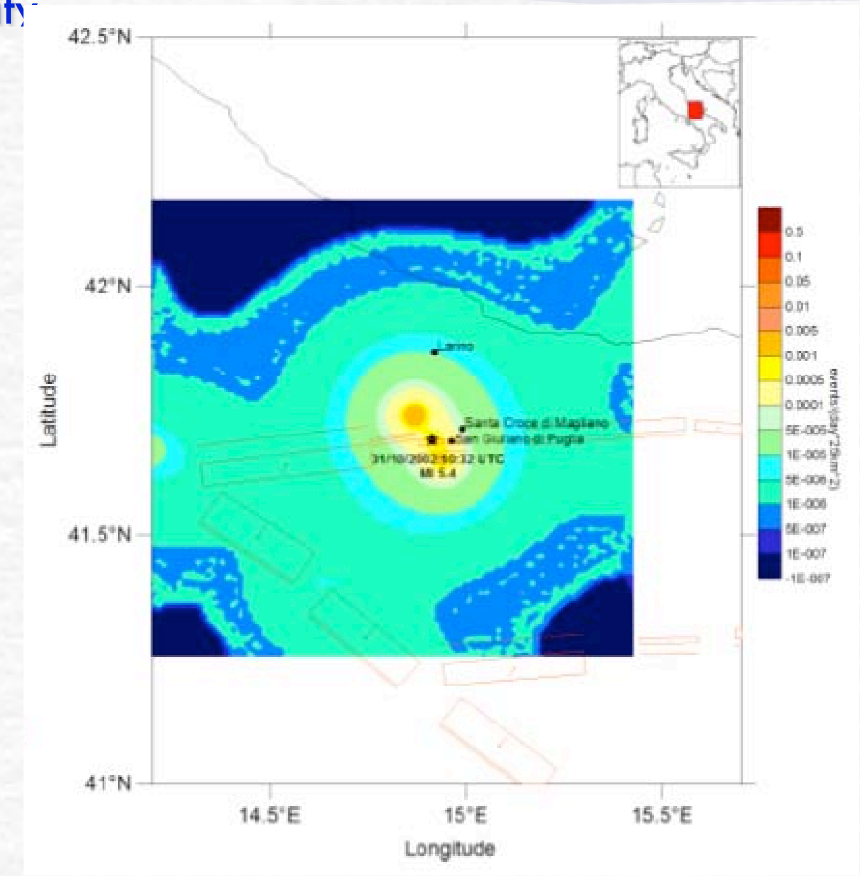

Occurrence rate increment before San Giuliano mainshock (ETAS model)

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2d Contribution of fault interaction

	Ovindoli-Pezza	Sulmona Basin	Fucino Basin	Aremogna-Cinquemiglia
R_0_Poisson	6.25e-04	1.18e-03	7.14e-04	4.67e-04
R_0_cond	4.29e-03	1.33e-04	5.00e-04	4.07e-03
R_0_mod	5.90e-03	1.32e-04	5.00e-04	4.40e-03
Delta_t (anni)	+63.00	-53.00	0.00	+21.30
P(30)Poisson (DISS 3.0.1)	1.90%	3.50%	2.10%	1.40%
P(30)cond (Peruzza, comm. pers.)	12.10%	0.40%	1.50%	11.00%
P(30)mod	16.20%	0.39%	1.50%	12.30%

3a) Probabilitie events based o derived from ar

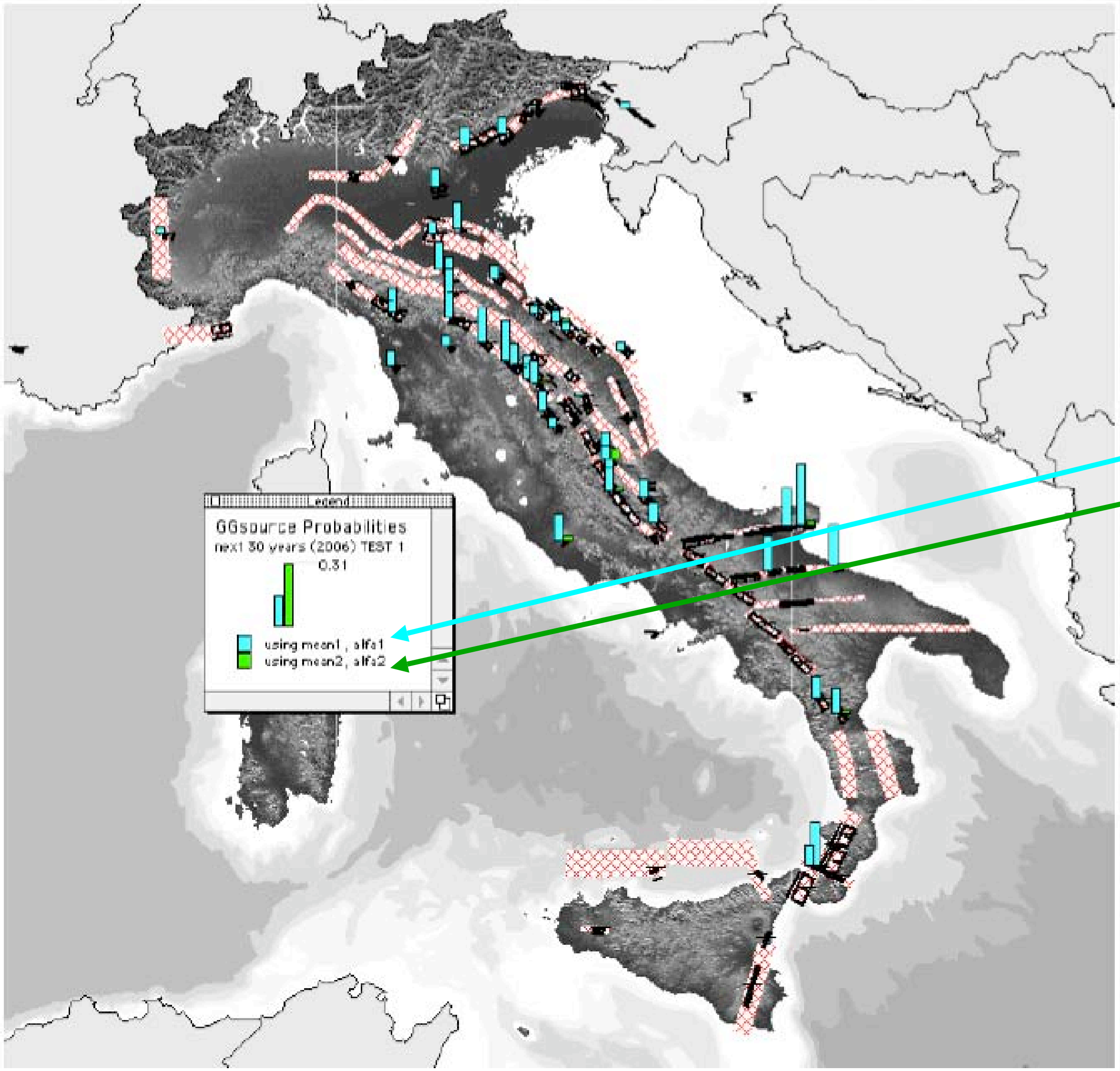
3b) Probabilities of main events based on fault data

Notable variation (33%)

Ro = seismicity rate (1/T), if it increases next eq approaches and probability increases;
cond = characteristic eq;
mod = cond modified by contribution of Coulomb stress

Tomorrow: Task 4

Probabilities of main events based on fault data

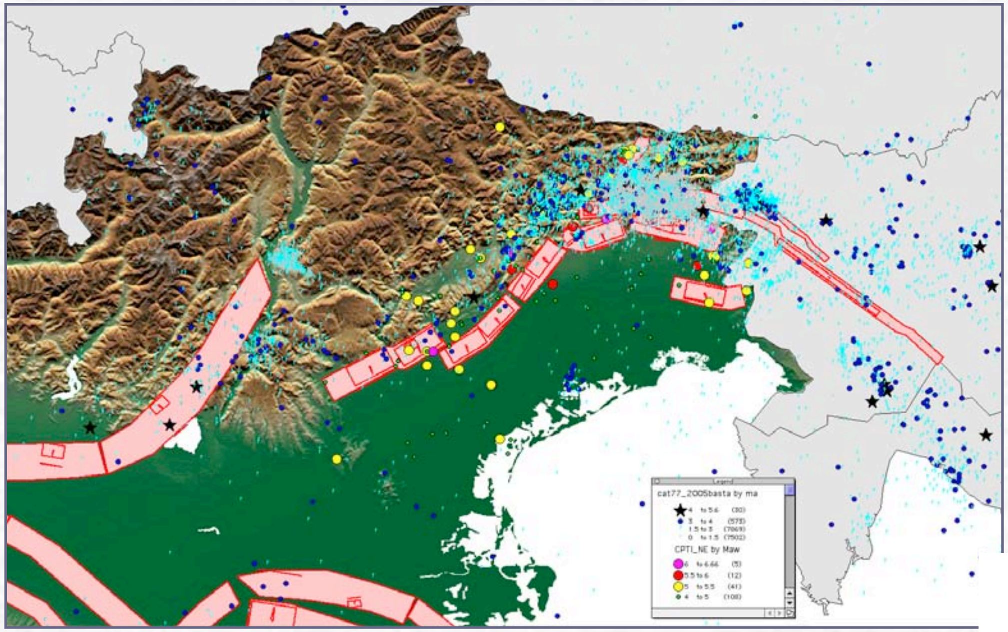


Probability in the next 30 yrs
on updated DISS faults
(seismogenic areas are reported only for information)

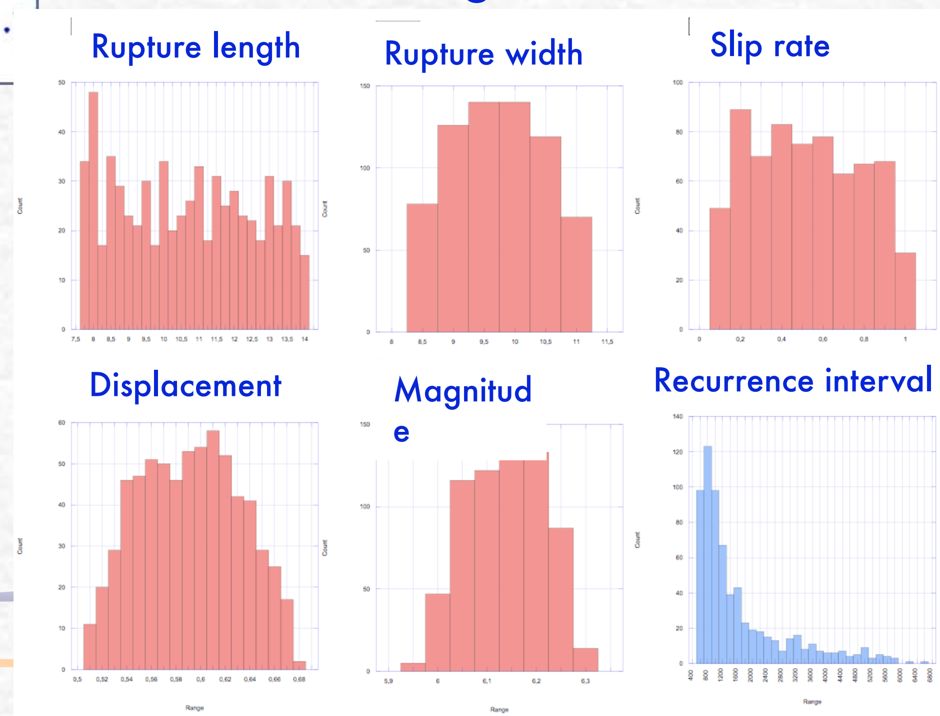
BPT model
blue = dispersion of the ch eq magnitude
green = slip rate dispersion

Sensitivity to time passed since last eq
(missing for 1/3 of the faults)

Statistical parametrization of the SAs



The SAs are occupied by SSs only partly: we can fill the empty space by fictitious SSs defined statistically according to the actual SS distribution in the region



Once we have defined (statistically) the rupture length, width, and slip rate of the fictitious SSs, we can derive all their seismic parameters and assigned them proportionally the total moment rate of the SA.

Things to be done before the end of the project

1) release of the updated version of the DISS database;

2) release of the final version of the geodynamic model and an updated set of slip rates derived from it;

3) release of the map of the occurrence probability of the characteristic earthquake for the individual SSs (actual or fictitious faults).

This is
THE END

Thanks for your attention

Task 4
3b) Probabilities of main events based on fault data

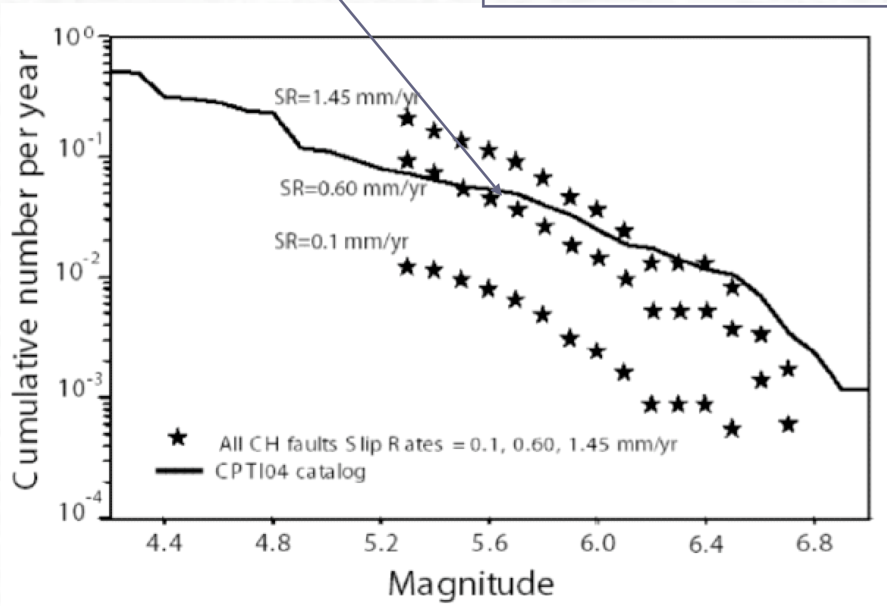
Slip rate bilancing

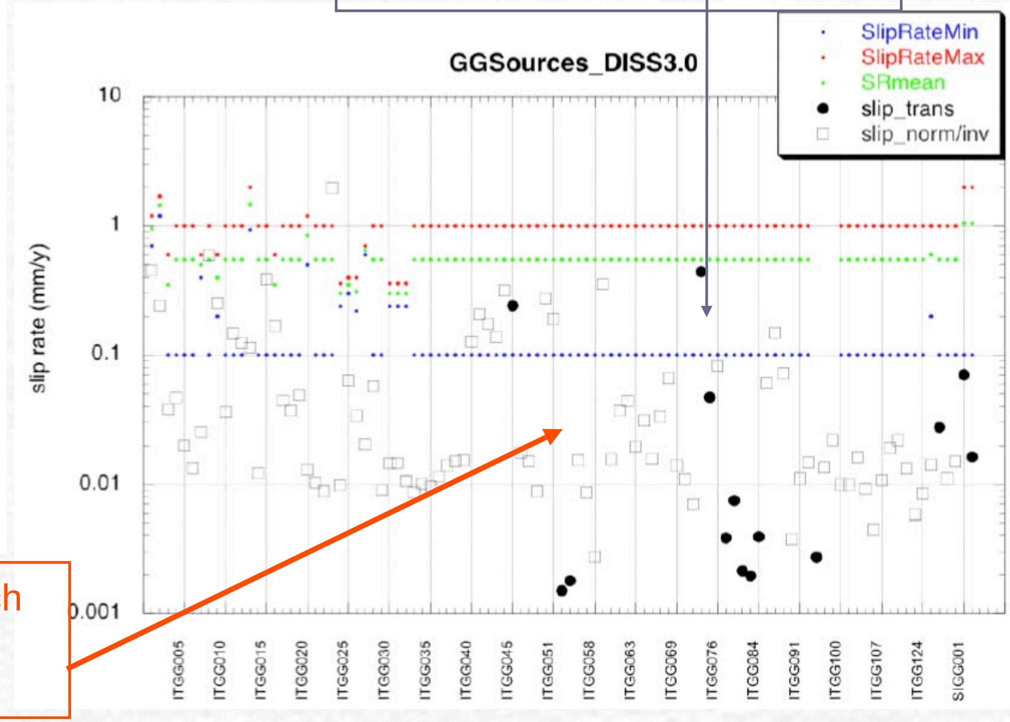
Slip rate bilancing

Historical seismicity limits the SR value

Bayes approach for slip rate distribution: posterior = prior * likelihood
Likelihood from misfit

Slip rates from geodesy modelling (on ZS9 basis taking into account the fault geometry) and slip rates in DISS





Geodetic slip rates much lower than seismic slip rates