# Computational Geodynamics and Earthquake Modeling as Research Tools for Seismic Hazard Analysis

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# 250 years ago

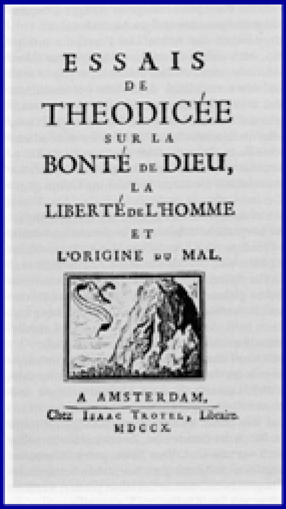
It was a time characterized by the end of religious wars and an enormous desire for peace. Economy and trade, emerging natural science and philosophy contributed to a stable world.

*I. Newton's* (1642-1727) laws allowed the prediction of the course of the planets. *G. Leibniz* (1646-1716) and *I. Newton* were trying to expand the notion of optimization from mathematical functions and physics into the metaphysics.

In the spirit of optimism prevailing

in the 18th century

***This world must be the best of all possible worlds***


ESSAIS
DE
THEODICÉE
SUR LA
BONTÉ DE DIEU,
LA
LIBERTÉ DE L'HOMME
ET
L'ORIGINE DU MAL.

A AMSTERDAM,
Chez ISAAC TROYEL, Libraire.
MDCCX.

[G.W. Leibniz, Essais de Theodicée sur la Bonté de Dieu, 1710]

# 250 years ago

The Lisbon Earthquake occurred on November 1st, **1755** at 9:40 local time

30 minutes later the Tsunami arrived in town!

# Extreme Seismic Events

Sumatra-Aceh, December 2004

Pakistan, October 2005

# Extreme Seismic Events

*"An extreme natural event is an occurrence that with respect to some class of related occurrences, is either notable, rare, unique, profound, or otherwise significant in terms of its impacts, effects, or outcomes"*

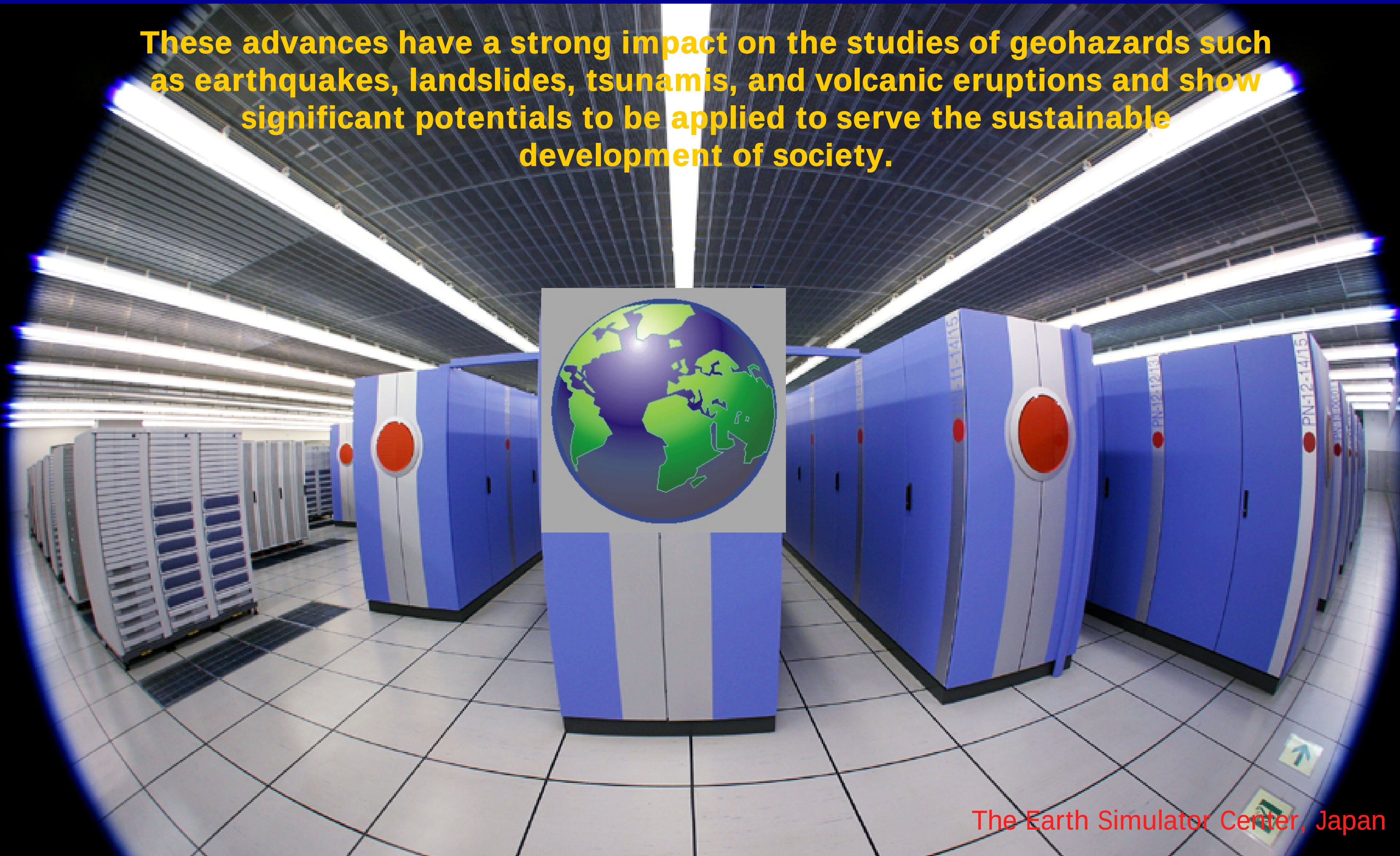
Conclusions of the Extreme Events Workshop, Boulder, Colorado, June 7-9, 2000

# Extreme Seismic Events

- Extreme seismic events are a key manifestation of dynamics of the lithosphere, a complex hierarchical nonlinear system evolving from stability to a catastrophe over space and time
- Understanding of dynamics of extreme events is most important scientific challenge
- From physical understanding of the phenomenon ***to accurate modeling and prediction***
- From sophisticated predictions to prompt information delivery to disaster management authorities to undertake preventive measures

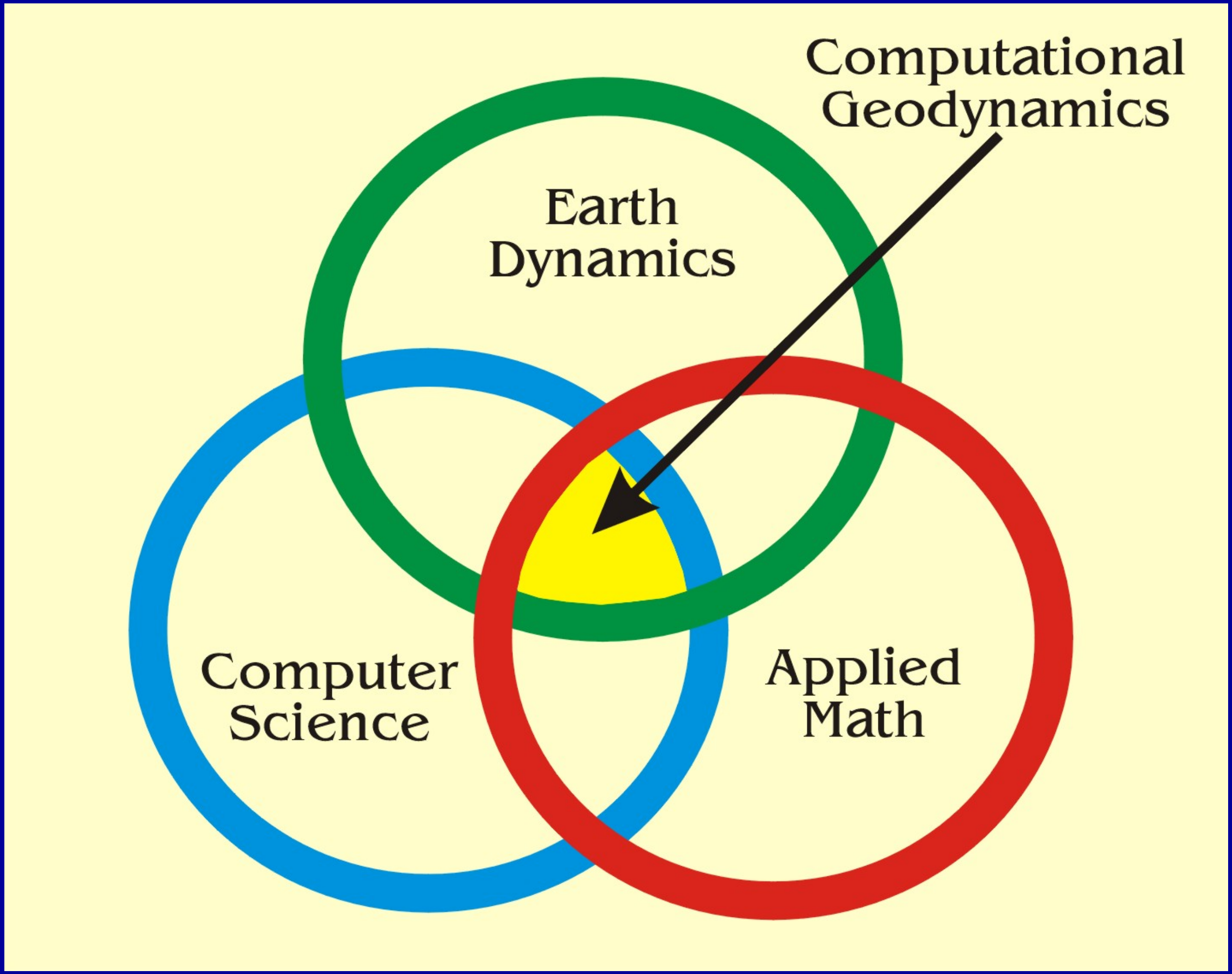
**Great advances in understanding of the complex Earth system and in computational tools, permitting accurate numerical modelling and forecasting, are transforming the geoscience.**

**These advances have a strong impact on the studies of geohazards such as earthquakes, landslides, tsunamis, and volcanic eruptions and show significant potentials to be applied to serve the sustainable development of society.**



The Earth Simulator Center, Japan

# Quantitative Scientific Approach to Understanding the Earth's Dynamics




Computational Geodynamics is a blending of the three areas to obtain a better understanding of some phenomena through a judicious match between the problem, a computer architecture, and algorithms.

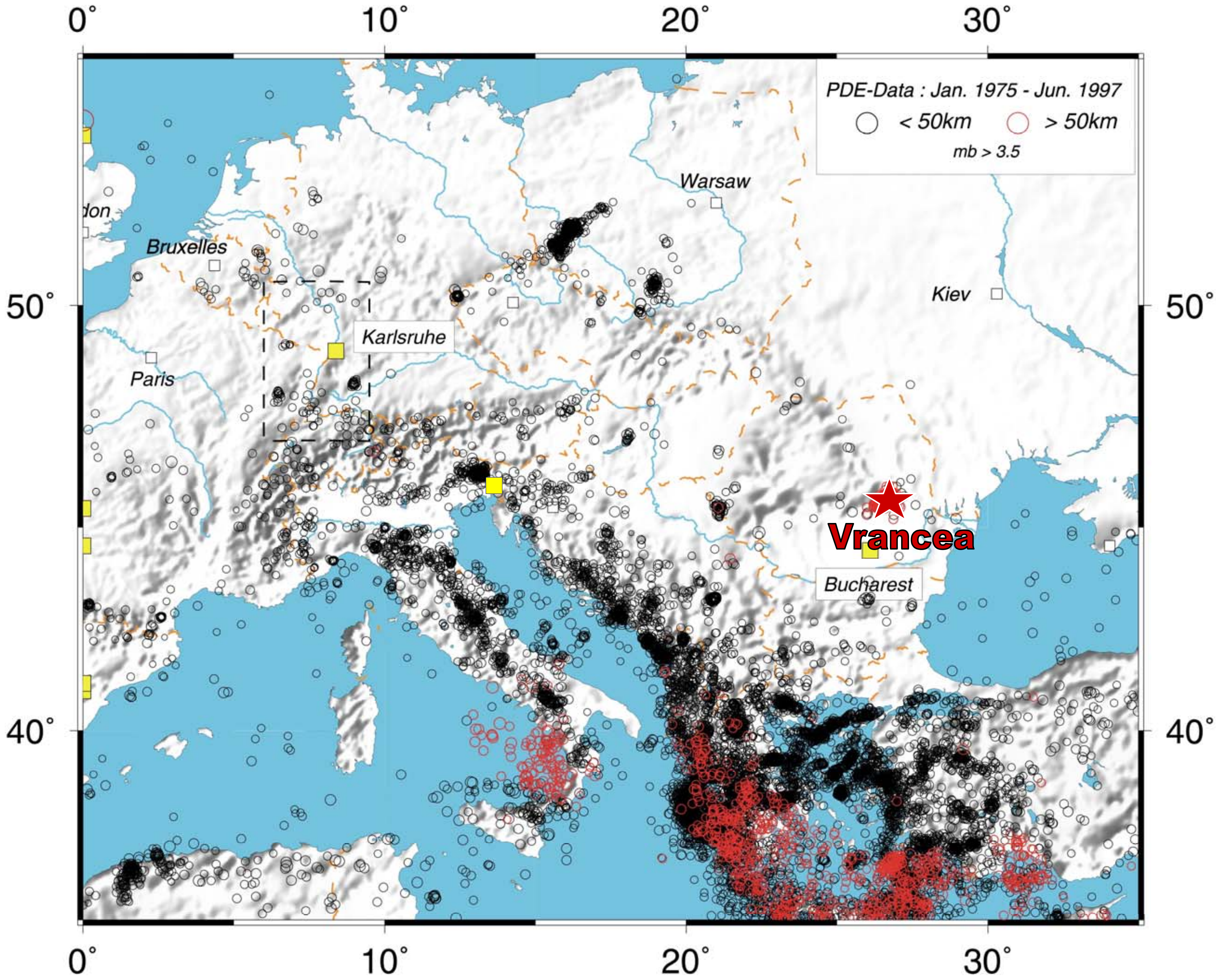
How Quantitative Geoscience Can Contribute to Understanding Geodynamics and Associated Geohazards ?

# Outline

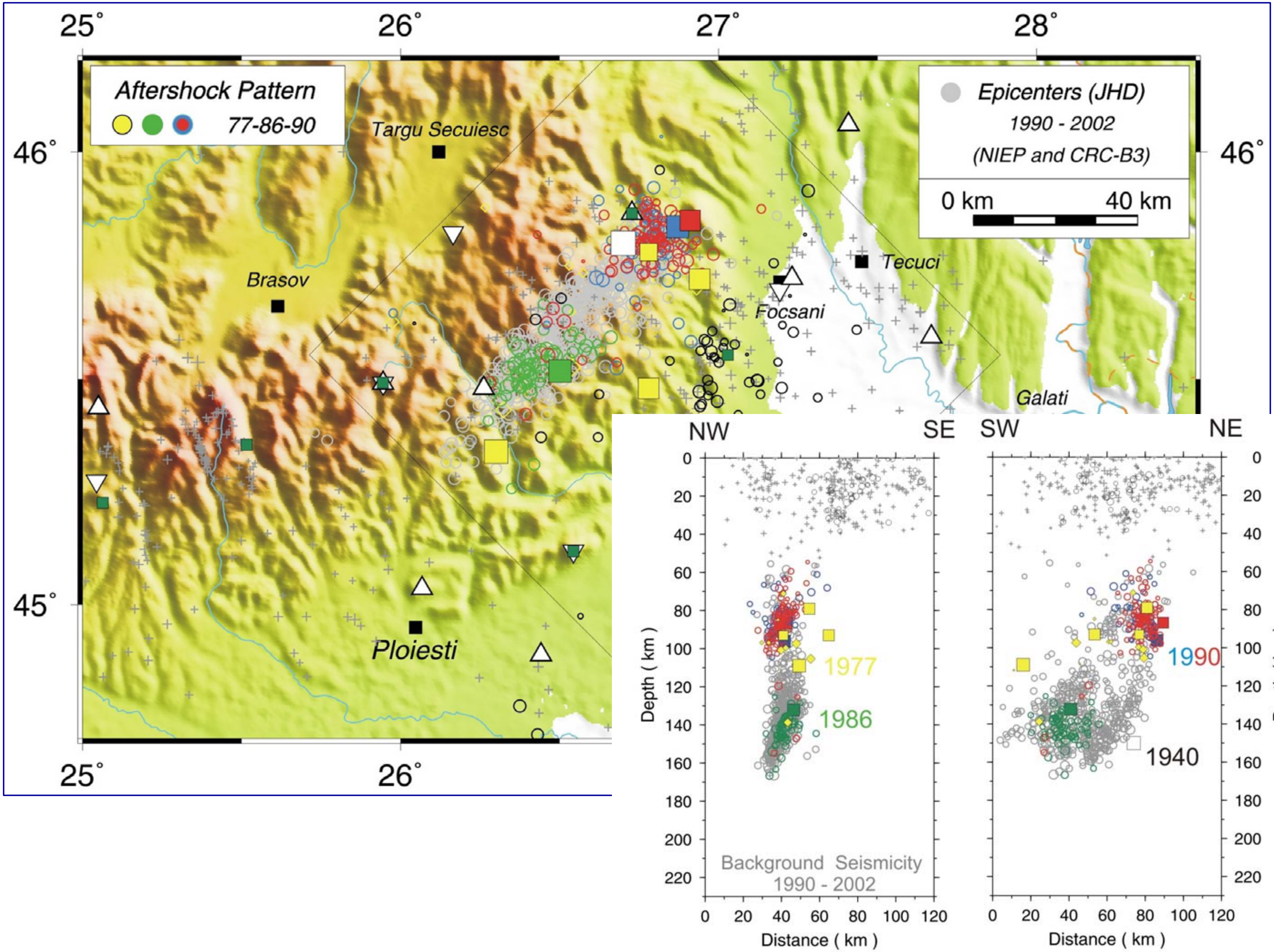
- Modelling of Tectonic Stress
- Modelling of Seismic Hazard
- Modelling of Seismicity

# Quantitative Modelling of Contemporary Tectonic Stress (SE-Carpathians)

Ismail-Zadeh, Mueller & Schubert (Physics of the Earth and Planetary Interior, 2005)

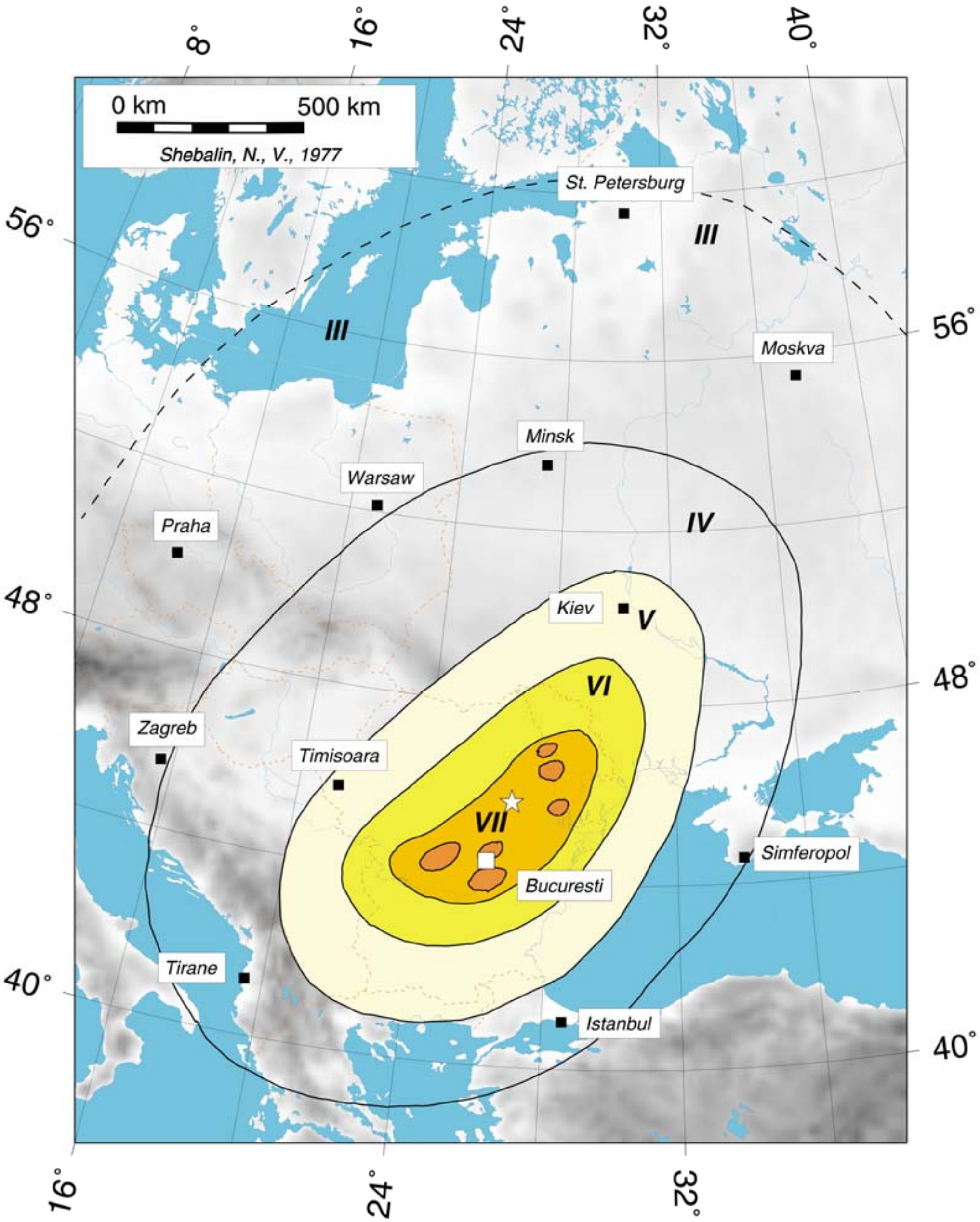


PDE-Data : Jan. 1975 - Jun. 1997
< 50km
> 50km
mb > 3.5
Warsaw
Kiev
Bruxelles
don
Karlsruhe
Paris
Vrancea
Bucharest
0°
10°
20°
30°
50°
40°



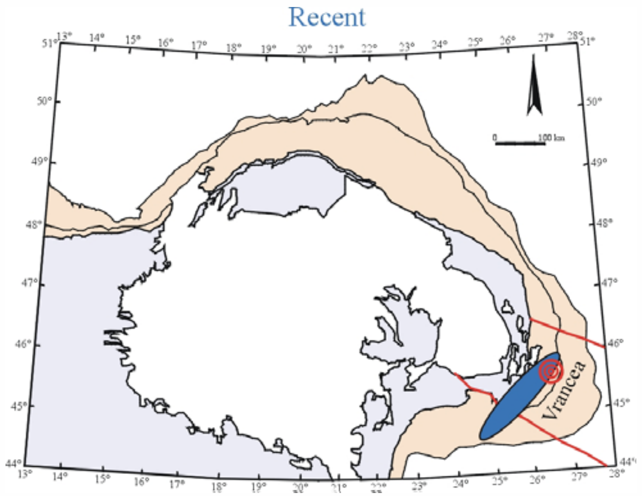
Aftershock Pattern
77-86-90
Epicenters (JHD)
1990 - 2002
(NIEP and CRC-B3)
0 km
40 km
Targu Secuiesc
Brasov
Tecuci
Focsani
Galati
Ploiesti
25°
26°
27°
28°
46°
45°
NW
SE
SW
NE
Depth ( km )
Distance ( km )
1977
1986
1990
1940
Background Seismicity
1990 - 2002

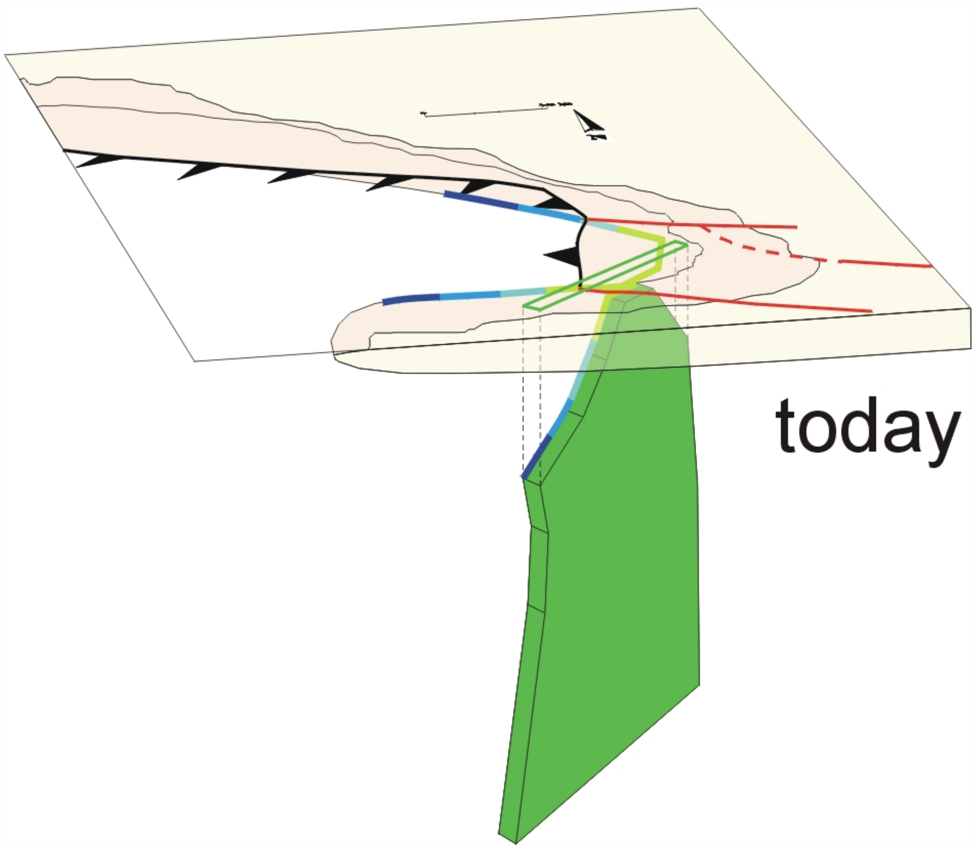
# March 4, 1977




Bucharest

# Geodynamic Model

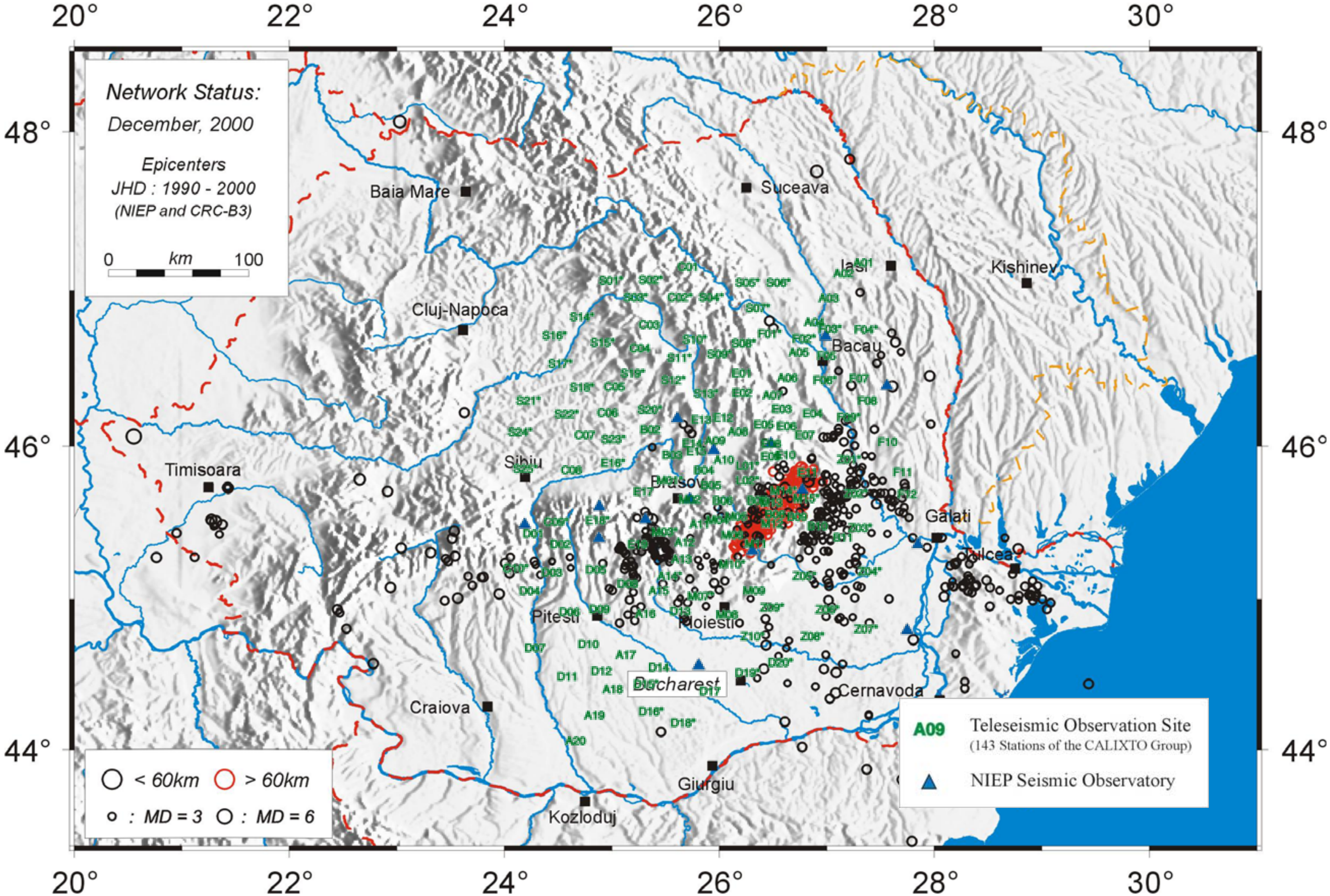


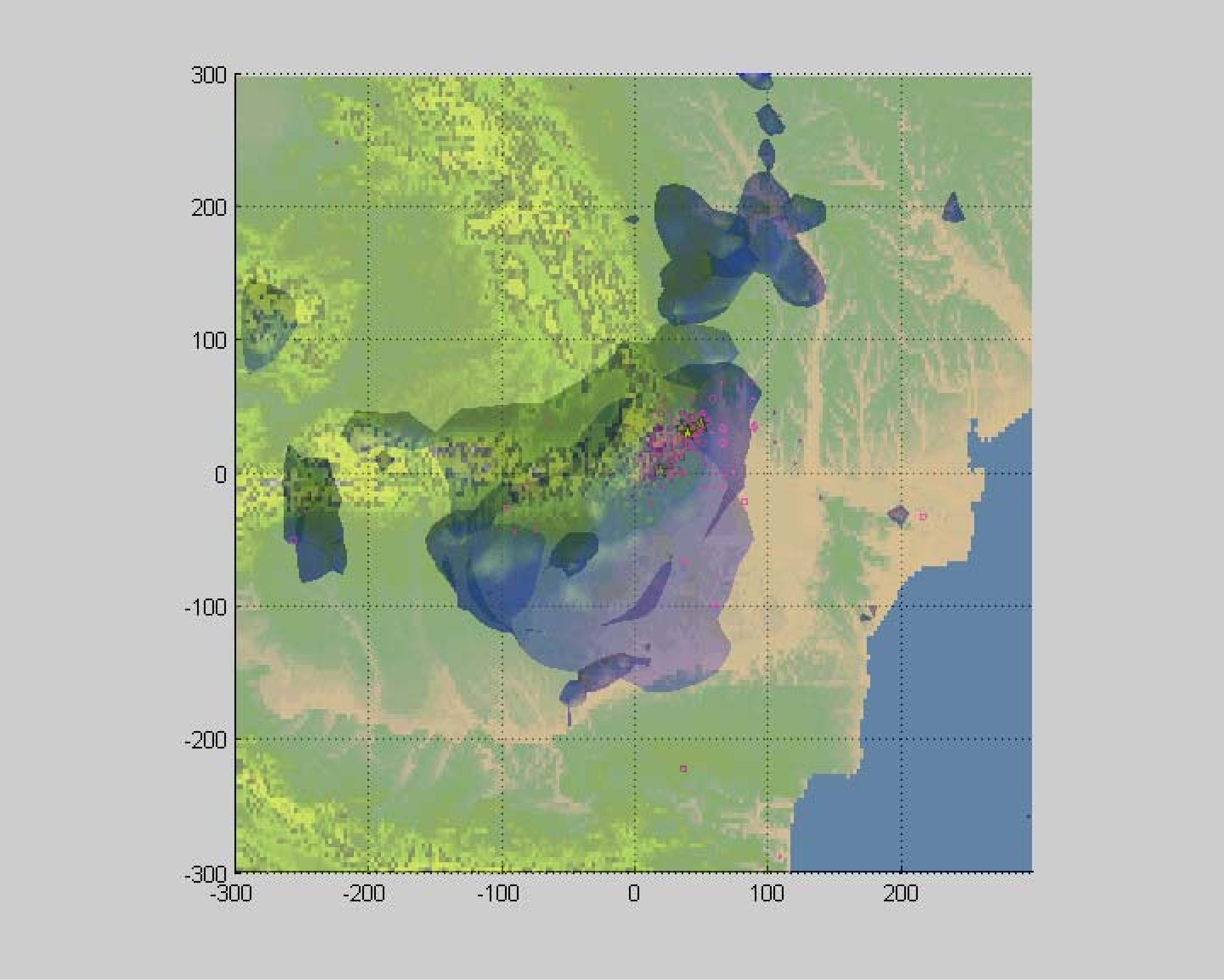

Sperner et al., 2001

# CALIXTO

Carpathian Arc Lithosphere Cross(X)-Tomography Project

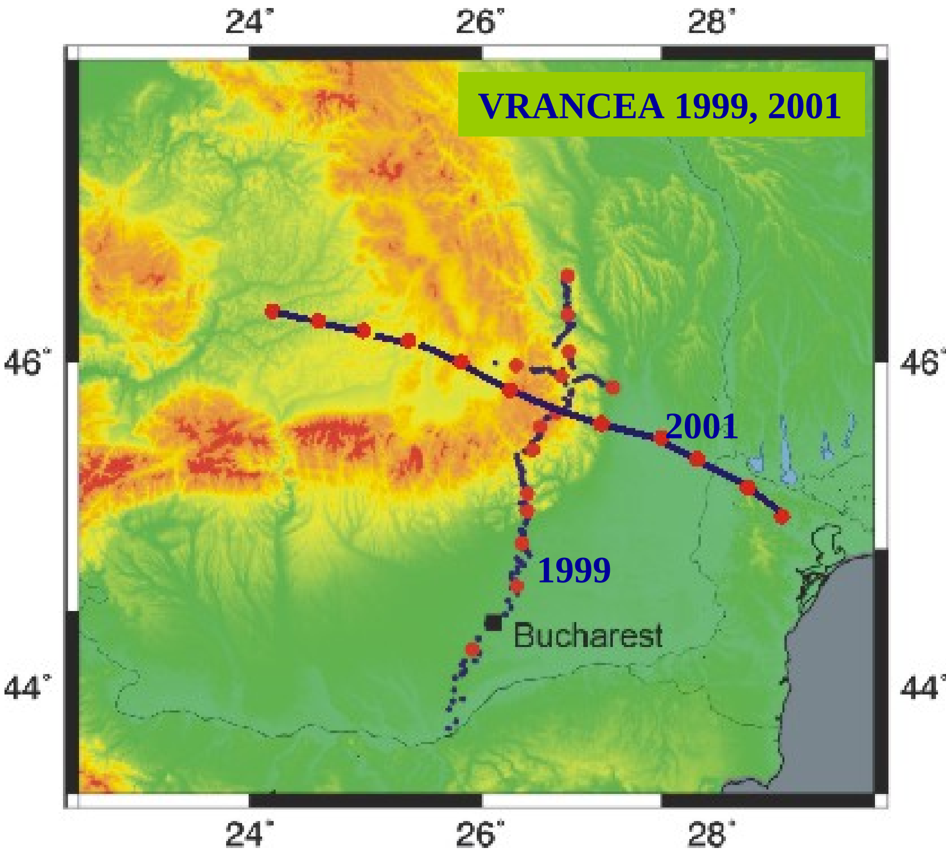


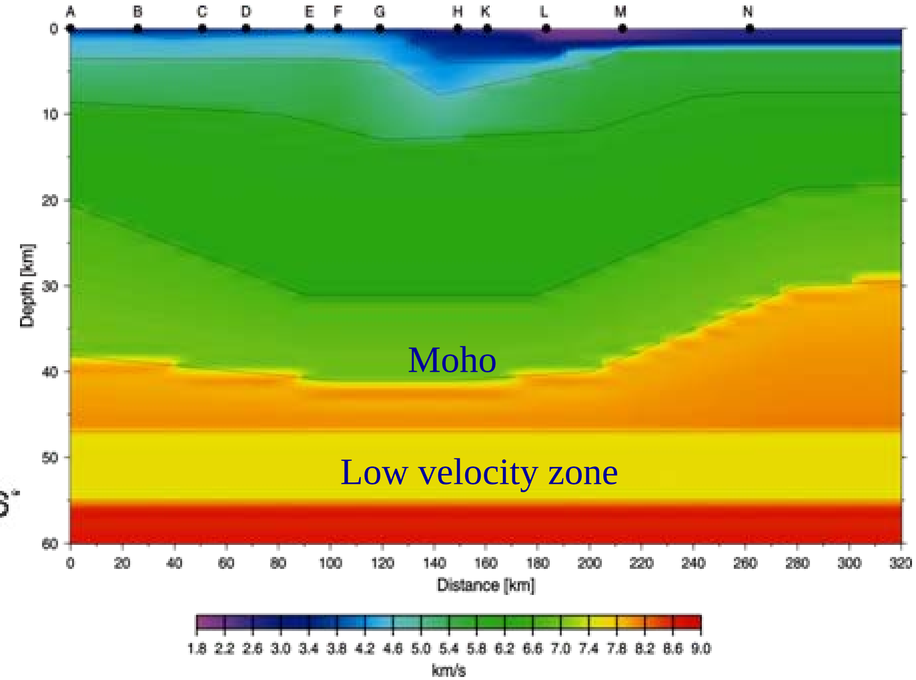
# Seismic-tomographic image of the 2% high P-wave velocity anomaly

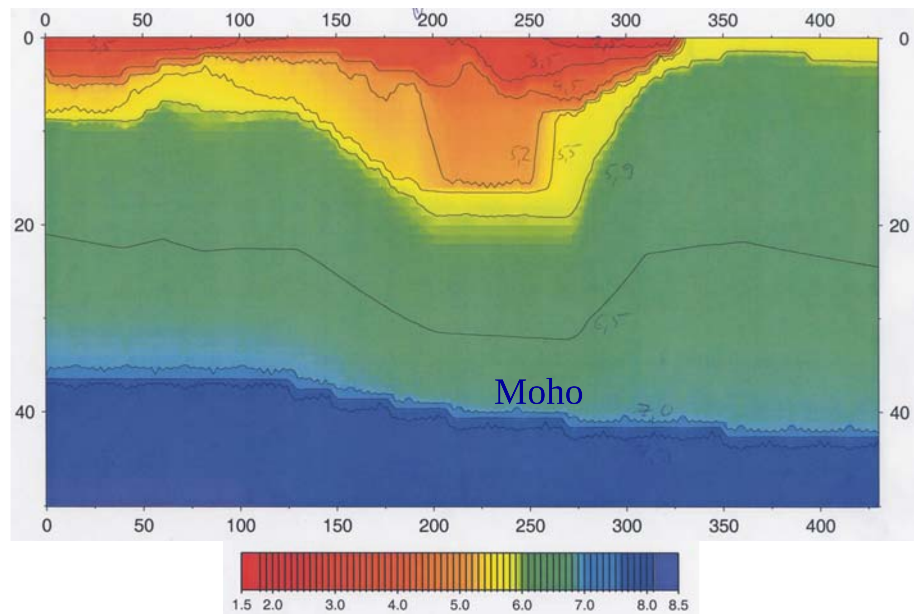



Martin et al., 2005

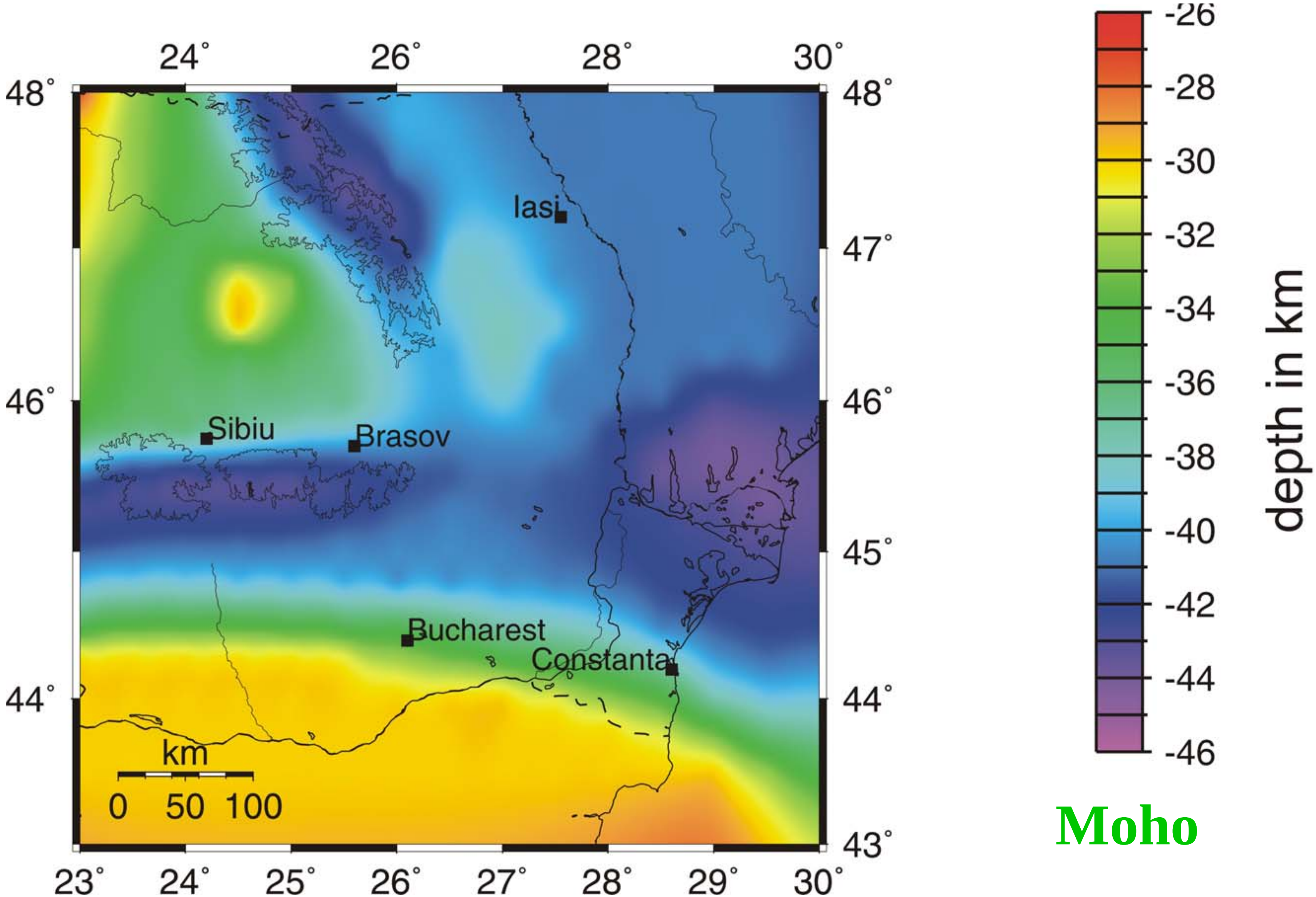
# Refraction SeismicsVRANCEA 1999, 2001



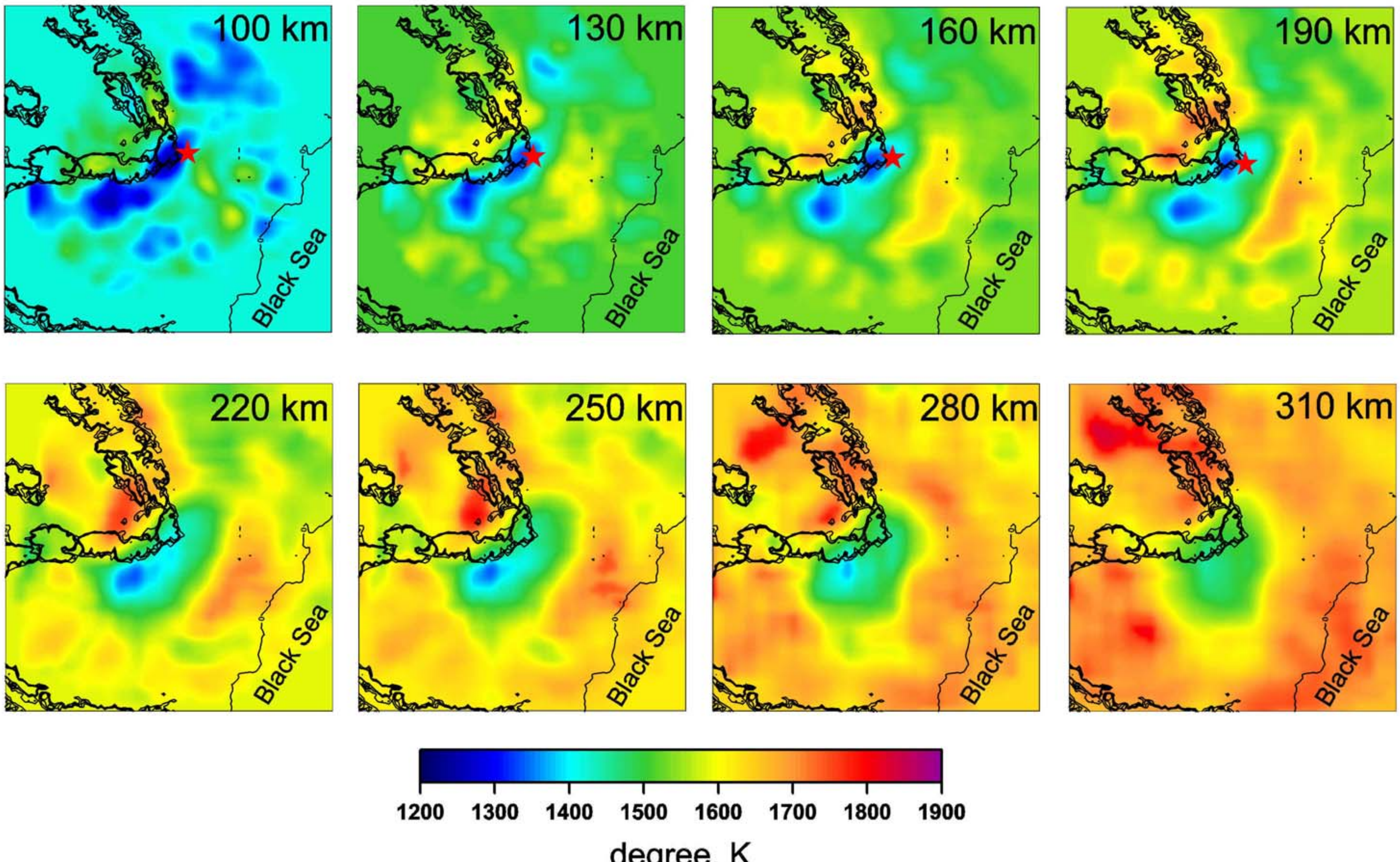

Hauser et al., 2001; 2003


Iasi
Sibiu
Brasov
Bucharest
Constanta
km
0 50 100
depth in km
-26
-28
-30
-32
-34
-36
-38
-40
-42
-44
-46

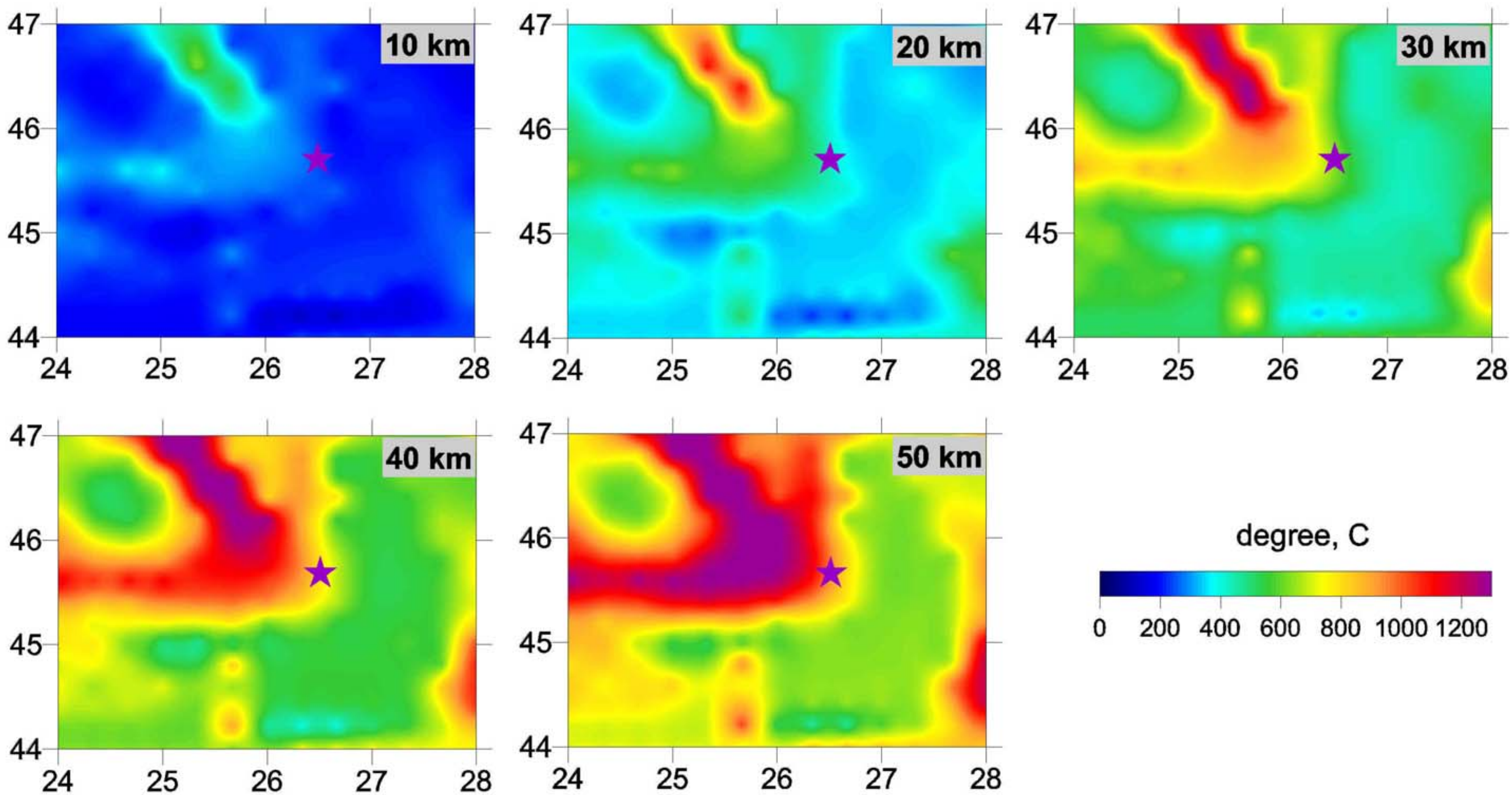
**Moho**

***How the earthquakes are associated with tectonic stress localizations in the region?***

# Temperature derived from P-wave velocity anomalies



# Temperature in the crust and uppermost mantle




Demetrescu and Andreescu (1994)

# Mathematical Statement

Momentum equations $$-\nabla P + \mathrm{div}\{\mu(T)e_{ij}\} + \rho(T)g = 0$$

Strain rate $$e_{ij} = 0.5\left(\partial u_i / \partial x_j + \partial u_j / \partial x_i\right)$$

Incompressibility condition $$\mathrm{div}\,\mathbf{u} = 0,\ \ \mathbf{u} = (u_1, u_2, u_3)$$

Equation of state $$\rho(T) = \rho_*(x)[1 - \alpha(T(x) - T_*)]$$

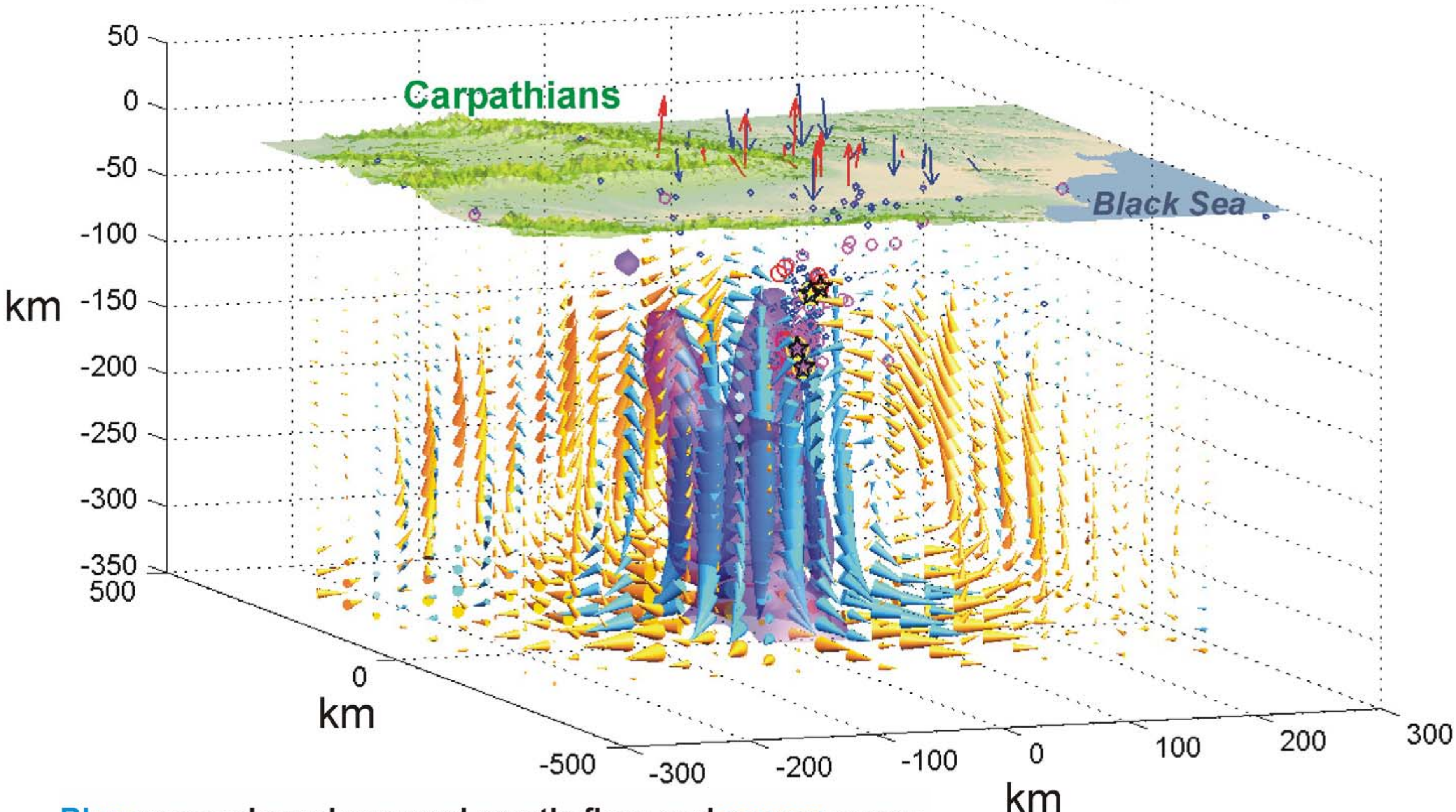
Viscosity $$\mu(T) = \mu_*(x)\exp\left(\frac{E}{RT} - \frac{E}{RT_*}\right)$$

Deviatoric stress $$\sigma_{ij} = \mu(T)\,e_{ij}$$

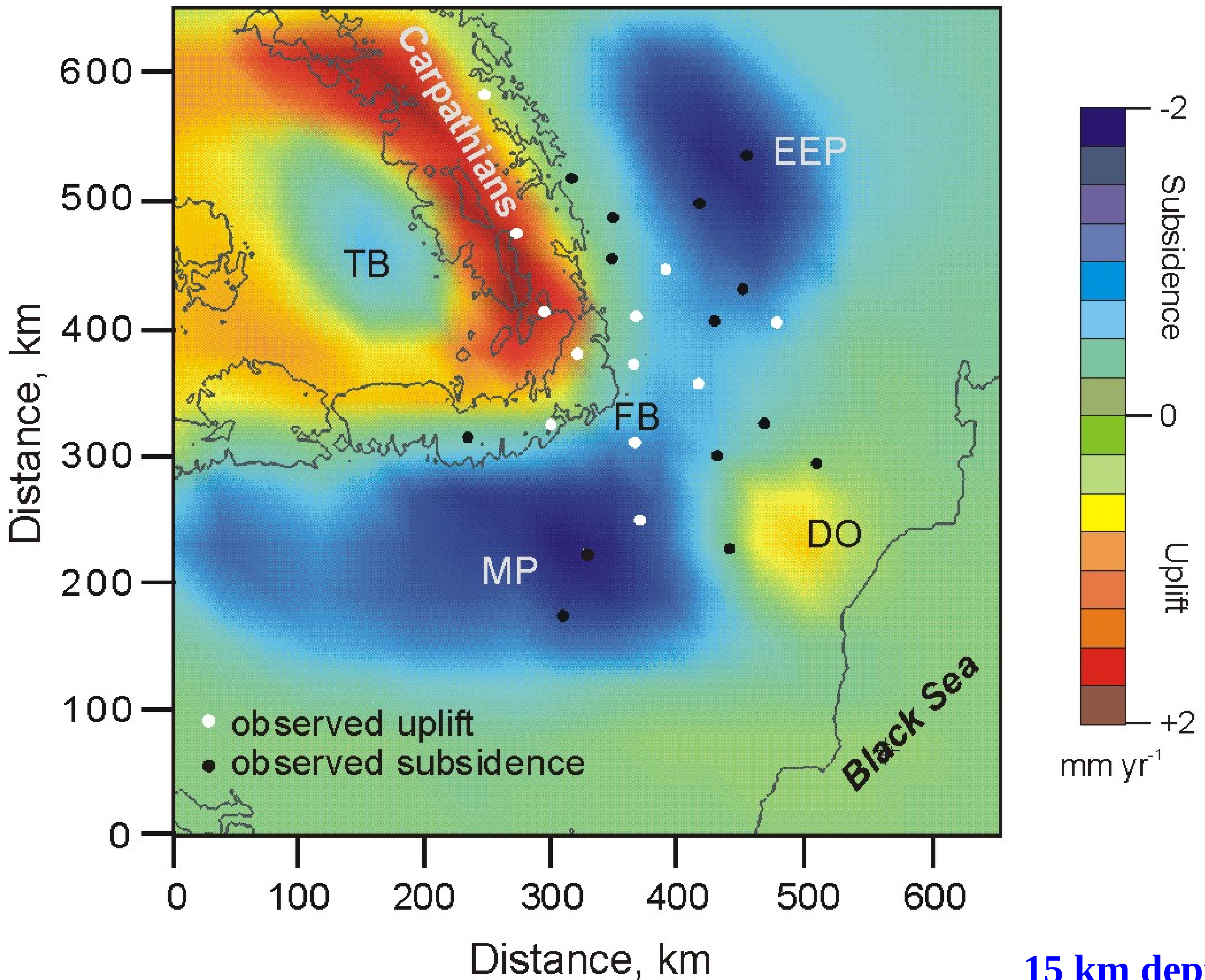
Free slip conditions at all model boundaries

Ismail-Zadeh et al. (Comp. Math & Math Phys., 2001)

# Mantle flow induced by the slab descending beneath the SE-Carpathians

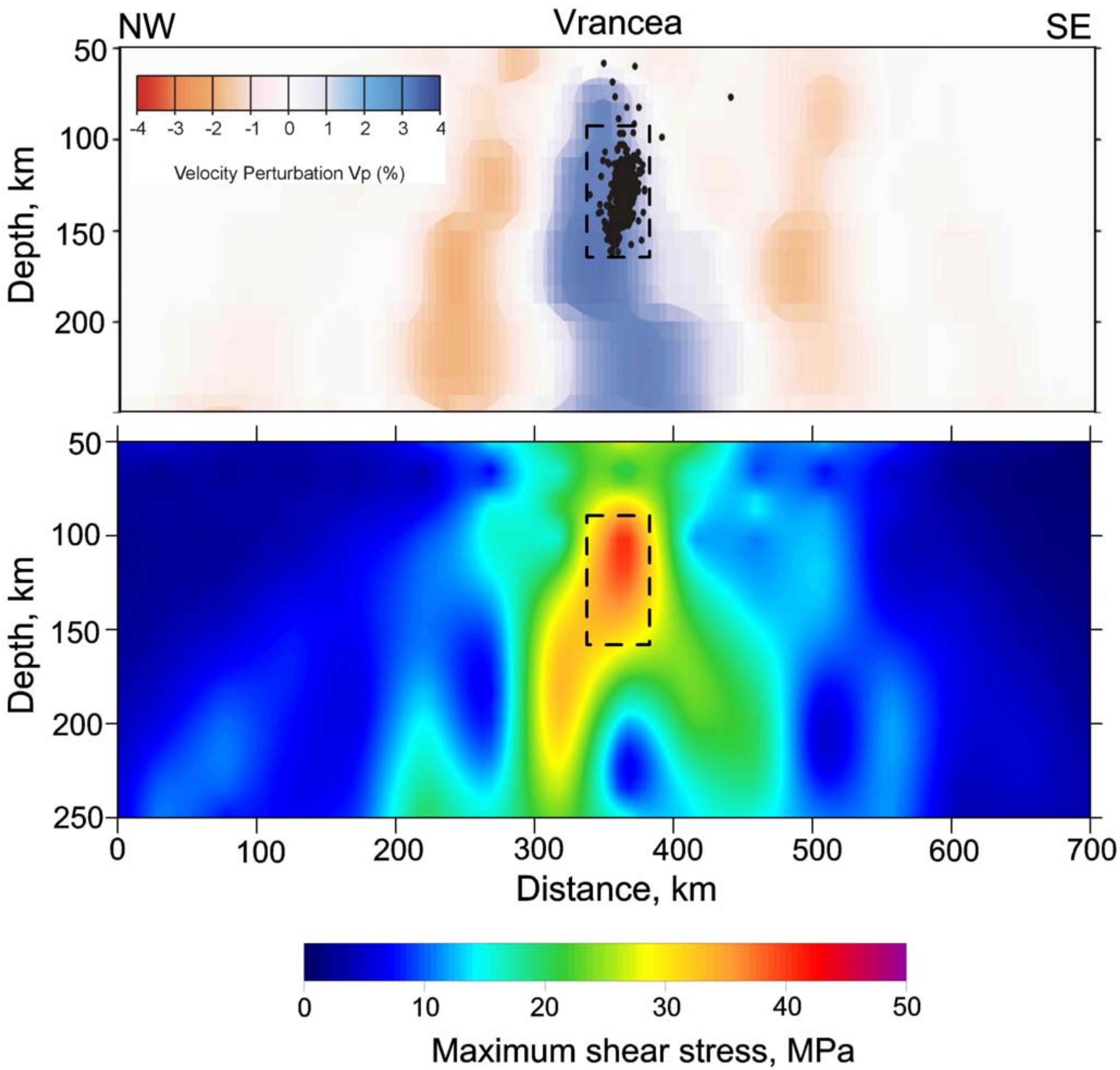



Blue cones show downward mantle flow, and orange cones illustrate upward mantle flow. Red and blue arrows on the top are GPS data on vertical movements. Circles and stars are earthquake hypocentres.



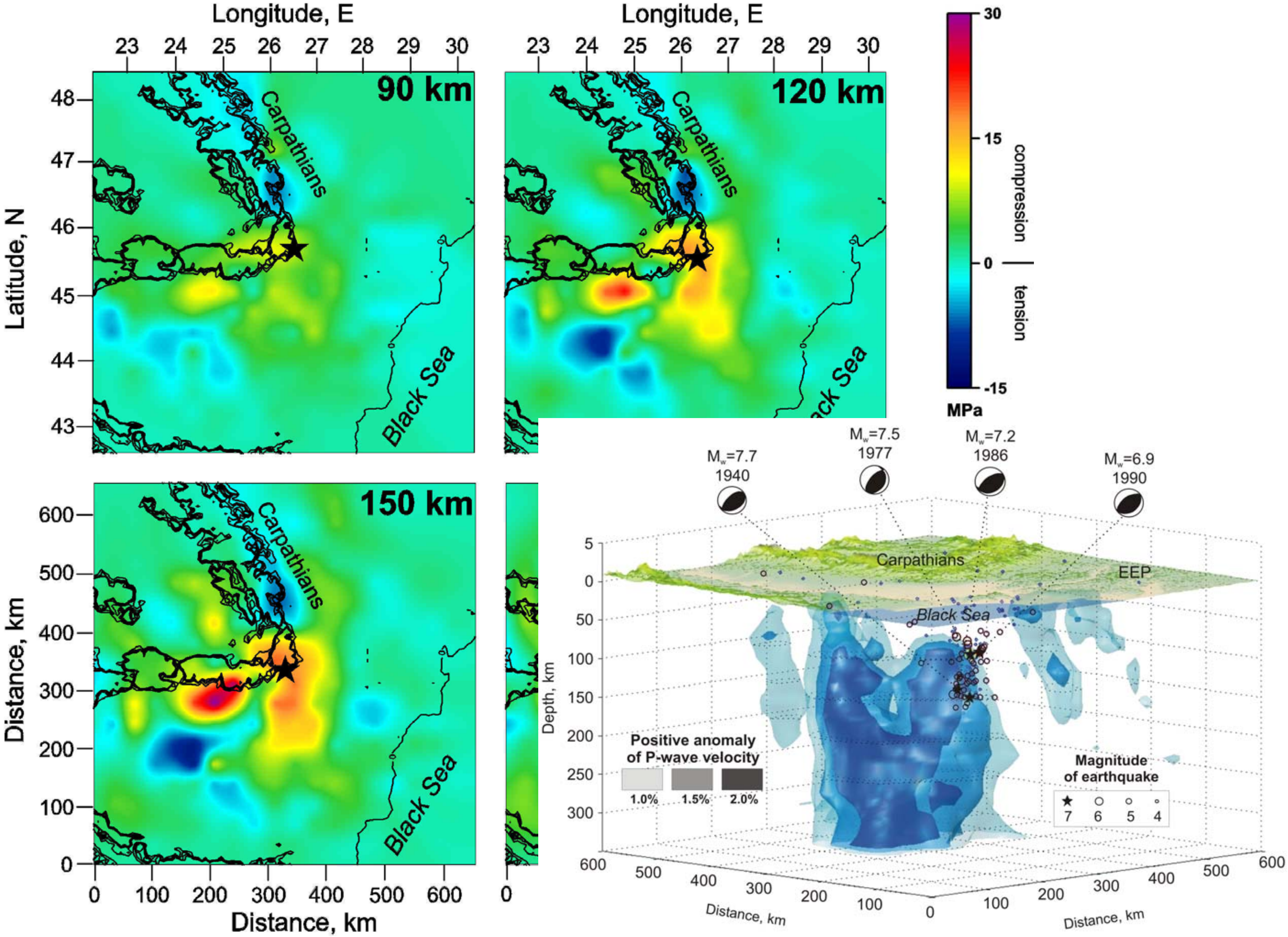
Carpathians
EEP
TB
FB
MP
DO
Black Sea
observed uplift
observed subsidence
Distance, km
Distance, km
0
100
200
300
400
500
600
Subsidence
Uplift
-2
0
+2
mm yr-1


15 km depth



NW
Vrancea
SE
Velocity Perturbation Vp (%)
-4 -3 -2 -1 0 1 2 3 4
Depth, km
50
100
150
200
250
0
100
200
300
400
500
600
700
Distance, km
0
10
20
30
40
50
Maximum shear stress, MPa

# Maximum tectonic horizontal stress



# Data Assimilation in Mantle-Lithosphere Dynamics

Ismail-Zadeh et al. (Journal of Geophysical Research, 2006)

# Data Assimilation -
# Basic Principles and Methods

*Basic principles of data assimilation*:

- To consider the initial condition as a control variable;
- To optimize the initial condition in order to minimize the discrepancy between the observations and the solution of the model.

*Data assimilation methods:*

- Variational assimilation
- Quasi-reversibility assimilation
- etc

# Mathematical Statement of the Problem

**Model domain** $\Omega = (0, x_1 = l_1) \times (0, x_2 = l_2) \times (0, x_3 = h), \quad t \in (0, \vartheta)$

**The boundary-value problem for flow velocity**

$$-\nabla P + \nabla \cdot (\mu(T)[\nabla \mathbf{u} + (\nabla \mathbf{u})^T]) + RaT\mathbf{e} = 0, \qquad \mathbf{x} \in \Omega$$

$$\nabla \cdot \mathbf{u} = 0, \qquad \mathbf{x} \in \Omega$$

$$\mathbf{u} = \mathbf{U}(\mathbf{x}), \quad \mathbf{x} \in \Gamma_1, \quad \Gamma_1 \subset \partial\Omega \qquad \Gamma_1 \cap \Gamma_2 = \varnothing$$

$$\mathbf{u} \cdot \mathbf{n} = 0, \quad \partial \mathbf{u}_\tau / \partial \mathbf{n} = 0, \qquad \mathbf{x} \in \Gamma_2, \quad \Gamma_2 \subset \partial\Omega \qquad \Gamma_1 \cup \Gamma_2 = \partial\Omega$$

**The initial-boundary-value problem for temperature**

$$\partial T / \partial t + \mathbf{u} \cdot \nabla T = \nabla^2 T + f, \qquad t \in (0, \vartheta), \ \mathbf{x} \in \Omega$$

$$\sigma_1 T + \sigma_2 \partial T / \partial \mathbf{n} = T_*(t, \mathbf{x}), \qquad t \in (0, \vartheta), \ \mathbf{x} \in \partial\Omega$$

$$T(0, \mathbf{x}) = T_0(\mathbf{x}), \qquad \mathbf{x} \in \Omega$$

# Variational method

The variational method finds the best fit between the forecast model state and the observations by minimizing an objective functional.

$$J(\varphi) = \left\| T(\vartheta, \cdot; \varphi) - \chi(\cdot) \right\|^2 = \int_\Omega \left| T(\vartheta, x; \varphi) - \chi(x) \right|^2 dx$$

$T(\vartheta, x; \varphi)$ solution of the forward heat equation with appropriate boundary conditions at final time, which corresponds to unknown as yet the initial temperature distribution $\varphi = \varphi(x)$;

$\chi(x) = T(\vartheta, x; T_0)$ known temperature distribution at the final time for the initial temperature $T_0 = T_0(x)$.

**The objective functional has its unique minimum at $\varphi = T_0$**

We seek **a minimum of the objective functional** with respect to initial temperature

$$\nabla J(\varphi) = 0$$

# Variational method

It can be shown that $\nabla J(\varphi) = \Psi(\vartheta, x),$ where

$$\partial\Psi / \partial t + \mathbf{u} \cdot \nabla\Psi = -\nabla^2\Psi, \quad x \in \Omega, \quad t \in (0, \vartheta),$$

$$\sigma_1\Psi + \sigma_2\partial\Psi / \partial\mathbf{n} = 0, \qquad x \in \partial\Omega, \quad t \in (0, \vartheta),$$

$$\Psi(\vartheta, x) = 2\left[T(\vartheta, x; \varphi) - \chi(x)\right], \quad x \in \Omega.$$

The boundary problem is referred to as the problem ***adjoint*** to the heat problem.

Note that the adjoint problem is *well-posed*.

To find a minimum of the functional *J*, we employ the gradient method

$$\varphi_{k+1} = \varphi_k - \alpha_k \nabla J(\varphi_k), \quad \varphi_0 = T_*, \quad k = 0, 1, 2, \ldots,$$

$$\alpha_k = \min\left[1/(k+1); J(\varphi_k) / \left\| \nabla J(\varphi_k) \right\|\right]$$

# Quasi-Reversibility Method

**The final-boundary-value problem to define temperature in the past**

$$\partial T_\beta / \partial t + \mathbf{u} \cdot \nabla T_\beta = \nabla^2 T_\beta + f - \beta \nabla^4 (\partial T_\beta / \partial t), \quad t \in (0, \vartheta), \; \mathbf{x} \in \Omega$$

$$\sigma_1 T_\beta + \sigma_2 \partial T_\beta / \partial \mathbf{n} = T_*(t, \mathbf{x}), \qquad t \in (0, \vartheta), \; \mathbf{x} \in \partial\Omega$$

$$\partial^2 T_\beta / \partial \mathbf{n}^2 = 0, \qquad t \in (0, \vartheta), \; \mathbf{x} \in \partial\Omega$$

$$T_\beta(0, \mathbf{x}) = T_\vartheta(\mathbf{x}), \qquad \mathbf{x} \in \Omega$$

The regularization parameter can be chosen such a way to minimize the temperature misfit:

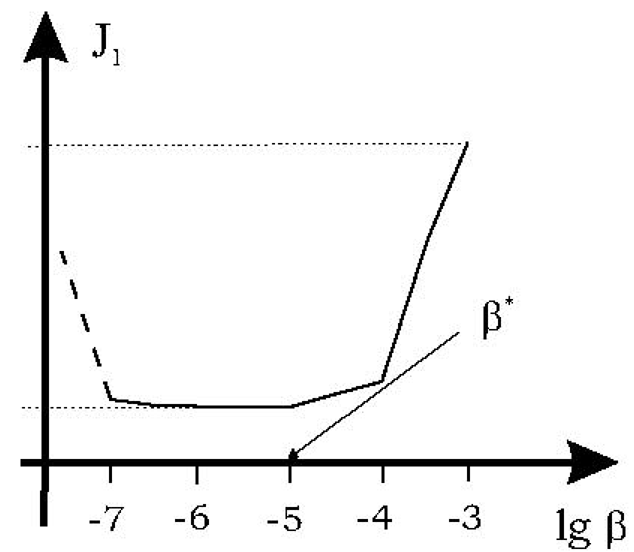
$$J_1 = \left\| T(\vartheta, \cdot; T_{\beta_k}(0, \cdot)) - \chi(\cdot) \right\|_{L_2(\Omega)} < \varepsilon$$

or

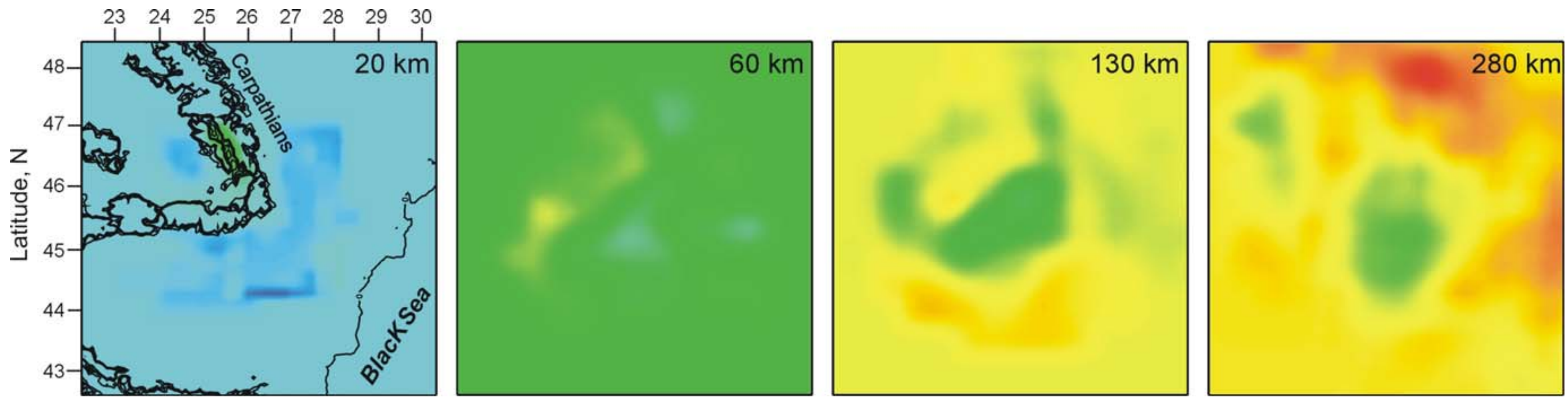
$$J_1 = \left\| T_{\beta_{k+1}}(0, \cdot) - T_{\beta_k}(0, \cdot) \right\|_{L_2(\Omega)} < \varepsilon$$

$$\beta_k = \beta_0 q^{k-1}, \quad \beta_0 = 10^{-3},$$

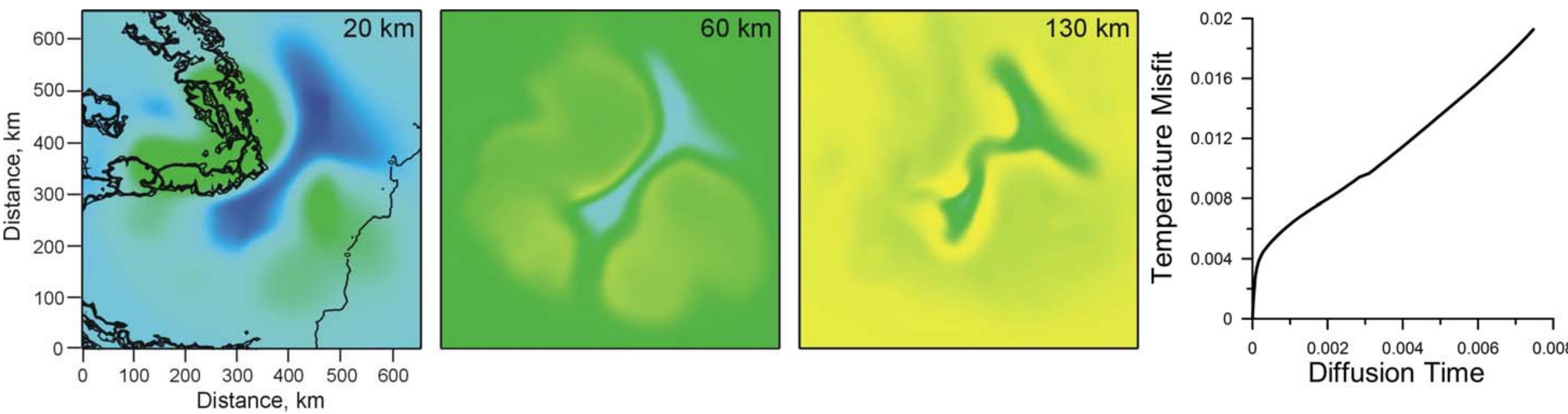
$$q = 0.1, \quad k = 1, 2, \ldots$$

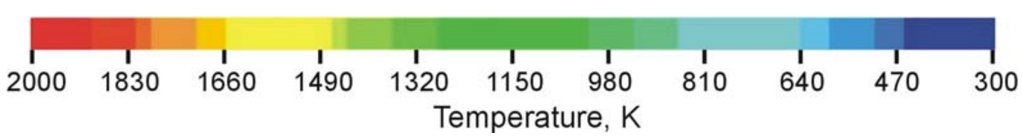


# Model of the Present Temperature in SE-Carpathians

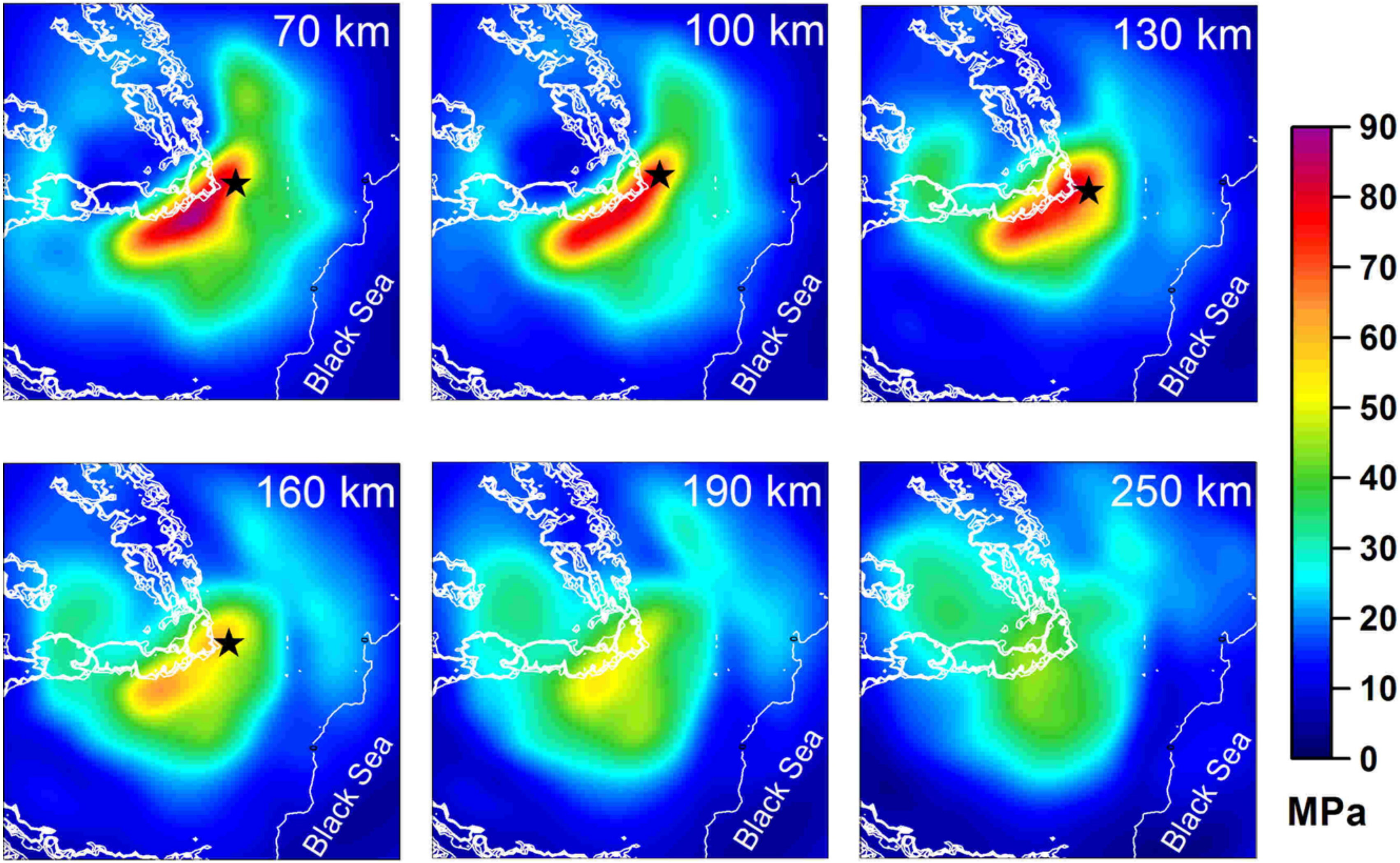



# Model of the Temperature in SE-Carpathians ~23 My ago



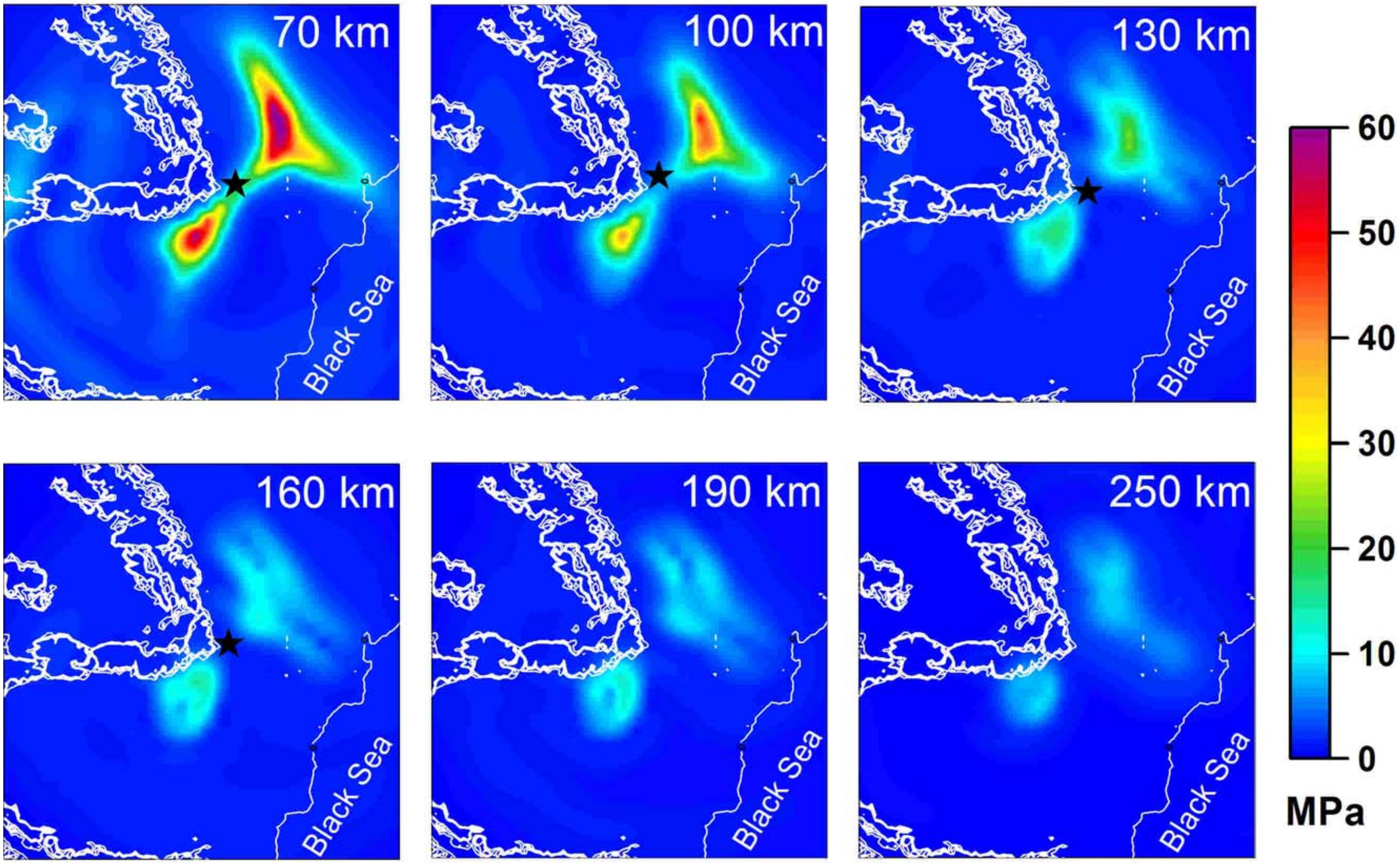



# Maximum Shear Stress




**Modeled tectonic stress, present**

# Maximum Shear Stress

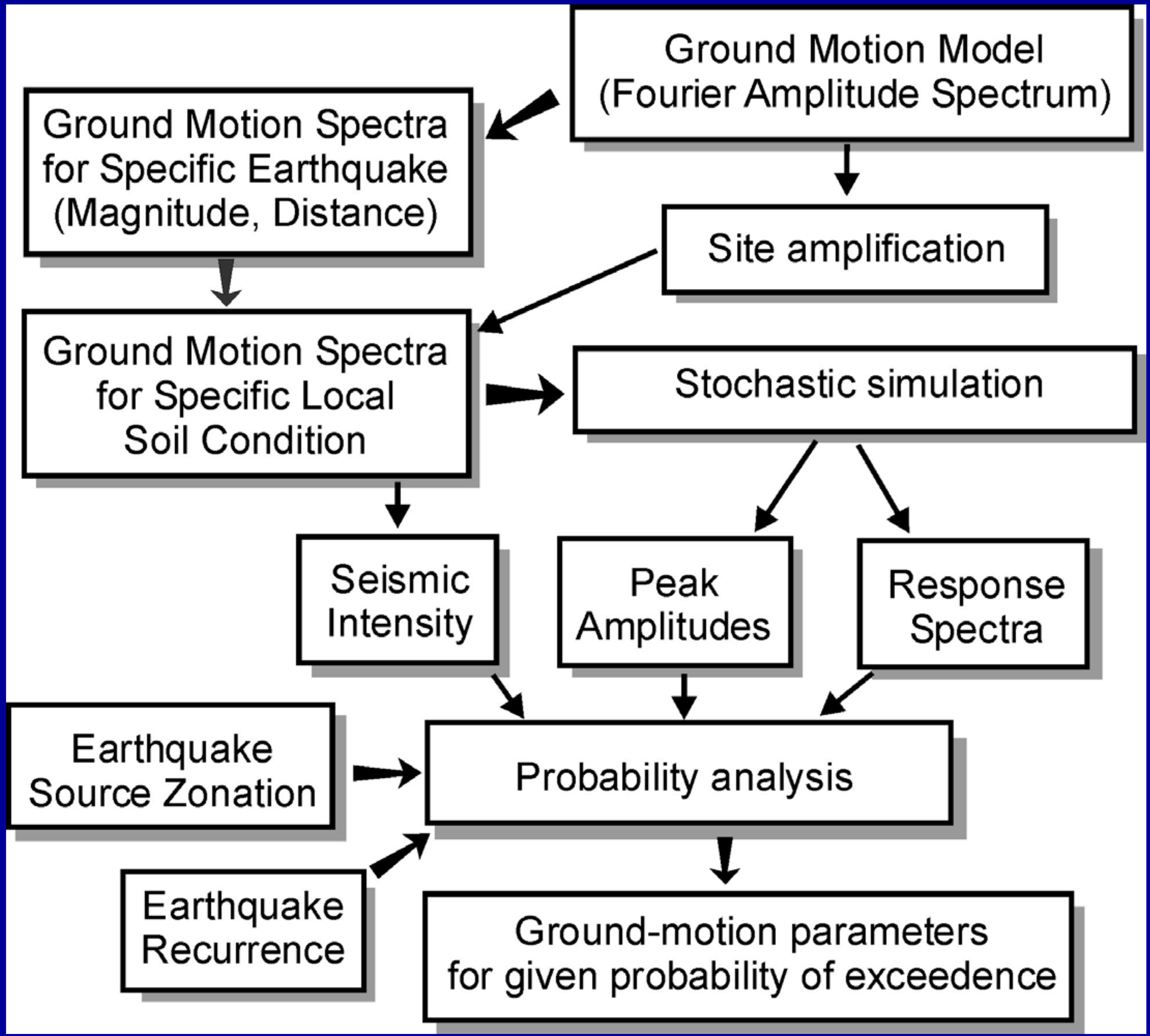



Model tectonic stress, 23 My ago

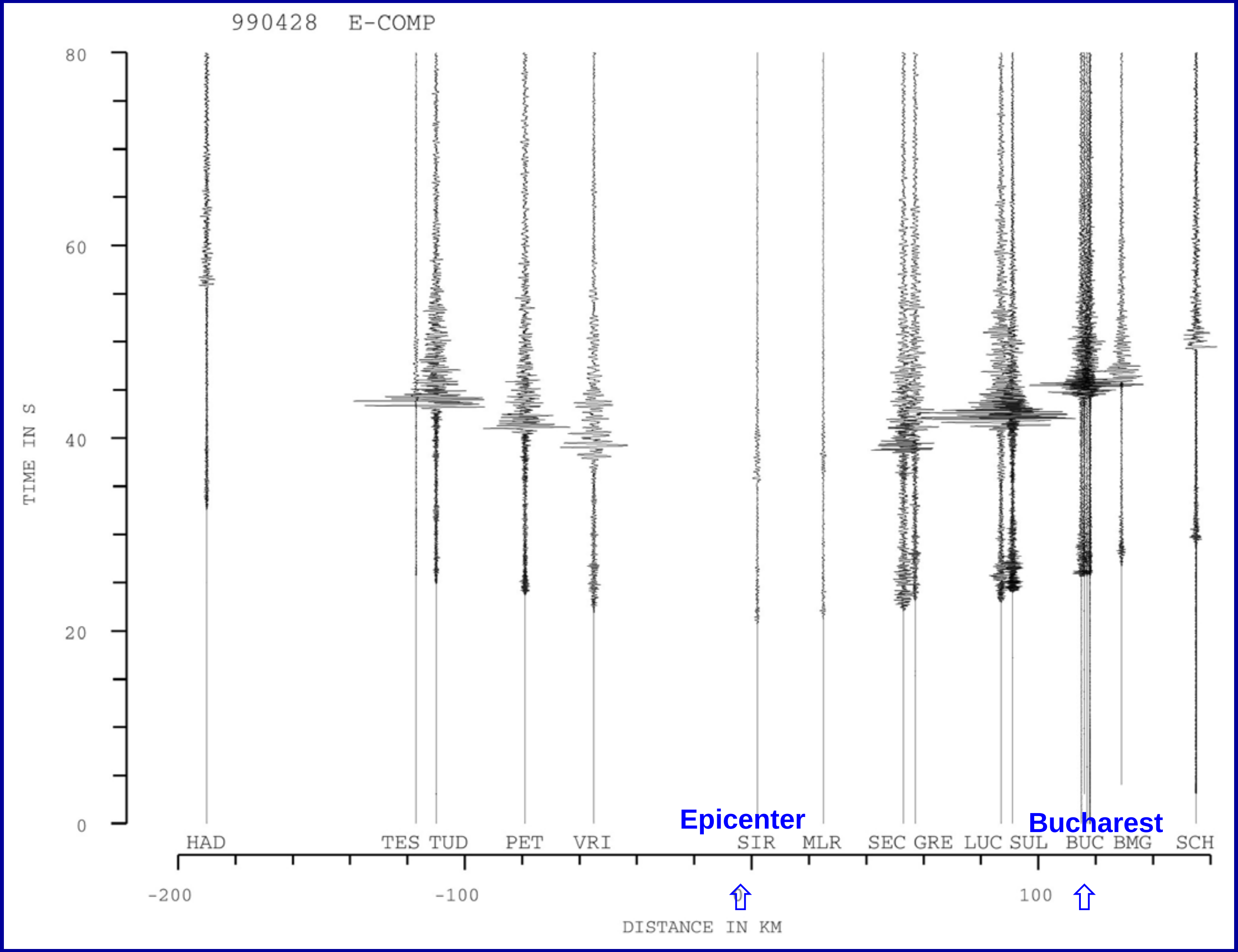
# Quantitative
# Seismic Hazard Assessment

Ismail-Zadeh, Sokolov and Bonjer (Natural Hazards, 2006, in press)

# Seismic Hazard Assessment Approach

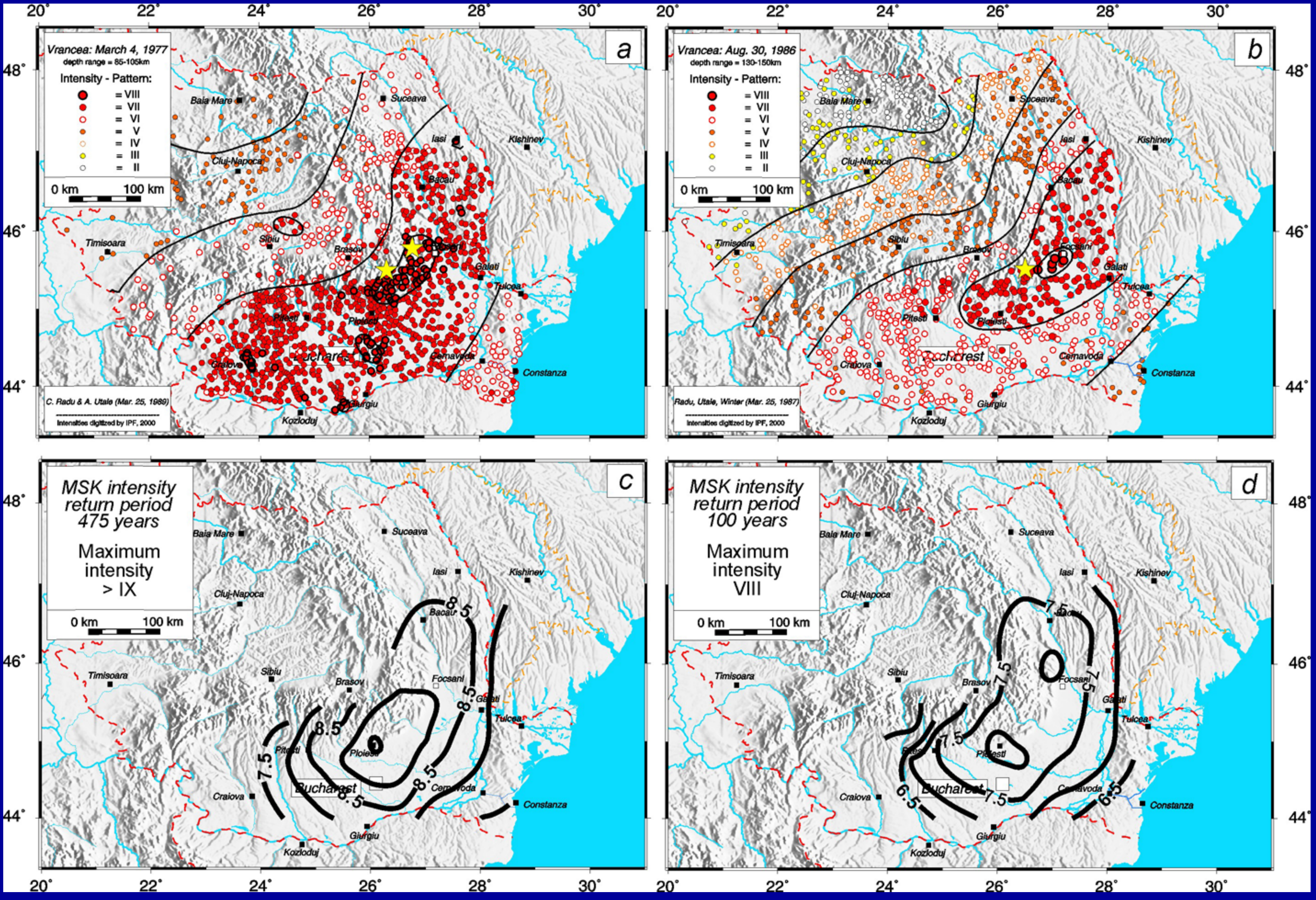


# NE-SW record section of the April 28, 1999 Mw=5.3 Vrancea event

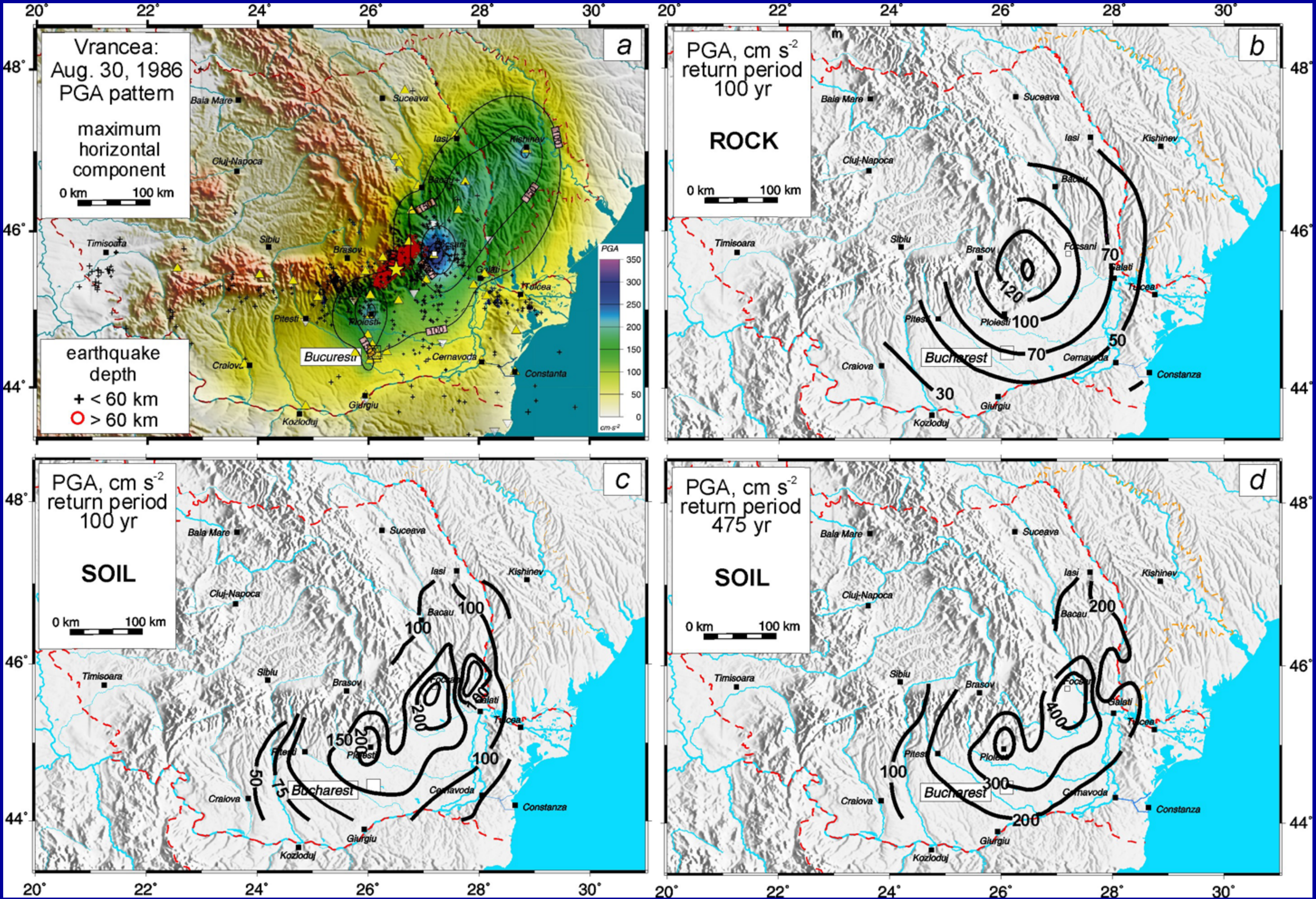



**Apparent increase of amplitudes with distance is a result of SITE EFFECTS!**

## Comparison of MSK intensity distribution during two large Vrancea earthquakes (*a*: $M_W$ = 7.4, March 4, 1977 and *b*: $M_W$ = 7.2, August 30, 1986) and the PSHA results evaluated for two return periods (*c*: $T$ = 475 yr and *d*: $T$ = 100 yr).



# Comparison of PGA distribution during the Vrancea earthquake (*a*: $M_W$ = 7.2, August 30, 1986) and the PSHA results evaluated for two types of site conditions (*b*: rock and *c*, *d*: soil) and for two return periods (*c*: *T* = 100 yr and *d*: *T* = 475 yr).



# Conclusion - 1

- Based on data from seismic tomography, seismic refraction profiles, heat flow and on the knowledge of geodynamic evolution of the region, we have performed the quantitative analysis of contemporary slow mantle flow and tectonic stress beneath the SE-Carpathians.
- We have demonstrated a correlation between the location of intermediate-depth earthquakes and the predicted localizations of maximum shear stress and horizontal compression.
- Buoyancy forces, which result from realistic temperature and density distributions in the crust and mantle, can govern the contemporary deformation beneath the SE-Carpathians and explain the regional stress pattern and intermediate-depth seismicity.
- The PSHA results are consistent with the general features of the observed earthquake effects in the SE-Carpathians. Based on these results, we can conclude that geological factors play an important part in the distribution of earthquake ground motion parameters within the region analyzed.

# Numerical Modelling of Seismicity: Block-and-Fault Dynamics

# BAFD Model
# Basic Principles

Gabrielov et al. (1990), Soloviev and Ismail-Zadeh (2003)

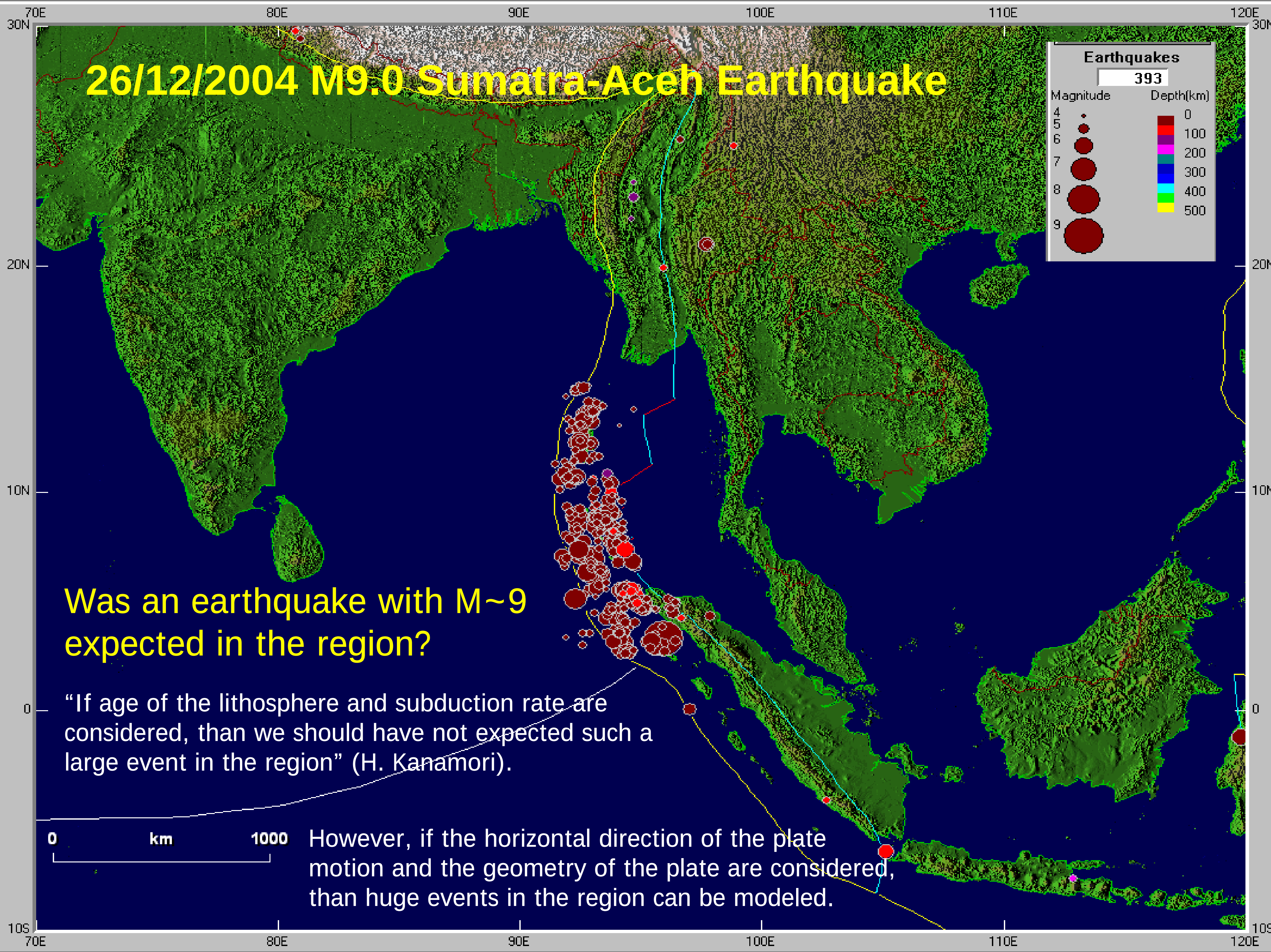
- A seismic region is considered as a structure of perfectly rigid (upper crustal or lithospheric) blocks divided by infinitely thin fault planes.
- The blocks interact between themselves and with the underlying medium (lower crust or asthenosphere).
- The structure of blocks moves in response to prescribed motion of the boundary blocks and of the underlying medium.
- Deformation is localized in the fault zones, and relative block displacements take place along the fault planes.

# BAFD Model-Generated Seismicity

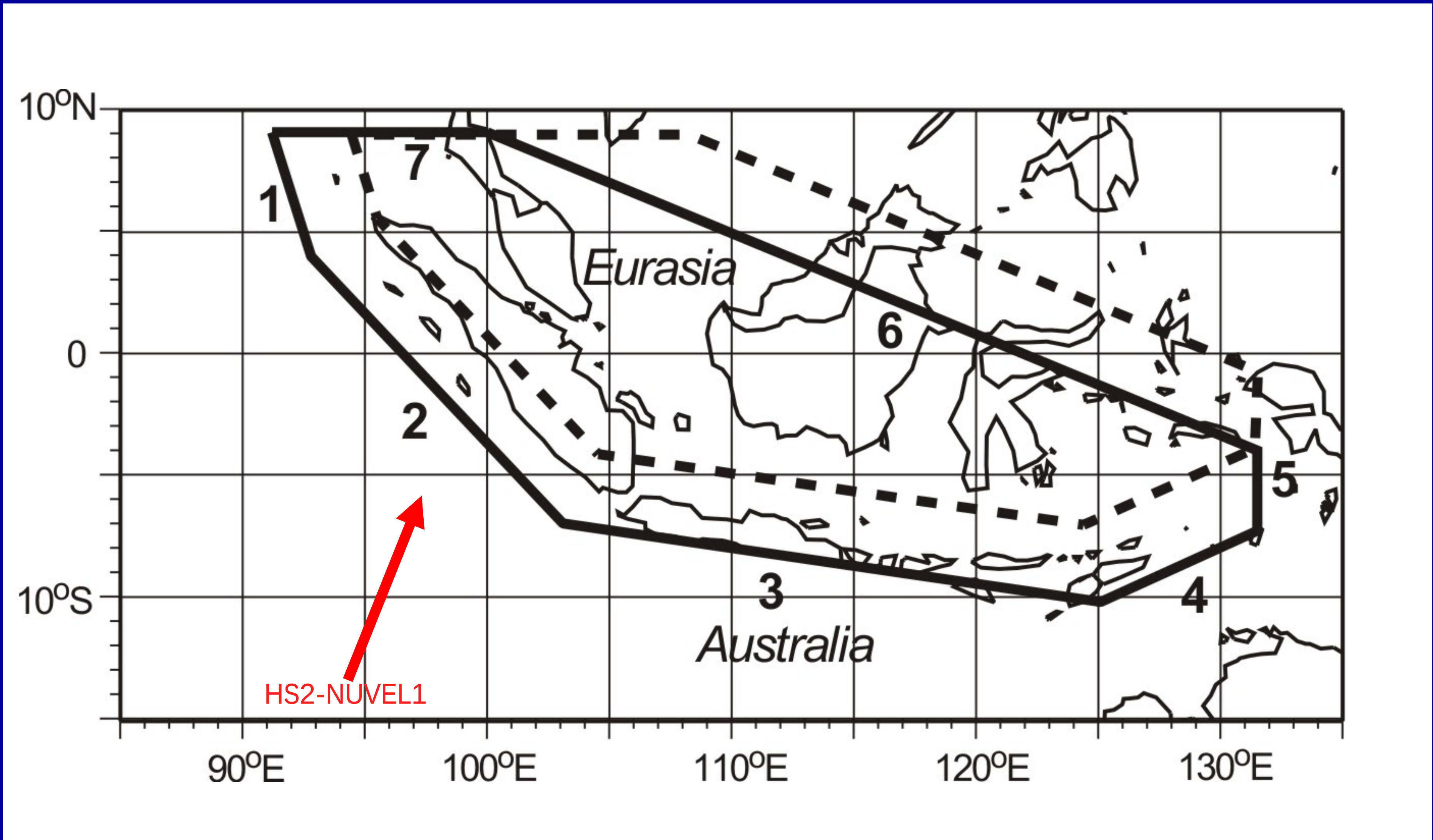
Synthetic catalogs of earthquakes allow for analysis of

- spatial-temporal correlation between earthquakes;
- earthquake clustering;
- long-range interaction between the events;
- fault slip rates;
- mechanism of earthquakes;
- seismic moment release

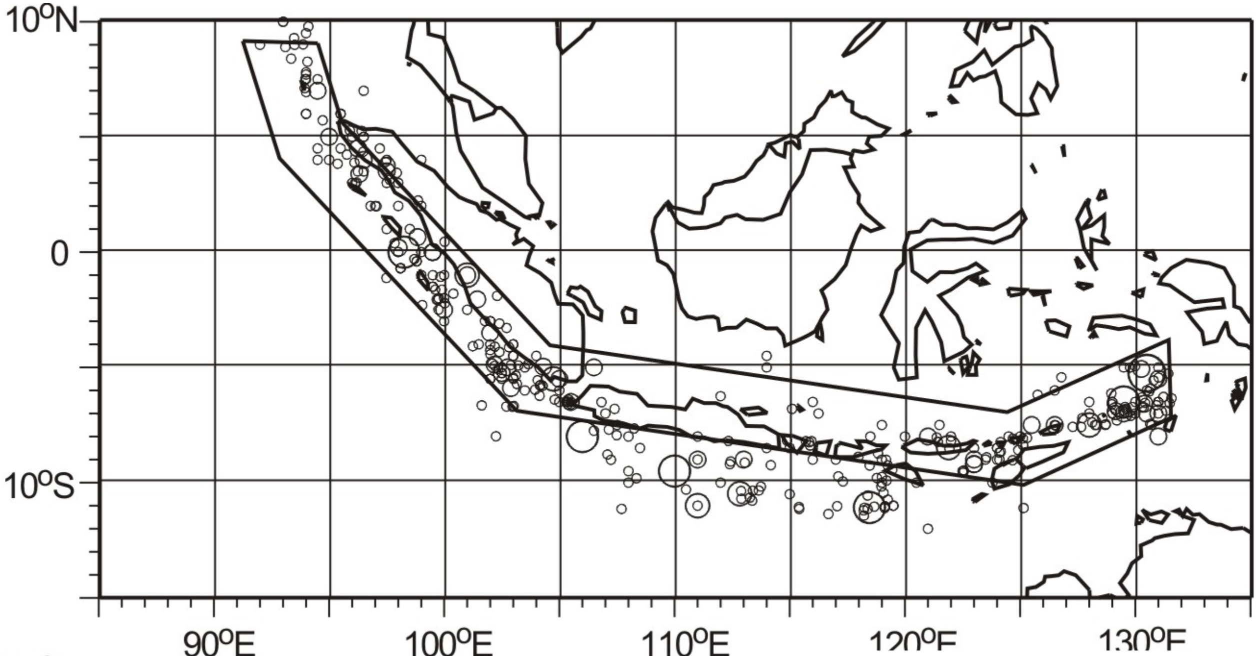
# Sudna Arc

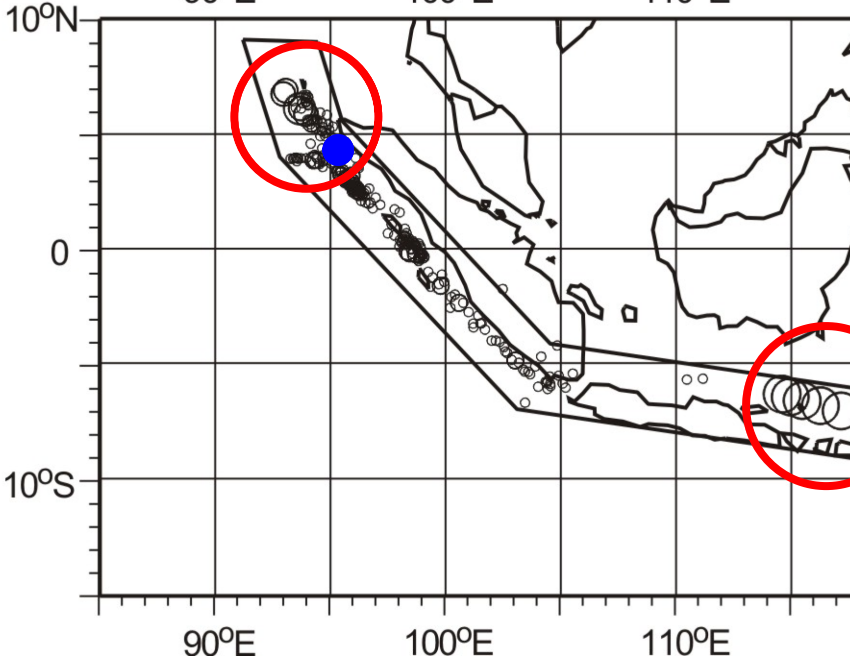

26/12/2004 M9.0 Sumatra-Aceh Earthquake
Was an earthquake with M~9 expected in the region?
"If age of the lithosphere and subduction rate are considered, than we should have not expected such a large event in the region" (H. Kanamori).
However, if the horizontal direction of the plate motion and the geometry of the plate are considered, than huge events in the region can be modeled.
Earthquakes
393
Magnitude
Depth(km)
4
5
6
7
8
9
0
100
200
300
400
500
0
km
1000
70E
80E
90E
100E
110E
120E
30N
20N
10N
0
10S

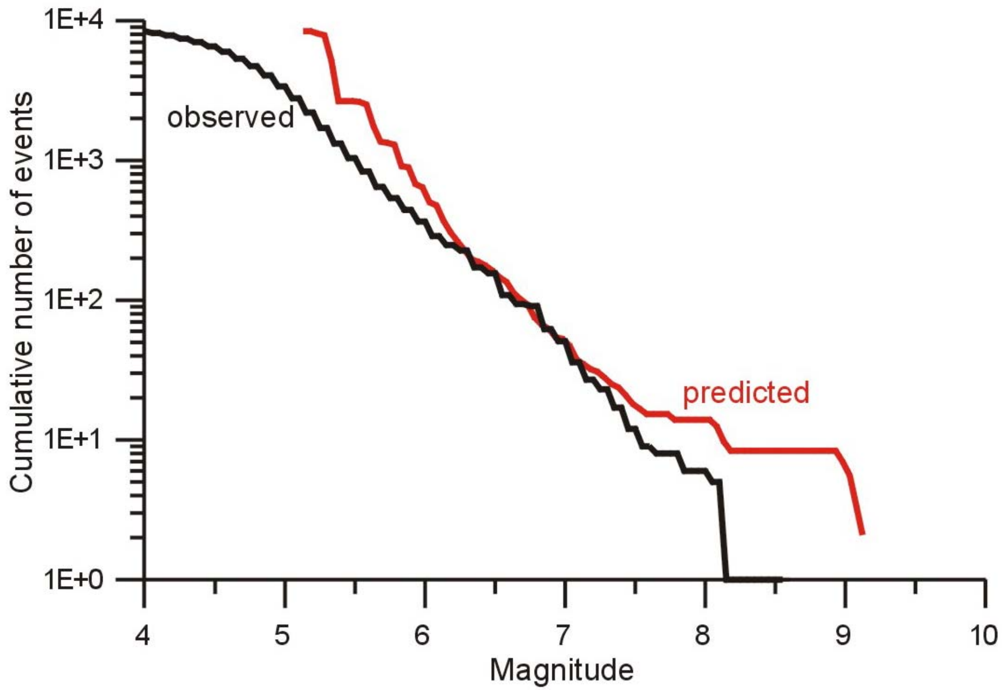
# BAFD model of the Sunda Arc (geometry)



# Observed seismicity, M>6

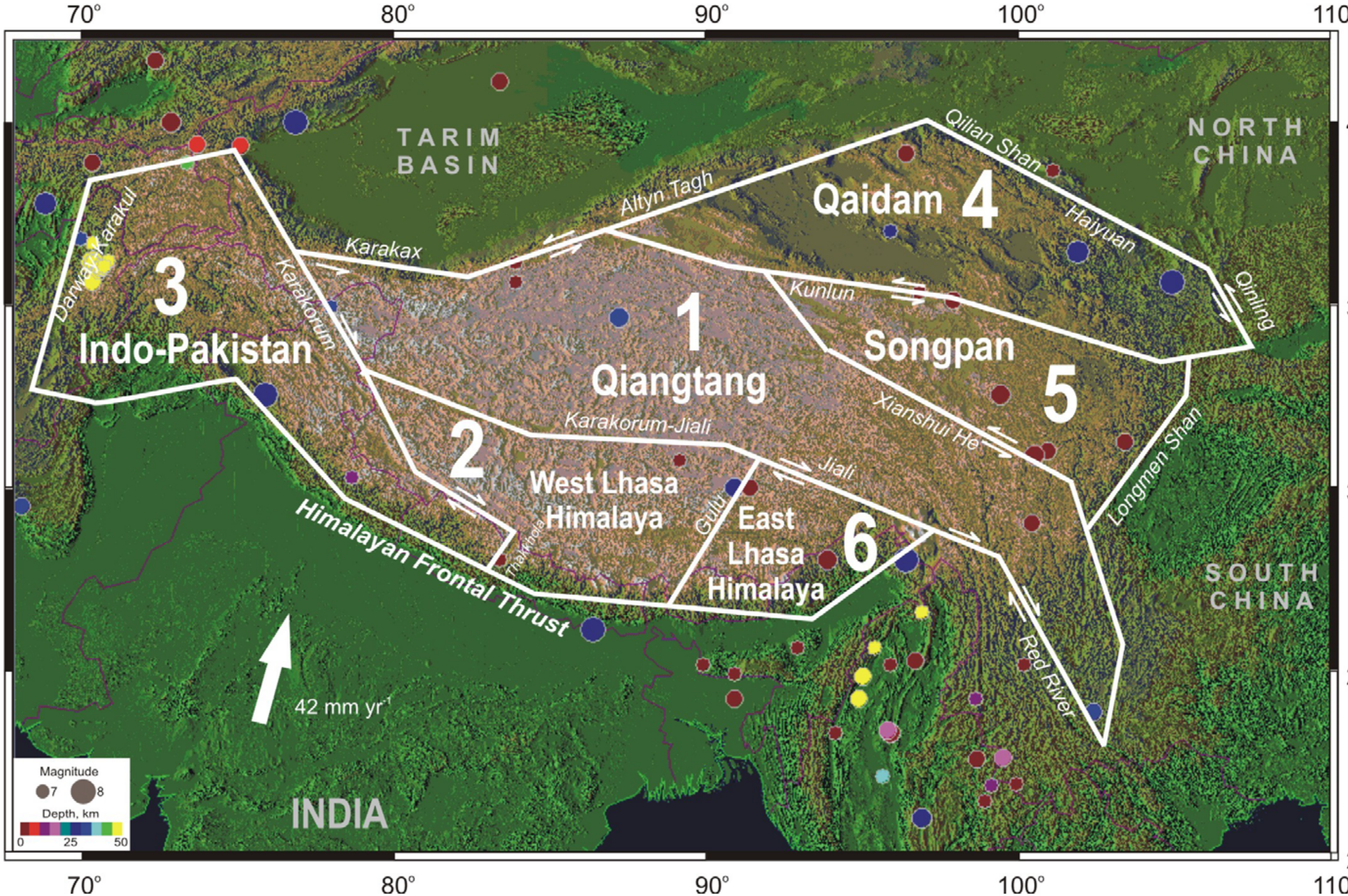


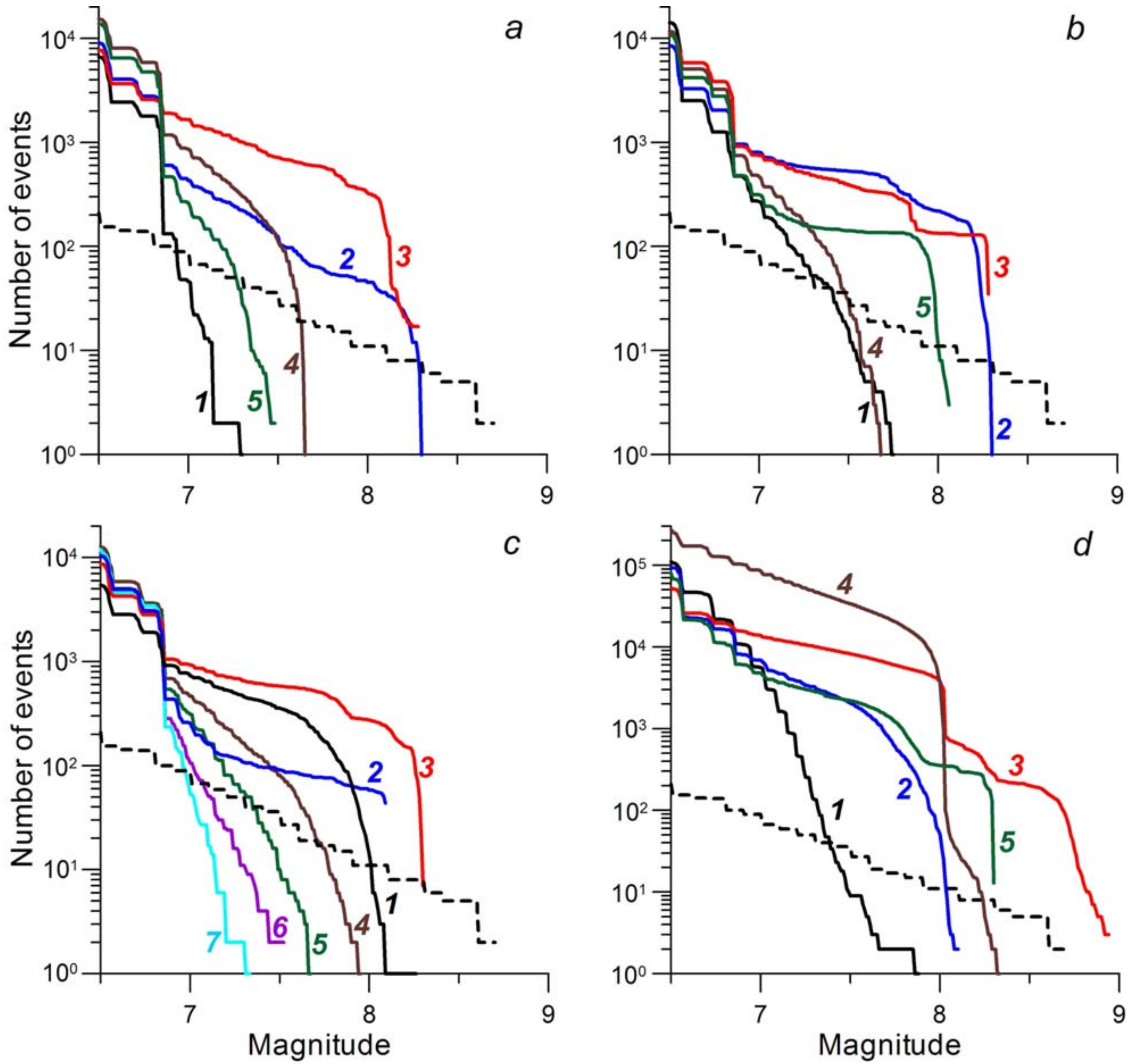



# Tibet-Himalayan Region

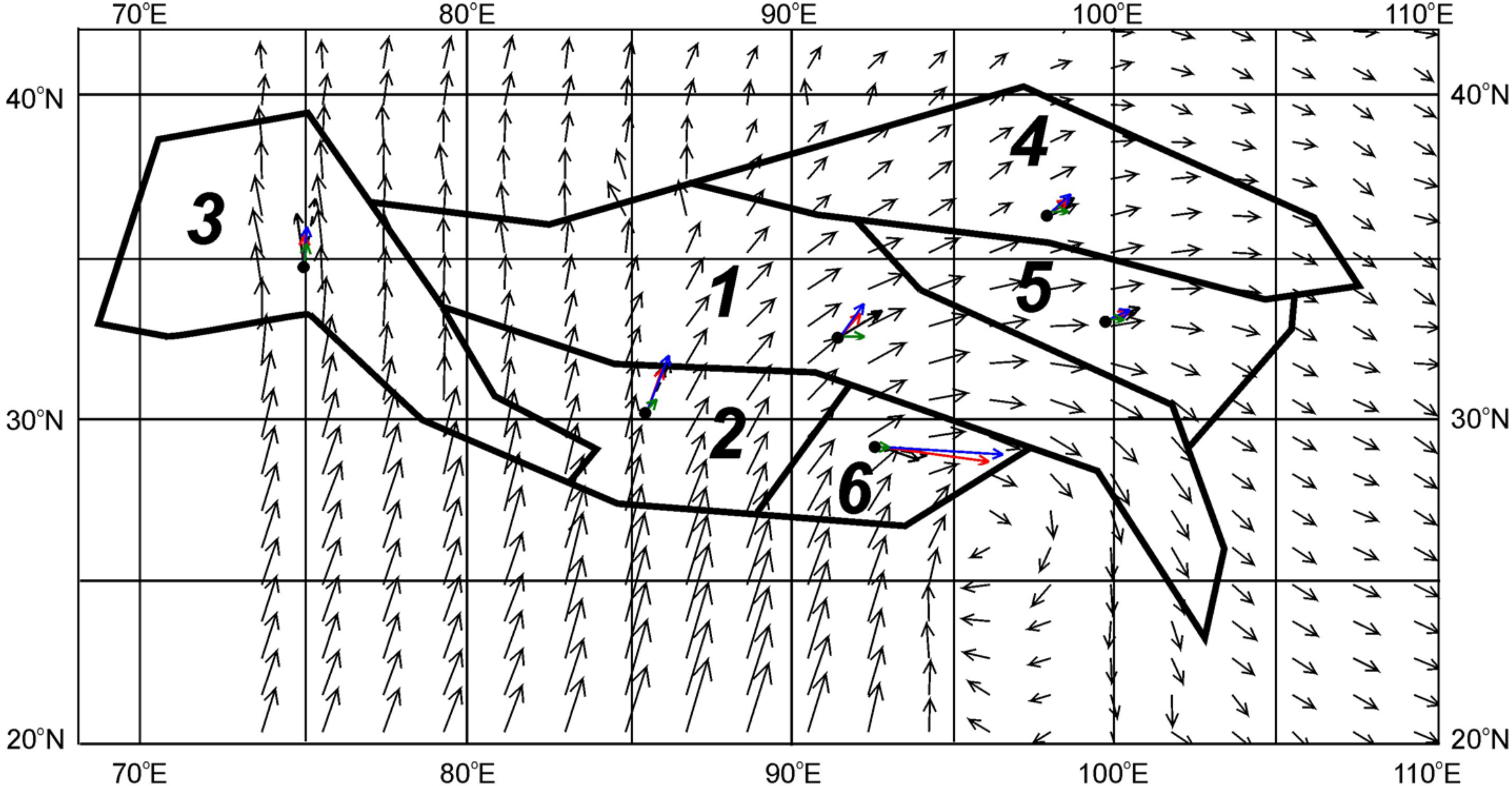
Ismail-Zadeh et al.  (EPSL, 2006, under review)


70°
80°
90°
100°
110°
40°
35°
30°
25°
20°
TARIM BASIN
NORTH CHINA
SOUTH CHINA
INDIA
Qilian Shan
Altyn Tagh
Qaidam
4
Haiyuan
Karakax
Karakorum
Darvaz-Karakul
3
Indo-Pakistan
1
Qiangtang
Kunlun
Qinling
Songpan
5
Xianshui He
Karakorum-Jiali
2
West Lhasa Himalaya
Jiali
Gulu
East Lhasa Himalaya
6
Longmen Shan
Thakkhola
Himalayan Frontal Thrust
Red River
42 mm yr-1
Magnitude
7
8
Depth, km
0
25
50

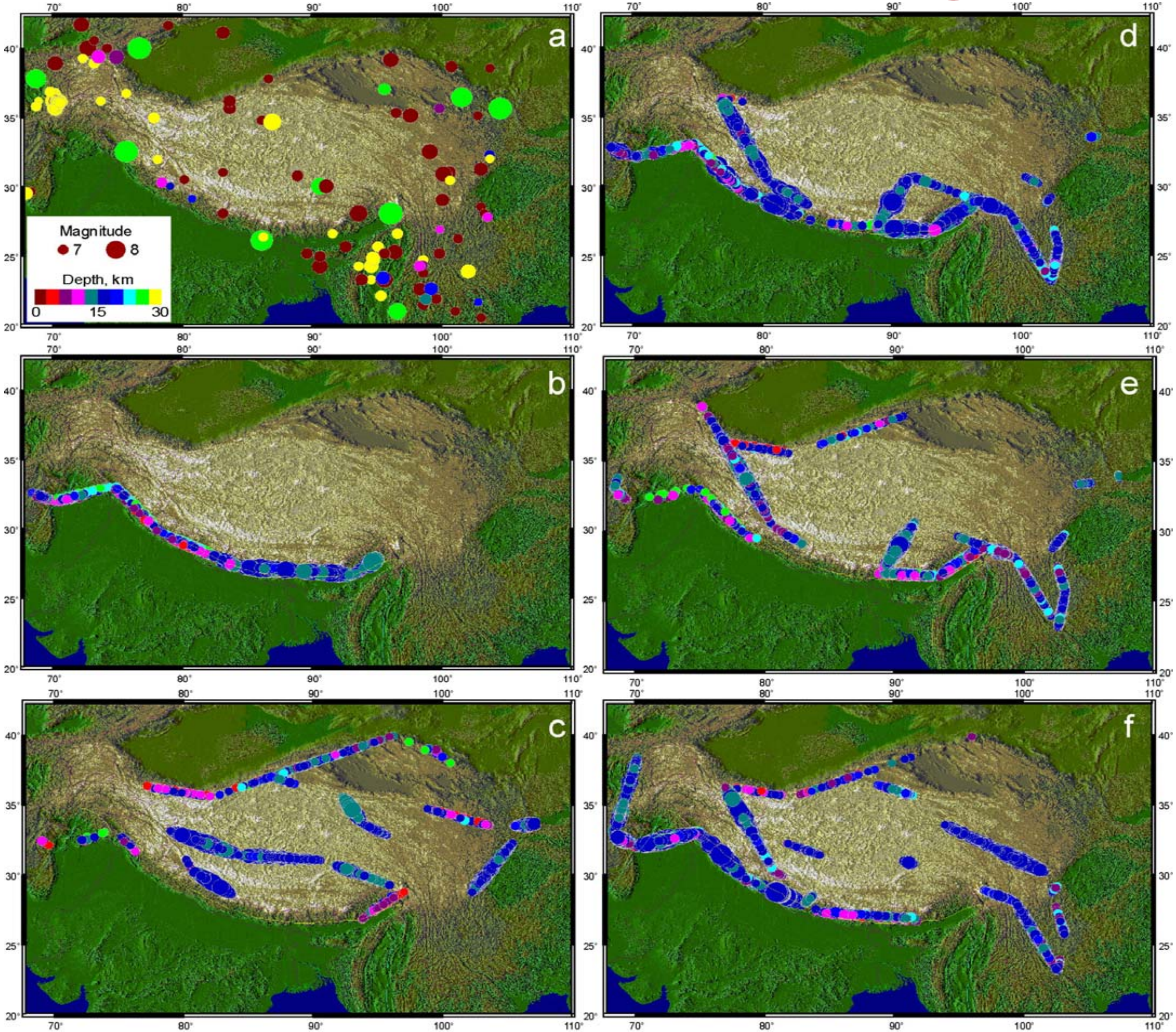
# Frequency-Magtinude Relationship



# Block movements & geodetical measurements




# Earthquake clustering



# Conclusion - 2

- The contemporary crustal dynamics and seismicity pattern in the Tibet-Himalayan region are determined by the N-NE motion of India relative to Eurasia and the movement of the lower crust overlain by the upper crustal rigid blocks.

- Clustering of earthquakes can be considered as a consequence of the dynamics of the crustal blocks and faults in the region. The number and maximum magnitude of synthetic earthquakes change with the variations in the movements of the crustal blocks and in the rheological properties of the lower crust and the fault zones.

# Final Conclusion

Basic science must become a "*brain*" of the preventive disaster management of extreme seismic events.

Geoscientists must *act today* and implement state-of-the-art measures to protect society from rare but recurrent extreme natural catastrophes and humanitarian tradegies. Otherwise we will witness again and again the tragic aftermaths of seismic disasters, which could have been avoided.