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Ninth Workshop on Non-linear Dynamics and Earthquake Predictions

1 - 13 October 2007

A Rational Complex Approach of
Neo-Deterministic Time-Variable
Seismic Hazard Assessment

G.F. Panza & SAND Group
Dept. of Earth Science & ICTP

A rational complex approach of neo-deterministic time-variable seismic hazard assessment

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Trieste, October 1 - 30, 2007

The evaluation of seismic hazard is based on the traditional Probabilistic Seismic Hazard Analysis, i.e. on the probabilistic analysis of earthquake catalogues and of ground motion, from macroseismic observations and instrumental recordings. This leads to severe bias in the estimation of seismic hazard, with artificially inflated errors, because the mathematical model of PSHA, as it is in use today, is inaccurate and leads to systematic errors in the calculation process.

Recently this approach showed its limitation in providing a reliable seismic hazard assessment, possibly due to the insufficient information about historical seismicity, which can introduce relevant errors in the purely statistical approach mainly based on the seismic history.

The probabilistic analysis supplies indications that can be useful but are not sufficiently reliable to characterize seismic hazard. Recent examples Kobe (17.1.1995), Bhuj (26.1.2001), Boumerdes (21.5.2003) and Bam (26.12.2003) events.

? GSHAP ?

Kobe (17.1.1995), Gujarat (26.1.2001), Boumerdes (21.5.2003) and Bam (26.12.2003) earthquakes PGA(g)

	Expected with a probability of exceedence of 10% in 50 years (return period 475 years)	Observed
Kobe	0.40-0.48	0.7-0.8
Gujarat	0.16-0.24	0.5-0.6
Boumerdes	0.08-0.16	0.3-0.4
Bam	0.16-0.24	0.7-0.8

To overcome the mentioned limitations and, above all, to improve the pre-seismic information which may lead to an effective mitigation of seismic risk, we are following an innovative approach, that combines Earth Observation (EO) data and new advanced approaches in seismological and geophysical data analysis.

ASI Pilot Project - SISMA

"Seismic Information System for Monitoring and Alert"

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agenzia spaziale italiana DST Università di Milano Politecnico di Milano galileian

The system we are developing is based on the neodeterministic approach for the estimation of seismic ground motion, integrated with the space and time dependent information provided by EO data analysis through geophysical forward modeling.

The need of integration of different geophysical observables is obvious when the process of earthquake preparation and occurrence is analysed: the lithosphere - a hierarchical system of interacting blocks - accumulates stress, according to strain and strain rates fields due to tectonics, which is partly released during the earthquake occurrence.

System's Overall Description

Seismological data analysis

- **INPUT**

Data on seismicity (earthquake catalogues), geomorphology and geodynamics and Earth structure (velocity, gravity data);

Worldwide tested pattern recognition algorithms for middle-range intermediate-term earthquake prediction and for identification of damaging earthquake prone areas;

Robust and tested codes for the earth structure retrieval and numerical modelling of lithosphere block dynamics.

Seismological data analysis

■ **OUTPUT (1)**

Regional alerted areas by the near real time monitoring of seismicity (TIPs for the occurrence of earthquakes with $M \geq M_0$);

Maps of the morphostructural zonation and selection of seismogenic nodes prone to earthquakes with $M \geq 6.0$ & $M \geq 6.5$ within the regional alerted regions;

Seismological data analysis

- **OUTPUT (2)**

Restrained local alerted areas for GPS and SAR investigations;

Multiscale velocity models of the Earth Structure for geophysical forward modelling;

Preferred models for the dynamics of the lithosphere at a regional scale.

Real-time monitoring of the seismic flow: CN and M8S algorithms

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CHIESA PARROCCHIALE
DI
SAN BIAGIO IN COSINA
DIOCESI E COMUNE DI FAENZA
(PROV. DI RAVENNA)
//

li 15 settembre 1950

Certifico io sottoscritto che Giuliano Panza di Giuseppe e di Giuseppina Liverani' nato a S. Biagio il 27 aprile 1945 ad ore 7.15 fu Battezzato a questo S. Fonte il 23 aprile 1945 dal M. R. D. D. Giuseppe [illegible] essendo madrina la sig. Lolli Colomba in Liverani.

Tanto risulta dai registri dei Battezzati esistenti in questo Archivio Parrocchiale, pag. 15 n. 43

L. ✠ S.

IL PARROCO

Curia Vescovile di Faenza

li

Visto per l'autenticazione della firma del M. R.

IL CANCELLIERE

L. ✠ S.

My earliest credential about prediction

This is my certificate of baptism, drafted on September 15, 1950, stating that I was **born** on April **27**, 1945 and I was **christened** on April **23**,1945

Intermediate-term middle-range earthquake prediction experiment

CN algorithm (*Keilis-Borok et al., 1990; Peresan et al., 2005*)

M8S algorithm (*Kossobokov et al, 2002*)

Main features:

- **Fully formalized algorithms and computer codes available for independent testing;**
- **Use of published & routine catalogues of earthquakes;**
- **Worldwide tests ongoing for more than 10 years permitted to assess the significance of the issued predictions** (*Kossobokov et al., 1999*; *Rotwain and Novikova, 1999)*

Intermediate-term middle-range earthquake prediction experiment in Italy

CN and M8S algorithms are based on a set of empirical functions of time to allow for a quantitative analysis of the premonitory patterns which can be detected in the seismic flow:

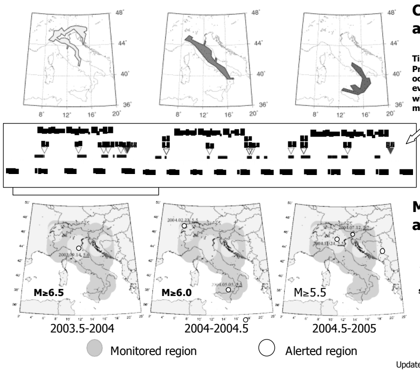
- ■ **Variations in the seismic activity**
- ■ **Seismic quiescence**
- ■ **Space-time clustering of events**

They allow to identify the TIPs
(Times of Increased Probability)
for the occurrence of a strong earthquake
within a delimited region

Intermediate-term middle-range earthquake prediction experiment in Italy

- **Stability tests with respect to several free parameters of the algorithms** *(e.g. Costa et al., 1995; Peresan et al., GJI, 2000; Peresan et al., PEPI, 130, 2002);*
- **CN predictions are regularly updated every two months since January 1998;**
- **M8S predictions are regularly updated every six months since January 2002;**

Real time prediction experiment
started in July 2003



CN algorithm

Times of Increased Probability for the occurrence of events with M>Mo within the monitored regions

M8s algorithm

Events with M_{max} ≥5.5 occurred since July 2003

Updated to January 2007

Intermediate-term middle-range earthquake prediction

Space-time volume of alarm in CN application in Italy

Experiment	Space-time volume of alarm (%)	n/N	Confidence level (%)
Retrospective* (1954 – 1963)	**41**	**3/3**	**93**
Retrospective (1964 – 1997)	**27**	**5/5**	**>99**
Forward (1998 – 2007)	**36**	**4/5**	**94**
All together (1954 – 2007)	**31**	**12/13**	**>99**

* Central and Southern regions only

Algorithm CN predicted 12 out of the 13 strong earthquakes occurred in the monitored zones of Italy, with 31% of the considered space-time volume occupied by alarms.
(updated to January 1 2007)

Intermediate-term middle-range earthquake prediction
Space-time volume of alarm in M8S application in Italy

Experiment	M6.5+		M6.0+		M5.5+	
	Space-time volume, %	n/N	Space-time volume, %	n/N	Space-time volume, %	n/N
Retrospective (1972-2001)	36	2/2	40	1/2	39	9/14
Forward (2002-2007)	49	0/0	43	0/0	25	5/9
All together (1972-2007)	37	2/2	40	1/2	38	14/23

Algorithm M8S predicted 64% of the events occurred in the monitored zones in Italy, i.e. 17 out of 27 events occurred within the area alerted for the corresponding magnitude range. The confidence level of M5.5+ predicitions since 1972 has been estimated to be about 97%; no estimation is yet possible for other magnitude levels.

(updated to January, 1 2007)

Intermediate-term middle-range earthquake prediction experiment in Italy

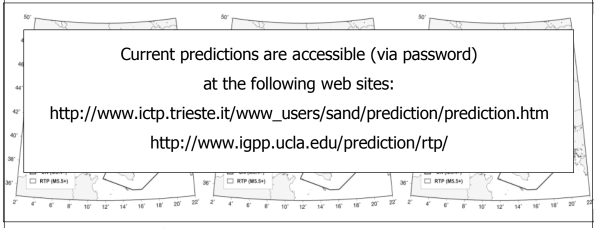
Prediction experiment: launched starting on July 2003, is aimed at a *real-time test* of CN and M8S predictions in Italy. Updated predictions are regularly posted at:

"http://www.ictp.trieste.it/www_users/sand/prediction/prediction.htm"

A complete archive of predictions is made accessible to a number of scientists, with the goal to accumulate a collection of correct and wrong predictions, that will permit to validate the considered methodology.

Current predictions are protected by password. Although these predictions are intermediate-term and by no means imply a "red alert", there is a legitimate concern about maintaining necessary confidentiality.

The current situation of alarms



Current predictions are accessible (via password)
at the following web sites:
http://www.ictp.trieste.it/www_users/sand/prediction/prediction.htm
http://www.igpp.ucla.edu/prediction/rtp/

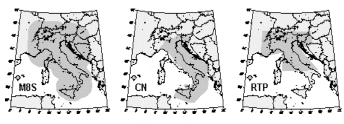
Alarmed areas by:

- M8S algorithm for M5.5+, M6.0+, M6.5+
- CN algorithm for M≥5.4

(Peresan , Kossobokov, Romashkova, Panza 2005, Earth Science Reviews, 69)

- RTP algorithm for M≥5.5

(Keilis-Borok , Shebalin, Gabrielov, Turcotte, 2004 , PEPI, 145)

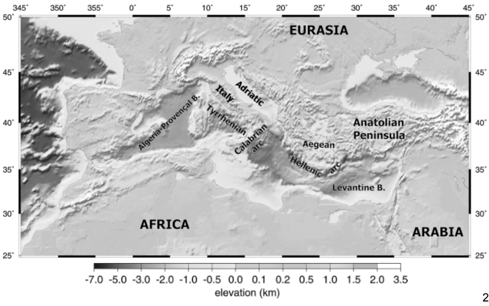


Monitored territory

Morphostructural zonation and pattern recognition of earthquake prone areas

Morphostructural zonation and pattern recognition of earthquake prone areas

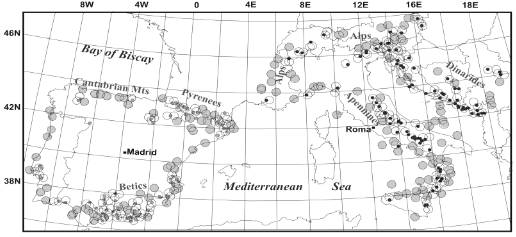
- **The Morphostructural Zonation method, MSZ *(Alekseevskaya et al., 1977),* allows to identify, independently from earthquake catalogues information, the sites where strong earthquakes are likely to occur.**



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

Target magnitudes: $M \geq 6.0$ - Alps, Apennines and Dinarides
$M \geq 5.0$ - Iberia

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



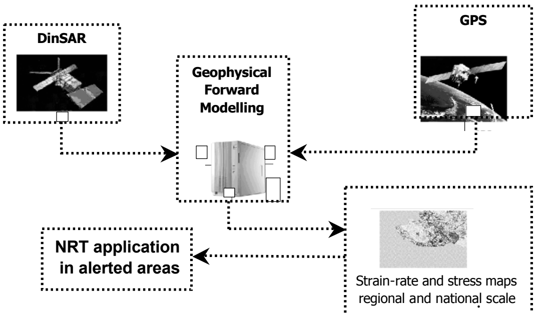
References
Gorshkov A.I., Panza G.F., Soloviev A.A. & Aoudia A. (2002). Morphostructural zoning and preliminary recognition of seismogenic nodes around the Adria margin in peninsular Italy and Sicily. *JSEE:* Spring 2002, 4, No.1, 1-24.
Gorshkov A.I., Panza G.F., Soloviev A.A., Aoudia A. (2004). Identification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

Seismic Flow and EO data

- **Maps of areas alerted by CN and M8s will be compared with EO information, taking into account modelling of the reology provided by Geophysical Modelling;**

- **EO observations, consisting of GPS and Din – SAR Images, will permit to draw deformation maps on the surface;**
- **Stress maps at the depth of the active faults will be obtained through integration of EO geodetic information into Geophysical Forward Modelling.**

EO Data in Near-Real-Time Application



DinSAR

GPS

Geophysical Forward Modelling

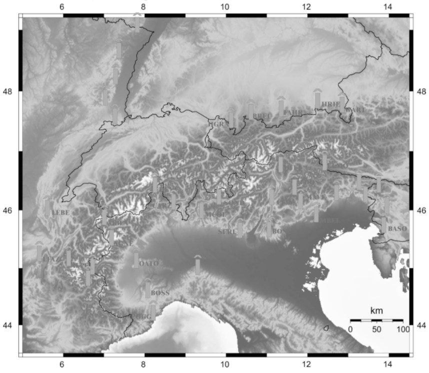
NRT application in alerted areas

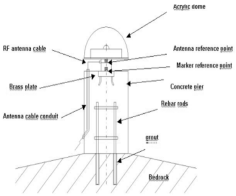
Strain-rate and stress maps regional and national scale

ALPS GPSQUAKENET

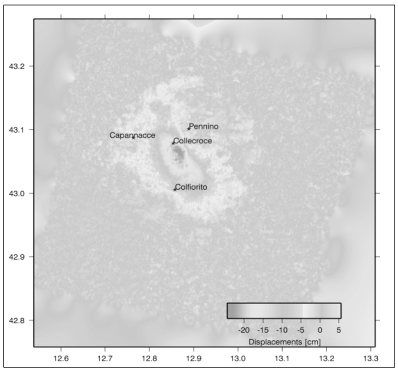
GAIN -
Geodetic Alpine Integrated Network

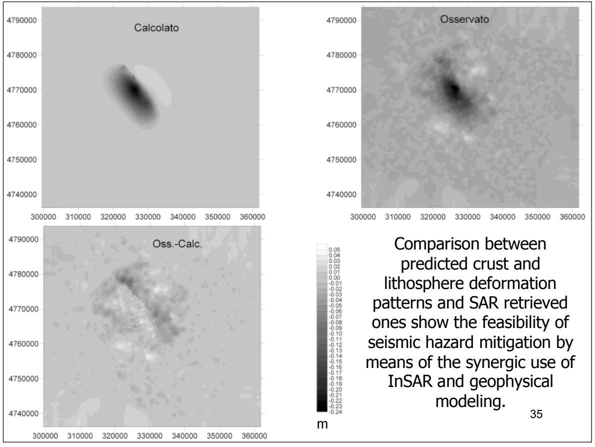
Interreg III B





Methodology for detecting the vertical movements during the
pre-seismic, co-seismic and post-seismic phases
in earthquake prone areas.





Comparison between predicted crust and lithosphere deformation patterns and SAR retrieved ones show the feasibility of seismic hazard mitigation by means of the synergic use of InSAR and geophysical modeling.

Multiscale Neo-deterministic Hazard Scenarios

Regional seismic hazard scenarios

(ground motion at bedrock)

- Scenarios associated to alerted CN and M8S regions (+ time)
- Scenarios associated to seismogenic nodes

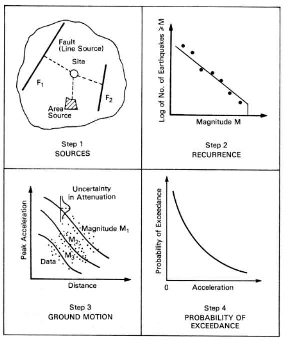


FIGURE 10.2 Basic steps of probabilistic seismic hazard analysis (after TERA Corporation 1978).

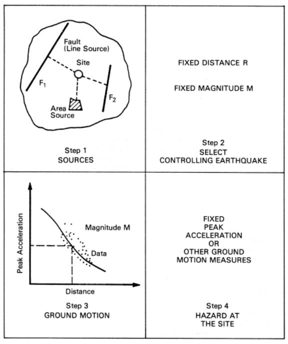


FIGURE 4.1 Basic steps of deterministic seismic hazard analysis (after TERA Corporation 1978).

Probabilistic and Deterministic procedures after Reiter (1990)

Probabilistic

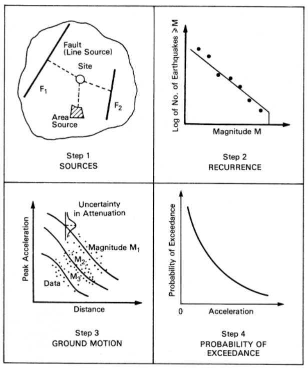


FIGURE 10.2 Basic steps of probabilistic seismic hazard analysis (after TERA Corporation 1978).

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 are not translation invariant in the phase space (M, R, S). Even when translation invariant they are not a conditional probability density function, they represent the functional dependency of the random spectral acceleration on the random variates, magnitude, distance and measurement error (Klügel, 2006).

↓

Step 4 - ???

M - magnitude; R - source distance; S - local soil conditions

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Deterministic

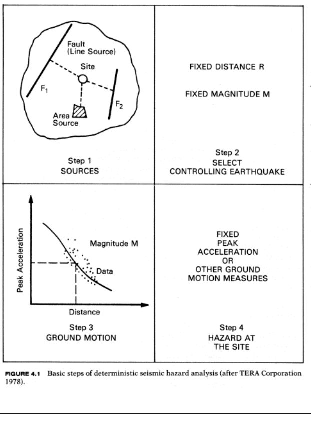

FIGURE 4.1 Basic steps of deterministic seismic hazard analysis (after TERA Corporation 1978).

Step 3 - Most of the attenuation relations are not translation invariant in the phase space (M, R, S). Even when translation invariant they are not a conditional probability density function, they represent the functional dependency of the random spectral acceleration on the random variates, magnitude, distance and measurement error (Klügel, 2006).

M - magnitude; R - source distance; S - local soil conditions

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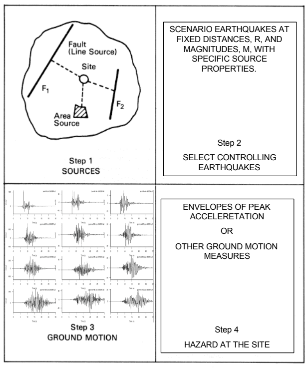
NEODETERMINISTIC



New approach based on synthetic signals computation

No need of attenuation relations

The laws of multivariate theory of probability are applied, as a rule, to calculate the conditional probability of exceedance of a certain hazard level z for a given set of parameters *m* and *r* by developing the joint probability density distribution for the spectral acceleration and relating it to the marginals of *m* and *r* (assuming independence between *m* and *r*).

The PSHA model is simplified by assuming that g(*m*,*r*) is constant and all the randomness of the problem is concentrated in the error term $\varepsilon\sigma$ (univariate approximation). As a result of the simplification for the probabilistic model we get:

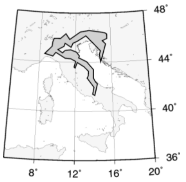
$$\ln (S_a(m,r))=E(g(m,r))+\varepsilon\sigma \qquad (2)$$

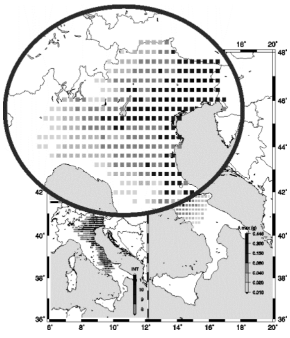
By multiplying the simplified equation (2) with the probability density function of ε, performing integration and converting the resulting expression to the complementary probability distribution function one can separate the randomness from the “quasi-deterministic” calculation of ground motion calculation.

This simplifying replacement is completely incorrect from the point of view of mathematics because a random parameter is replaced by a number, by its expected value and this introduces a systematic error. We can show this by replacing the distribution *g(m,r)* by a series (assuming that the development into a series is possible, which is the case here) around its expected value *E(g(m,r))*.

Neo-deterministic hazard scenarios associated to alerted regions

CN algorithm
Northern Region
Prediction of earthquakes with M≥5.4





Pattern Recognition of Earthquake Prone areas

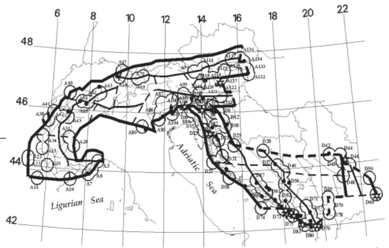
- **Pattern recognition technique is used to identify, independently from earthquake catalogues information, the sites where strong earthquakes are likely to occur.**
- **Assumption: strong events nucleate at the nodes, specific structures that are formed around intersections of fault zones.**

⇩

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

Morphostructural zonation of the Alps and Dinarides

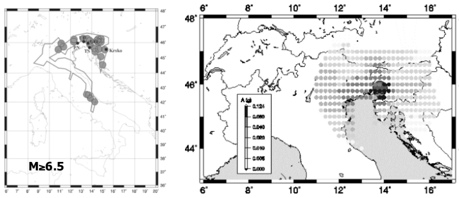
Lineaments (lines), epicenters (dots) and Nodes (circles) prone to earthquakes with M≥6.0 in the Alps and Dinarides



Gorshkov et al. (2003)

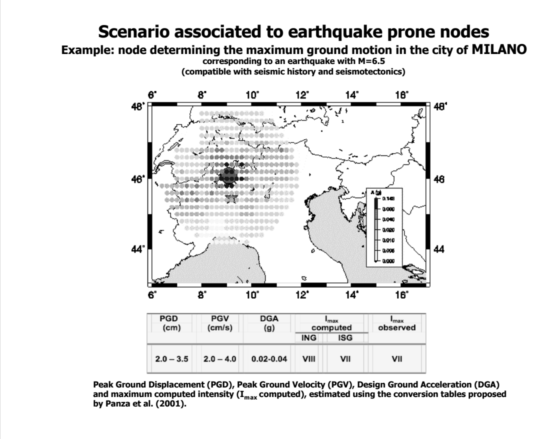
Scenario associated to earthquake prone nodes

Example: node determining the maximum ground motion in the city of TRIESTE
corresponding to an earthquake with M=6.5
(compatible with seismic history and seismotectonics)



PGD (cm)	PGV (cm/s)	DGA (g)	I_{max} computed		I_{max} observed
			ING	ISG	
2.0 – 3.5	4.0 – 8.0	0.08-0.15	IX	VIII	VII

Peak Ground Displacement (PGD), Peak Ground Velocity (PGV), Design Ground Acceleration (DGA) and maximum computed intensity (I_{max} computed), estimated using the conversion tables proposed by Panza et al. (2001). The observed intensity in the city of Trieste is the same in the ING and ISG data sets.



Scenario associated to earthquake prone nodes

Example: node determining the maximum ground motion in the city of MILANO

corresponding to an earthquake with M=6.5

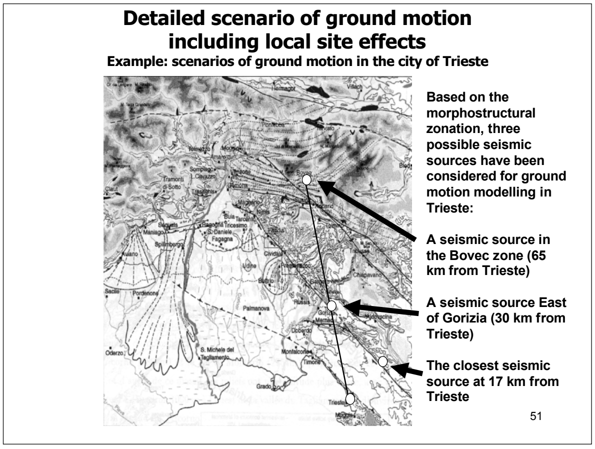
(compatible with seismic history and seismotectonics)

PGD (cm)	PGV (cm/s)	DGA (g)	I_{max} computed		I_{max} observed
			ING	ISG	
2.0 – 3.5	2.0 – 4.0	0.02-0.04	VIII	VII	VII

Peak Ground Displacement (PGD), Peak Ground Velocity (PGV), Design Ground Acceleration (DGA) and maximum computed intensity (I_{max} computed), estimated using the conversion tables proposed by Panza et al. (2001).

Multiscale Neo-deterministic Hazard Scenarios

Detailed scenarios of ground motion including local site effects



Detailed scenario of ground motion including local site effects

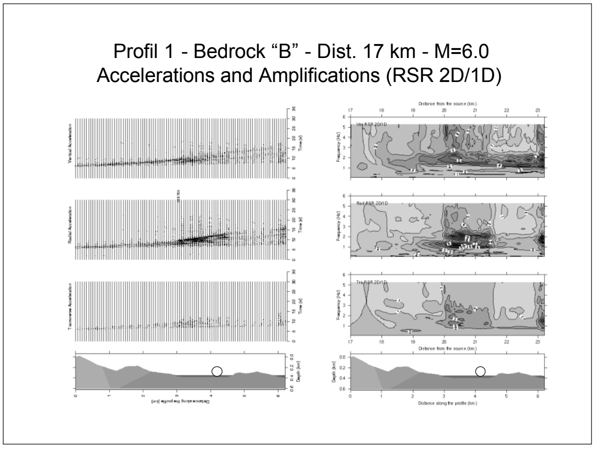
Example: scenarios of ground motion in the city of Trieste

Based on the morphostructural zonation, three possible seismic sources have been considered for ground motion modelling in Trieste:

A seismic source in the Bovec zone (65 km from Trieste)

A seismic source East of Gorizia (30 km from Trieste)

The closest seismic source at 17 km from Trieste



Profil 1 - Bedrock “B” - Dist. 17 km - M=6.0
Accelerations and Amplifications (RSR 2D/1D)

Good news towards implementation:

An agreement has been signed among the Abdus Salam International Centre for Theorethical Physics, ICTP, and the Civil Defence of the Friuli Venezia Giulia Region (NE Italy) for the practical implementation of the integrated neo-deterministic hazard procedure.

Routinely updated time dependent seismic hazard maps will be made available to the Civil Defence (end user).

The GPS network in the Alps

ALPS GPS
QUAKENET
Project leader
A. Aoudia - ICTP

ALPS GPSQUAKENET

Alpine Integrated GPS Network: Master Model for Continental Deformation and Earthquake Hazard

Interreg III B

build-up a high-performance transnational space geodetic network of more than 40 GPS receivers in the Alps

ALPS GPSQUAKENET

Alpine Integrated GPS Network: Master Model for Continental Deformation and Earthquake Hazard

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image the distributed continental deformation over the widest possible range of spatial and temporal scales

ALPS GPSQUAKENET

Interreg III B

**Alpine Integrated GPS Network:
Master Model for Continental Deformation and
Earthquake Hazard**

particular emphasis on the detection of transient deformation signals in test sites

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ALPS GPSQUAKENET

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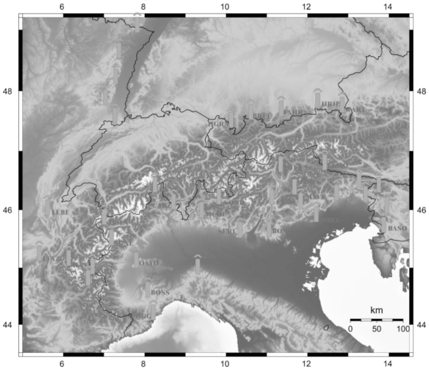
GAIN -
Geodetic Alpine Integrated Network



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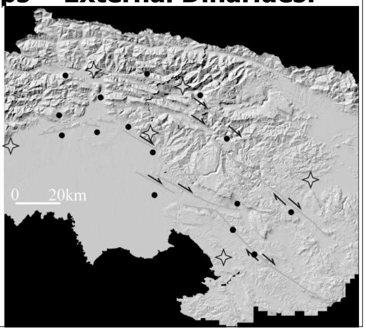
Southeastern Alps – External Dinarides:

**Active faults
Continuous GPS
Campaign GPS**



ALPS GPSQUAKENET

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the 1976 Friuli earthquake initiated a lithosphere-scale rock mechanics experiment:

ALPS GPSQUAKENET

Interreg III B

establish geometry, initial and boundary conditions:

(e.g. surface geology and geomorphology, kinematic parameters of faulting, Earth structure through surface wave tomography and non-linear inversion)

take relevant deformation measurments:

(e.g. seismicity, continuous and campaign GPS, plaeoseismology)

use models to resolve fault/rock constitutive properties:

(e.g. visco-elastic modeling, rate and state friction laws)

⇩

A physical model for strain accumulation that carries a predictive power for future stress patterns

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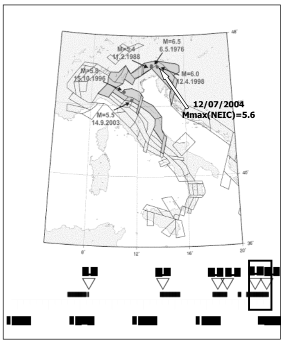
The Slovenia earthquake, July 12 2004



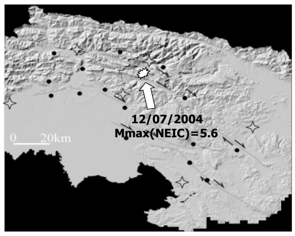
Alarmed area for M≥5.4

by CN algorithm *(Peresan et al., 2004)*

(As on 1 July 2004)

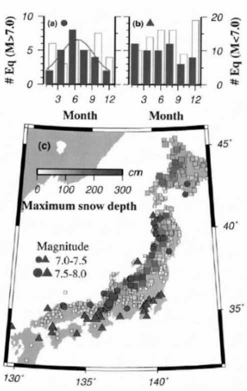
⇦

Southeastern Alps – External Dinarides
InSAR - CGPS - Campaign GPS monitoring

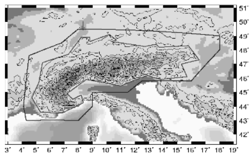


Glaciation and earthquakes

Snow load effect on seimicity



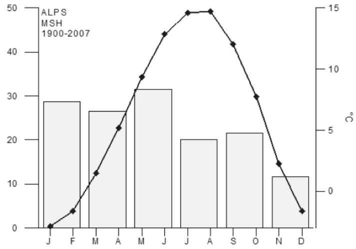
Number of earthquakes occurred in 2-month intervals, within (a) and outside (b) the snowy region. Red and white histograms show M≥7.0 (left) and 7.0>M≥6.0 (right) events, respectively. In (c) blue squares show maximum snow depths in a winter at AMeDAS stations (only points with snows deeper than 20.0 cm are shown). Epicenters of M≥7.0 earthquakes are shown in (c) as circles (snowy region) and triangles (outside). Red curve in (a) is the best-fit probability density function of the earthquake occurrence based on the two-component (stationary and annual) model (Heki, EPSL, 2003).

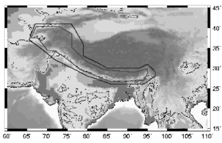


ALPS
SEASONAL ANALYSIS

Magnitudo threshold: M=5.0
Time interval: 1900-2007
Area: within the blue polygon

Yellow bars: bimonthly Benioff strain release
Blue line: Average temperature (bimonthly)

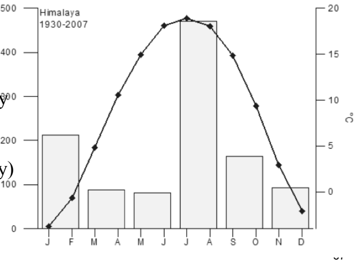




HIMALAYA
SEASONAL ANALYSIS

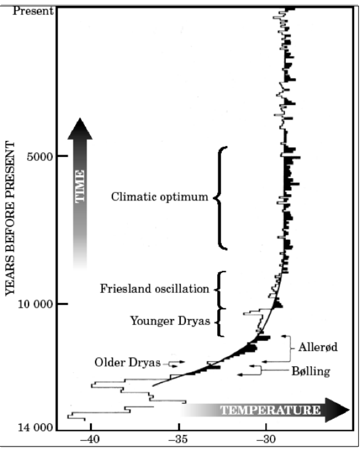
Magnitudo threshold: M=5.5
Time interval: 1930-2007
Area: within the blue polygon

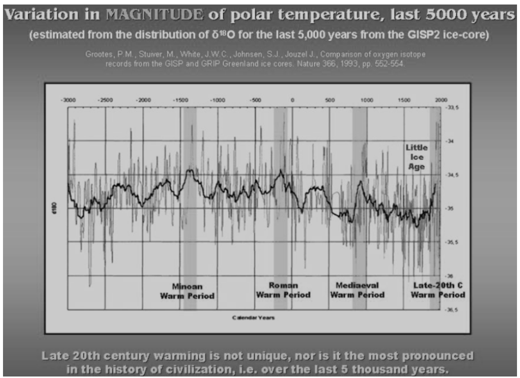
Yellow bars: bimonthly Benioff strain release
Blue line: Average temperature (bimonthly)



Effect of past temperatures and climate changes on seismicity

Cores from the ice at Camp Century, processed on the spot, in 1964 revealed ancient climate changes in unprecedented detail. The ratio of O18/O16 isotopes in the annual snow layers serves as a thermometer. Part per thousands variations to the right indicate warmer temperatures; those to the left, cooler ones. The large rise in temperature started about 14,000 years ago at the end of the last ice age. The plot also shows 1-2°C temperature leaps even within the one-century resolution of the data. (S. Weart, Physics today, August 2003)

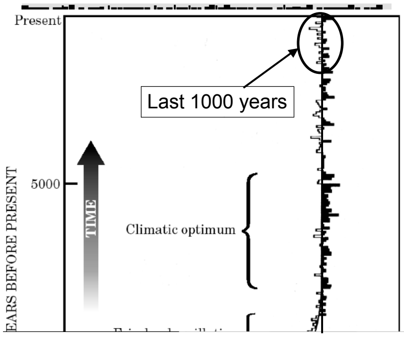


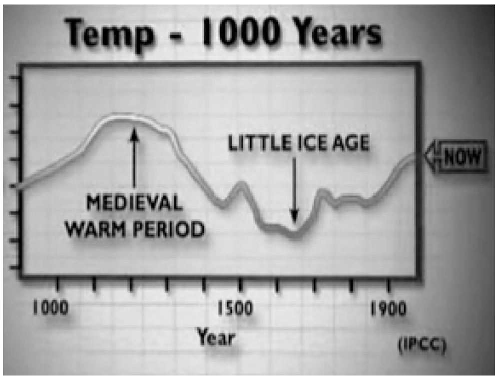

Variation in MAGNITUDE of polar temperature, last 5000 years

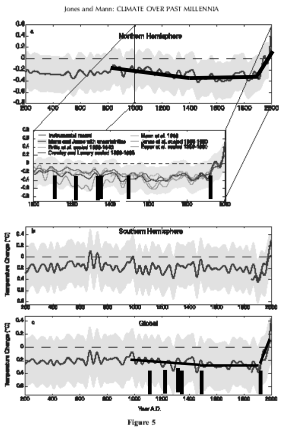
(estimated from the distribution of δ18O for the last 5,000 years from the GISP2 ice-core)

Grootes, P.M., Stuiver, M., White, J.W.C., Johnsen, S.J., Jouzel J., Comparison of oxygen isotope records from the GISP and GRIP Greenland ice cores. Nature 366, 1993, pp. 552-554.

Late 20th century warming is not unique, nor is it the most pronounced in the history of civilization, i.e. over the last 5 thousand years.







Occurrence year of major events in the Alps area

1117 Po valley

1222 Verona

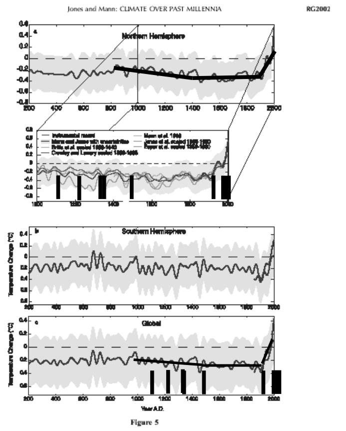
1348 Carnia

1356 Basel

1511 Istria

1976 Friuli

Reviews of Geophysics, 42, RG2002 / 2004, fig.5



Occurrence year of major events in the Alps area

1117 Po valley

1222 Verona

1348 Carnia

1356 Basel

1511 Istria

1976 Friuli

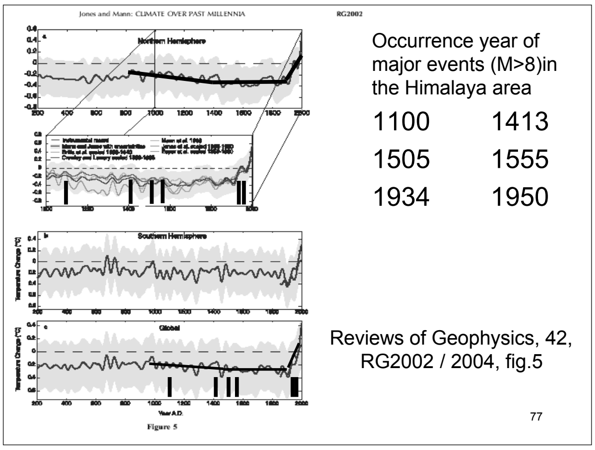
1998
2004 } Slo

Major events in Himalaya

~1100 (>8.5)	1255 (7.5-8.0)?
~1413 (>8.5)	1505 (>8.5)
1555 (8.0-8.5)	1681 (7.5-8.0)?
1724 (7.5-8.0)	1803 (7.5-8.0)
1833 (7.5-8.0)	1897 (7.5-8.0)
1905 (7.5-8.0)	1934 (8.0-8.5)
1947 (7.5-8.0)	1950 (>8.5)
2005 (7.5-8.0)	

(Upreti, 2007, personal communication)

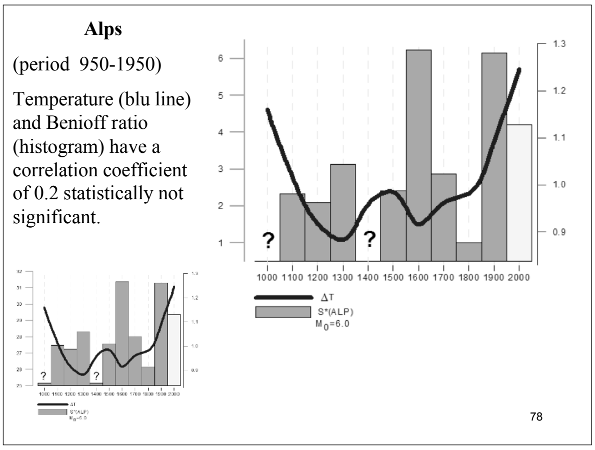
This false-color satellite image shows the retreat of the Gangotri Glacier, one of the largest glaciers in the Himalaya. Gangotri has been receding since 1780. Research work has shown that the retreat of this glacier accelerated after 1971.



Occurrence year of major events (M>8)in the Himalaya area

1100	1413
1505	1555
1934	1950

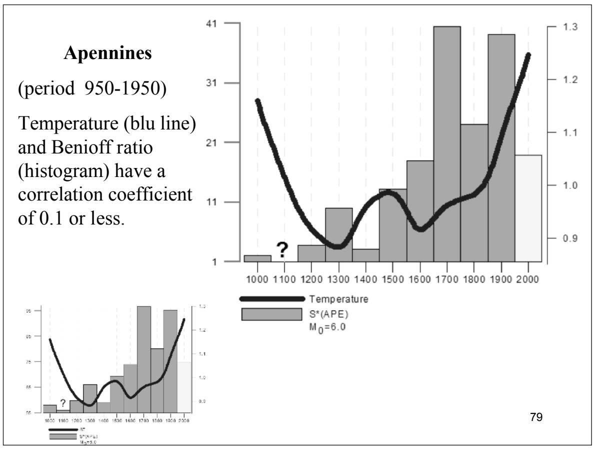
Reviews of Geophysics, 42, RG2002 / 2004, fig.5



Alps

(period 950-1950)

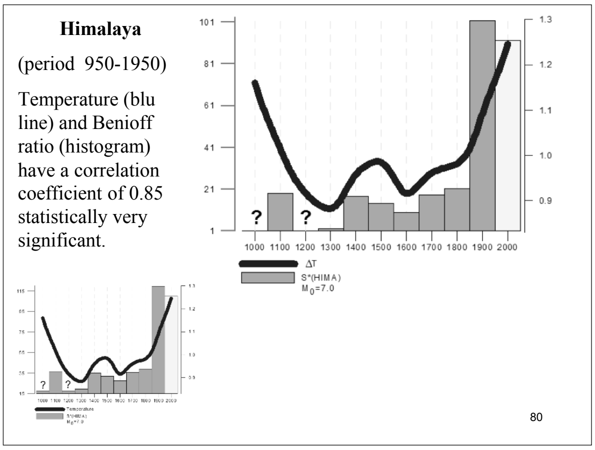
Temperature (blu line) and Benioff ratio (histogram) have a correlation coefficient of 0.2 statistically not significant.



Apennines

(period 950-1950)

Temperature (blu line) and Benioff ratio (histogram) have a correlation coefficient of 0.1 or less.



Himalaya

(period 950-1950)

Temperature (blu line) and Benioff ratio (histogram) have a correlation coefficient of 0.85 statistically very significant.

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