Nonlinear dynamics in Vrancea source: numerical simulation

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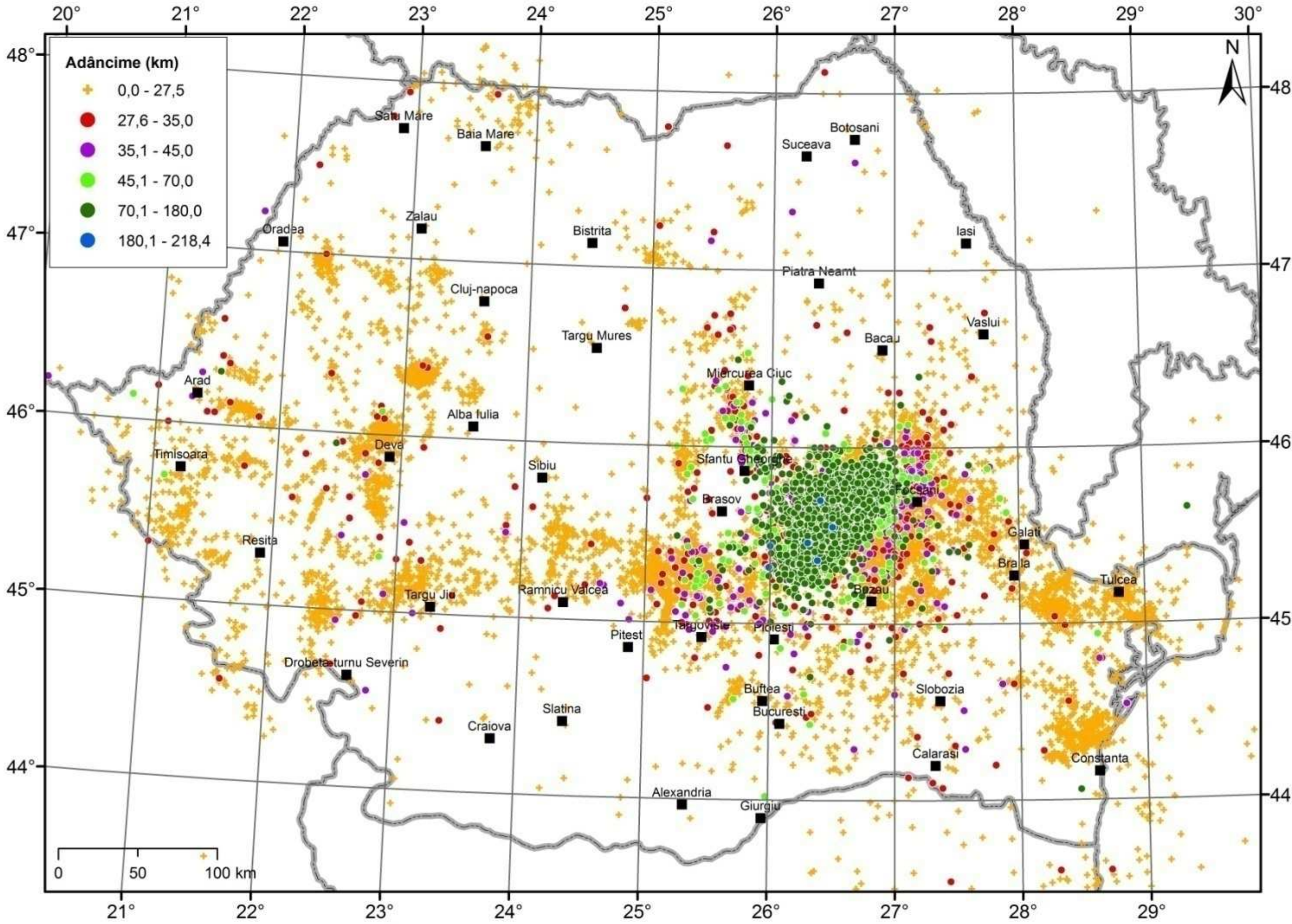
Summary

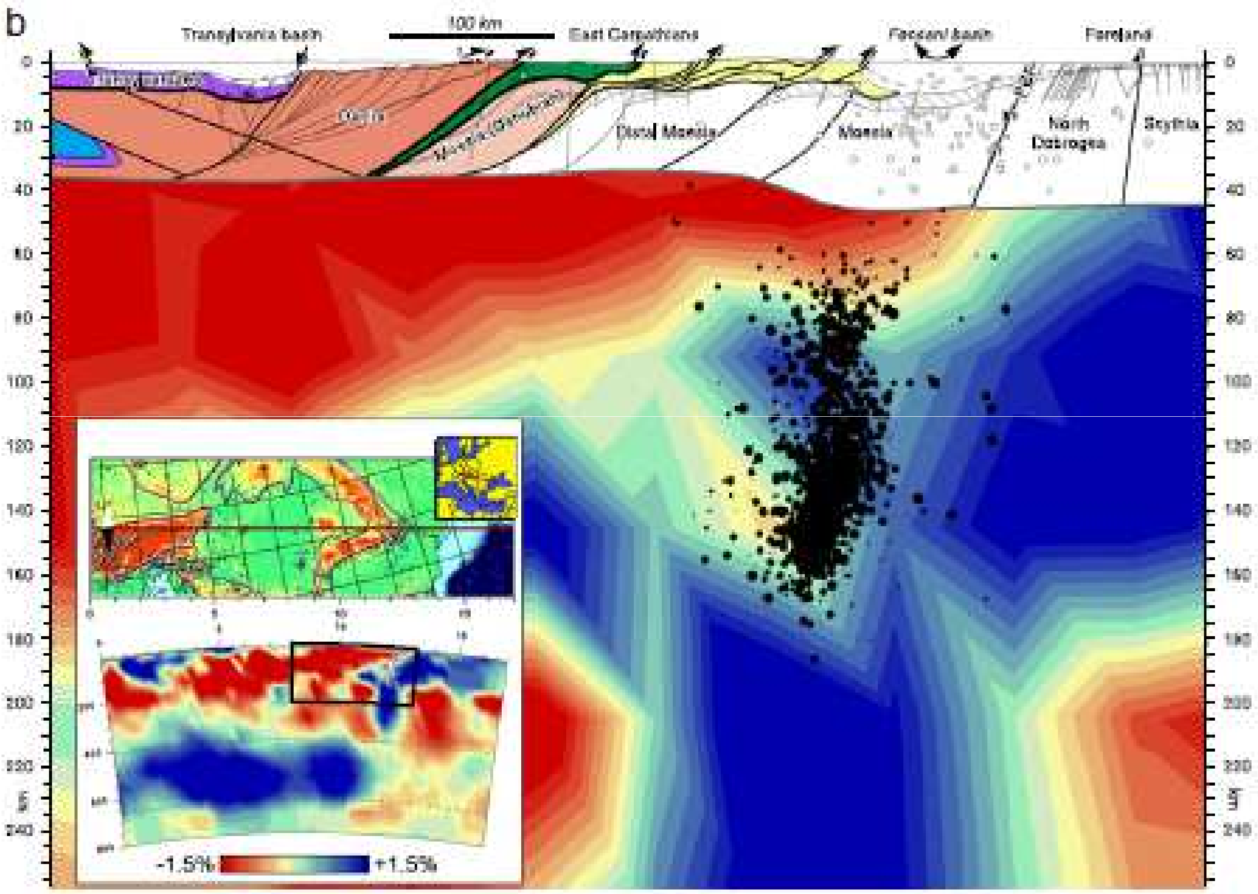
- Specific patterns of seismicity in Vrancea
- Simulation algorithm
- Test of the seismicity patterns and seismic cycle characteristics
- Conclusions and implications for future developments

Specific patterns of seismicity in Vrancea



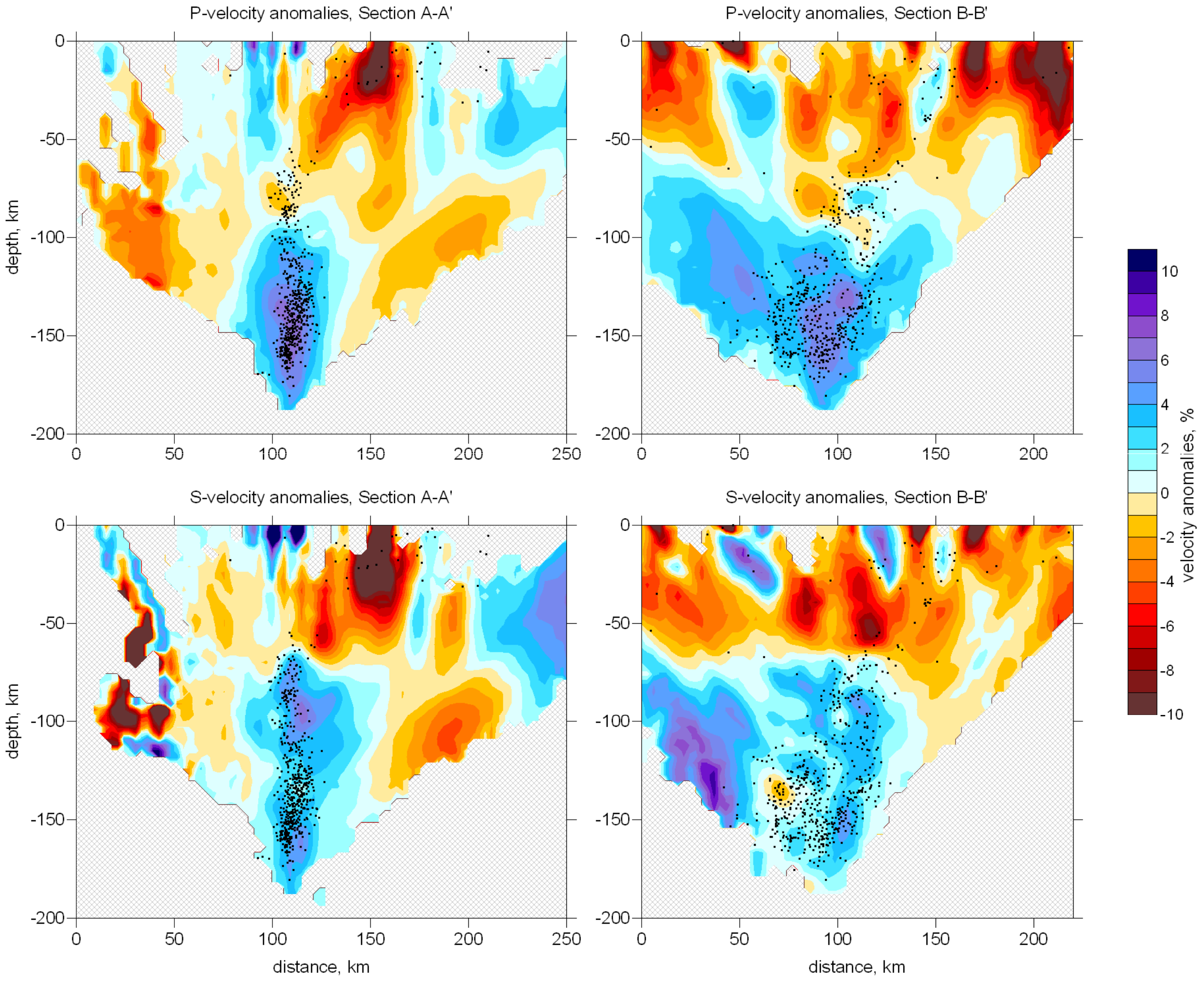
Specific patterns of seismicity in Vrancea

Vertical cross section across the Transylvanian Basin, SE Carpathians and their foreland (after *Matenco et al., 2007*) overlaid over regional P-wave tomography (*Bijwaard and Spakman, 2000*; *Wortel and Spakman, 2000*).



Specific patterns of seismicity in Vrancea

Local tomography for P- and S-wave velocities (after *Koulakov et al., 2009*): Geometry of the high-velocity body and seismicity location.



Specific patterns of seismicity in Vrancea

- **Cluster of seismicity concentrated at intermediate depth**

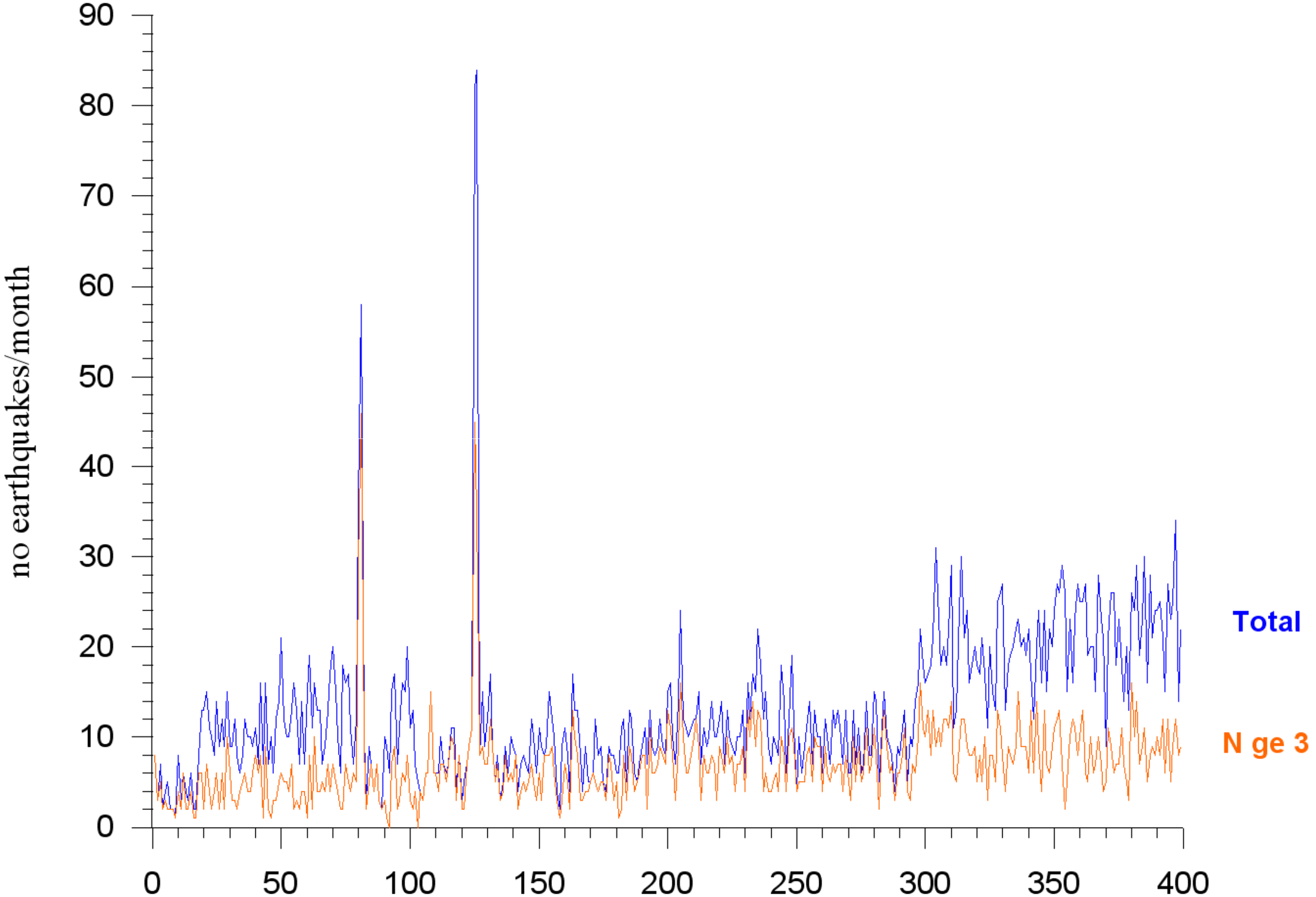
Vrancea - the most concentrated seismic area in Europe. The moment release rate here is as high as the moment release rate of Southern California (Wenzel et al., 1998)

- **Frequent major earthquakes of M around 7**

October 6th 1908 (Mw = 7.1)
November 10th 1940 (M_W = 7.7)
March 4th 1977 (M_W = 7.4) - since the last century
August 30th 1986 (M_W = 7.1)
May 30th 1990 (M_W = 6.9)

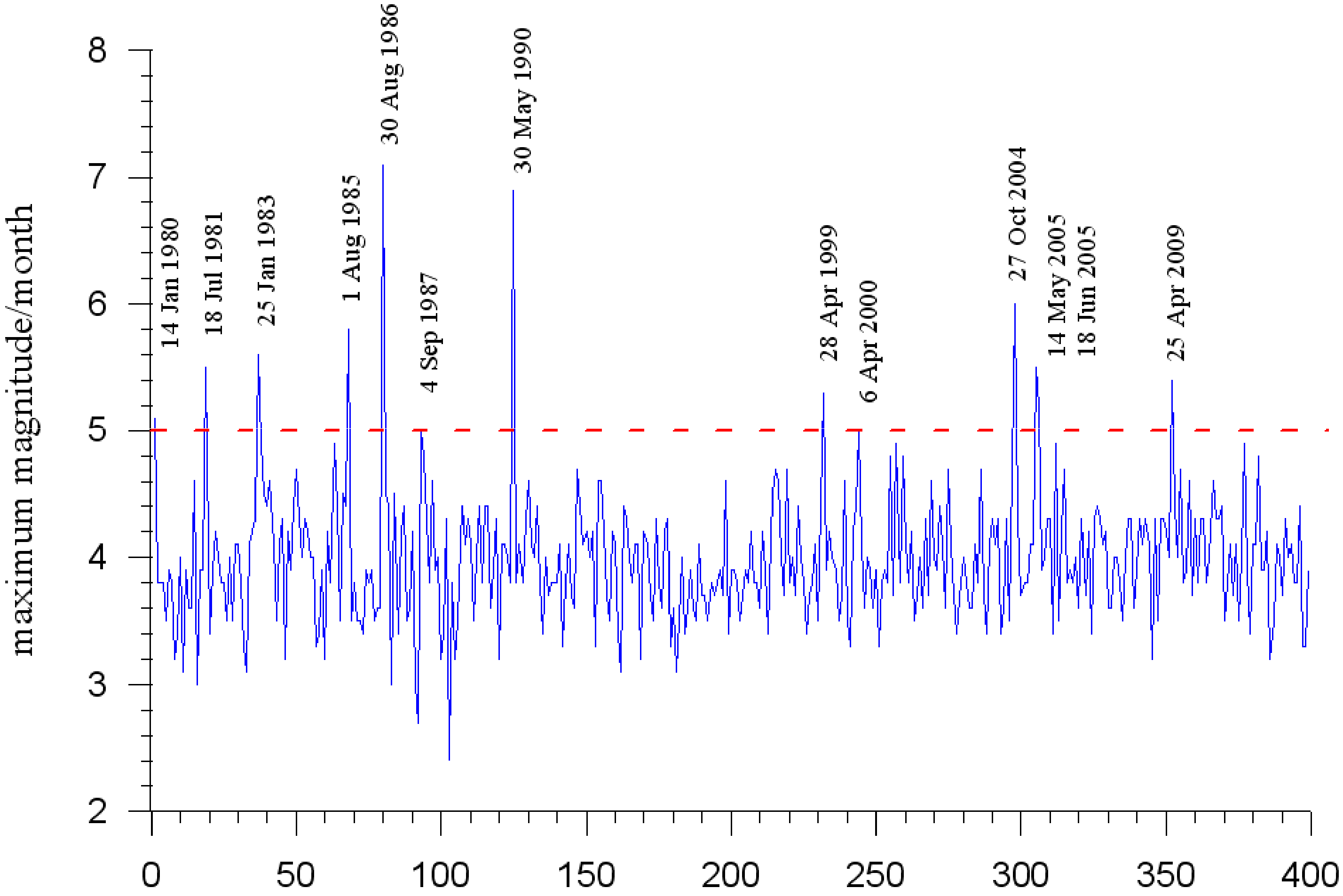
October 27th 2004 (M_W = 6.0) - the largest shock since 1990

Specific patterns of seismicity in Vrancea



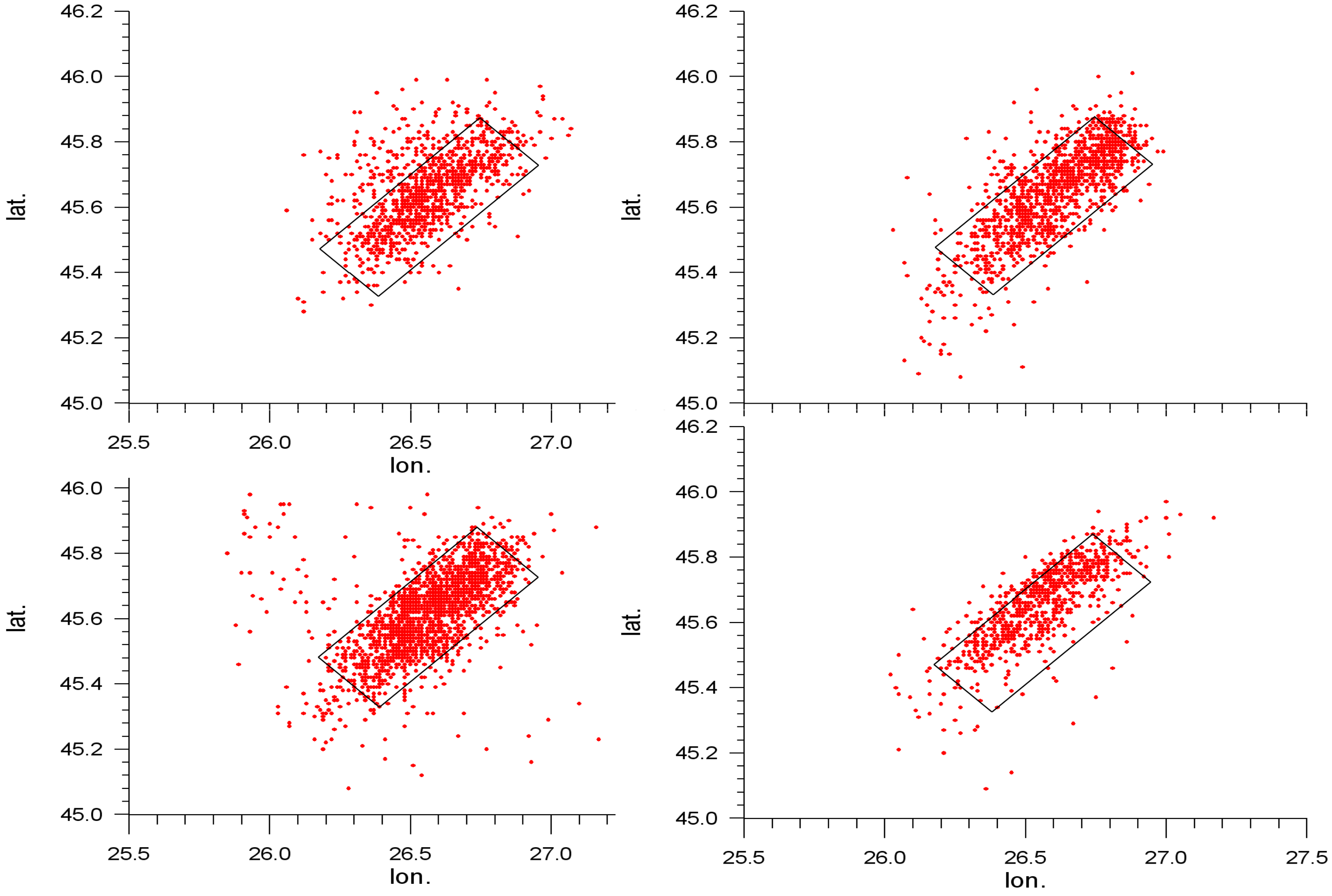
1980 - 2013

Specific patterns of seismicity in Vrancea

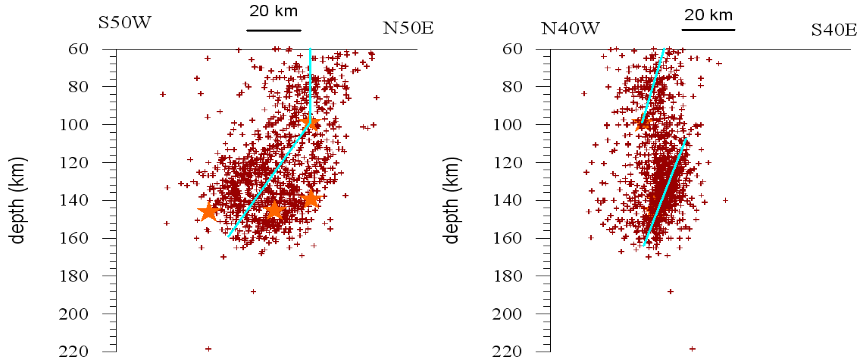


1980 - 2013

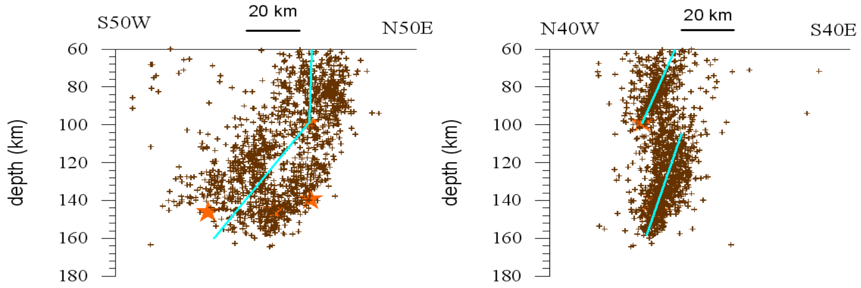
Specific patterns of seismicity in Vrancea



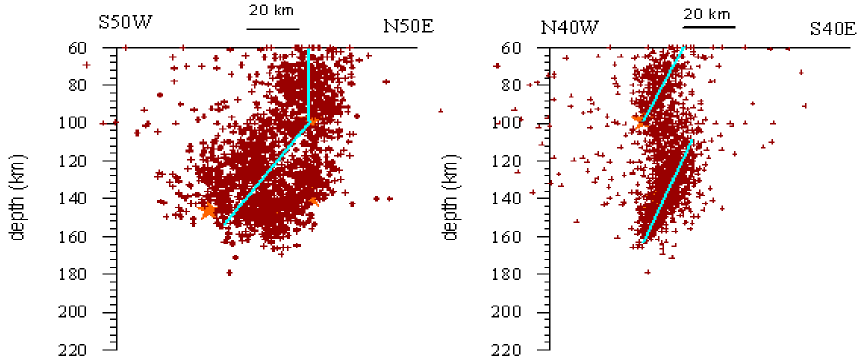
Specific patterns of seismicity in Vrancea



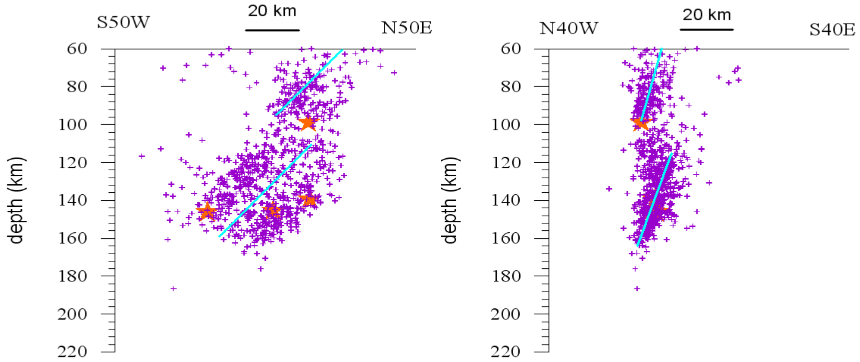
1980 - 1989



1990 - 1999

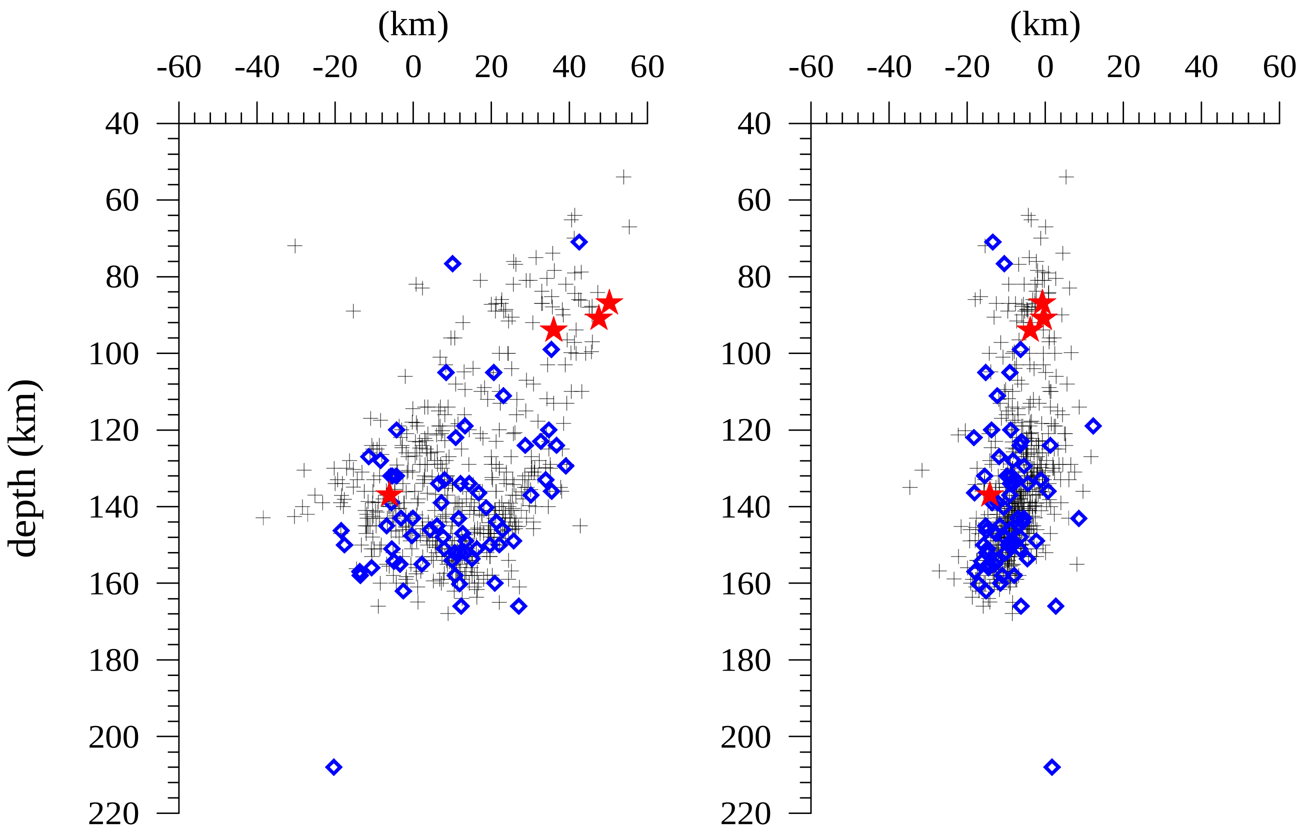


2000 - 2009



2010 - 2013

Specific patterns of seismicity in Vrancea



Hypocentral distribution on two vertical cross sections beneath Vrancea (reference site 45.5°N, 26.5°E); catalogue data: 1976 - 2007.

+: 4 ≤ M < 5; ◊: 5 ≤ M < 6; ★: M ≥ 6.

Specific patterns of seismicity in Vrancea

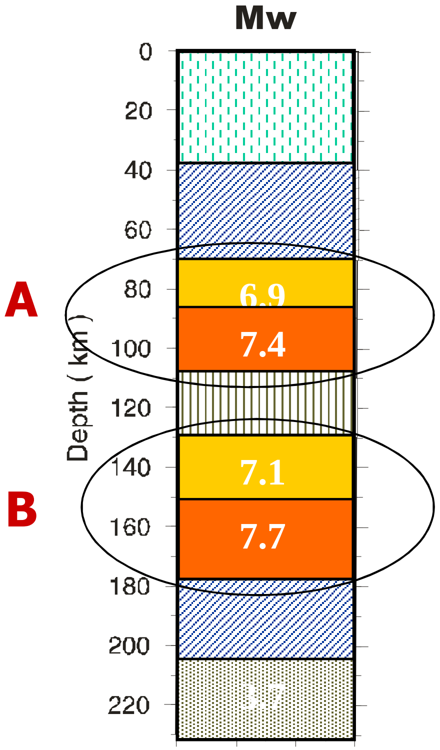
Two active segments where the last 4 major Vrancea earthquakes were generated:

A: in the upper part of the subducted lithosphere (around 90 km of depth)

B: in the lower part of the subducted lithosphere (around 140 km of depth)

Key issue:

Can the zone separating the two segments generate large earthquakes or it behaves like a barrier (as it did for more than 100 years)?



Moderate crustal seismic activity

Low seismic activity, low velocities

May 30, 1990

March 4, 1977

Not ruptured since 1802 or 1838

August 30, 1986

November 10, 1940

No present seismic activity

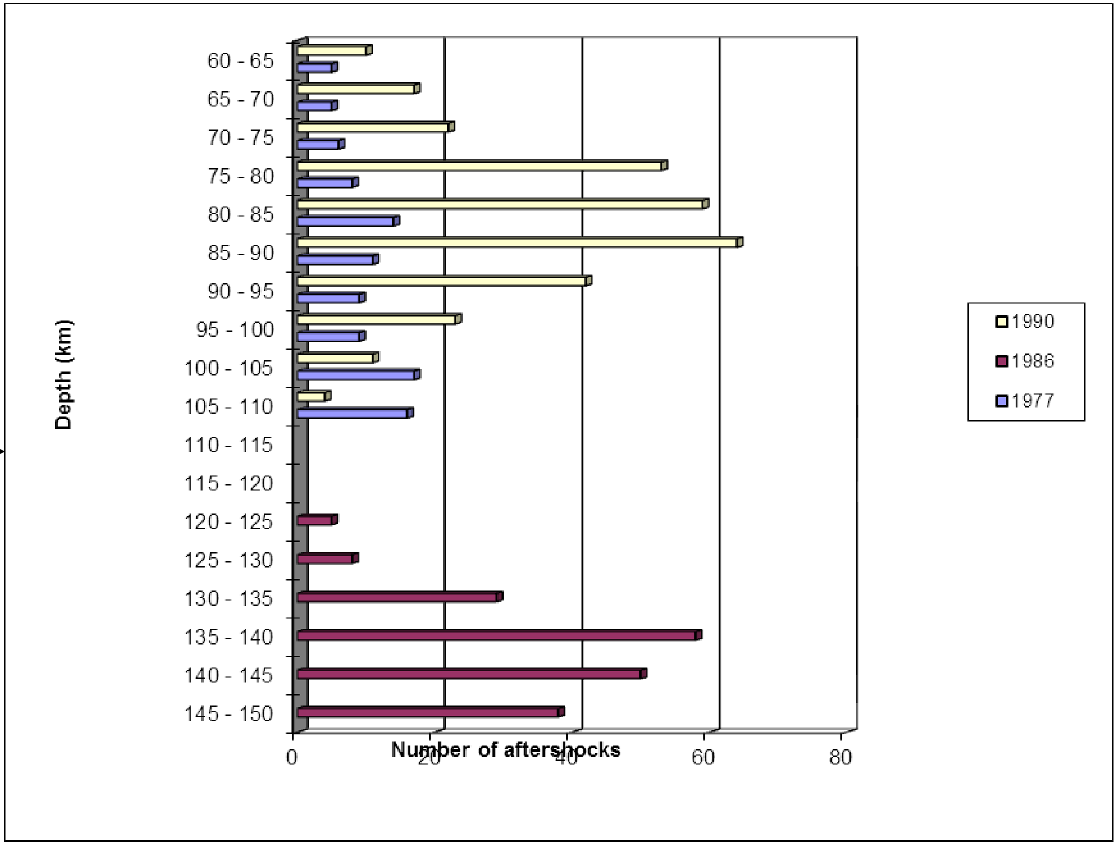
Deepest event ever recorded (May 16, 1982)

Specific patterns of seismicity in Vrancea

Zone A

Barrier?

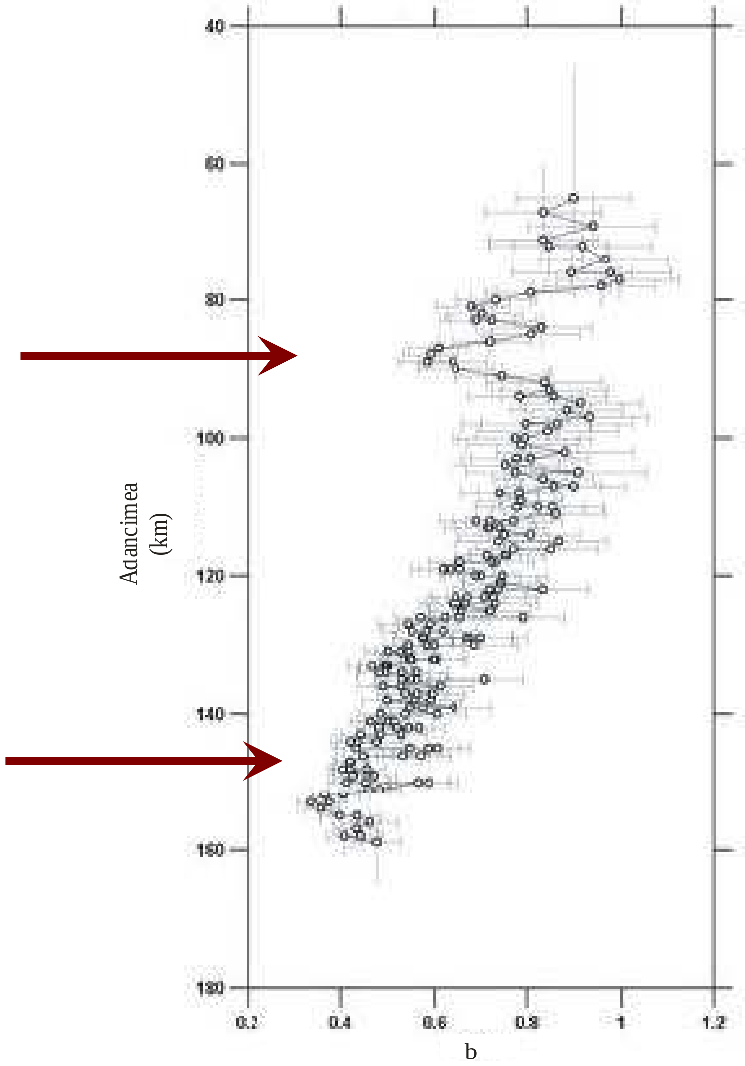
Zone B



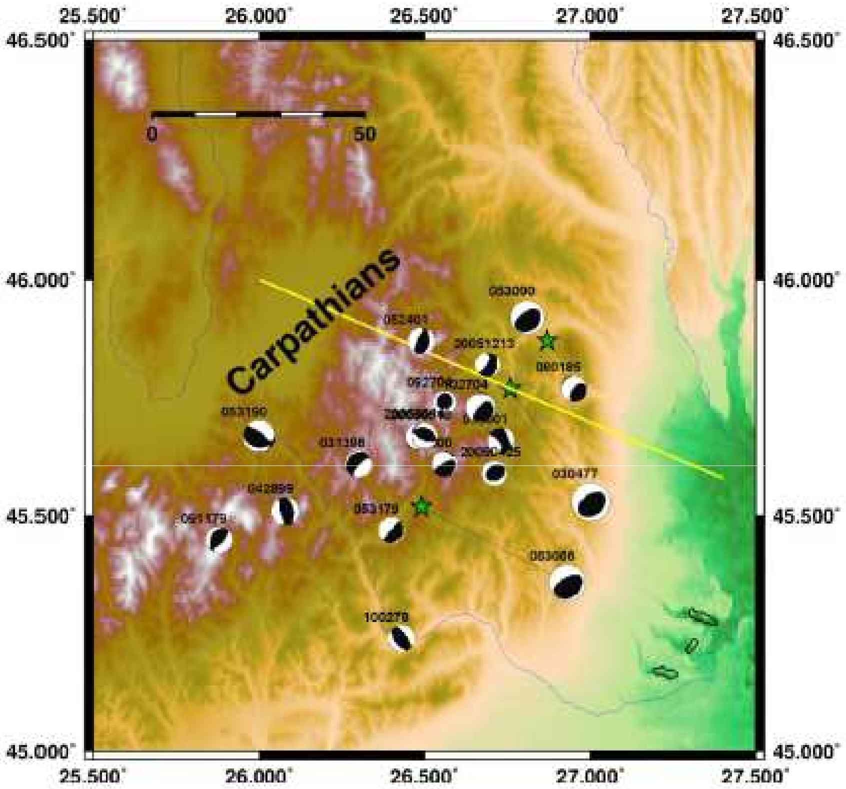
Specific patterns of seismicity in Vrancea

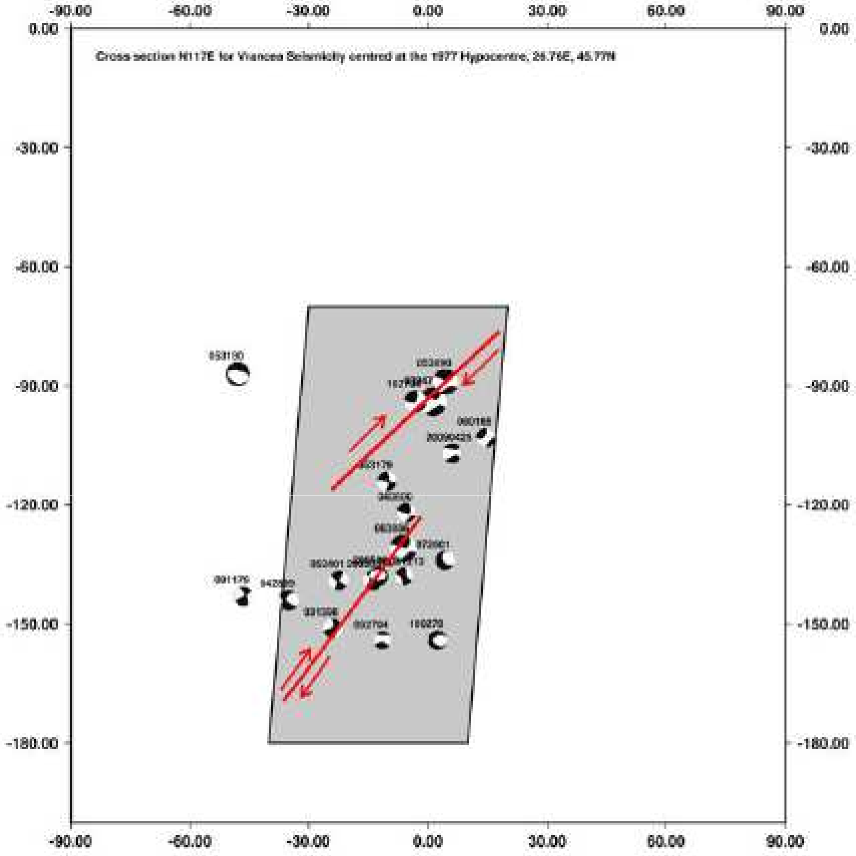
Variation of the b slope on depth in Vrancea (1995 – 2006 catalog)

Low b values indicate zones of high stress



Specific patterns of seismicity in Vrancea





CMT solutions for Vrancea earthquakes Mw > 4.8
http://www.globalcmt.org/

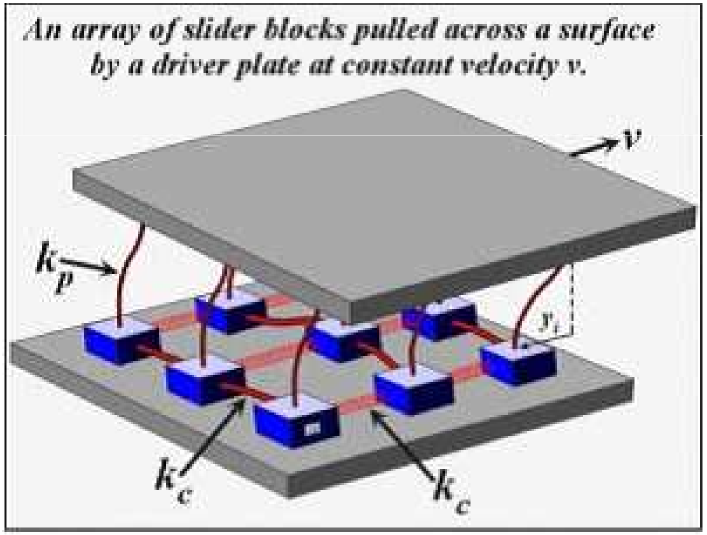
Ganas et al., 2010

Projected mechanisms indicate down-dip extension along west dipping planes. Possible two major planes of weakness in the slab.

Simulation algorithm

Cellular automata: simulation of interactions in a complex system of cells (faultlets)

Classical example of a an array of slider blocks connected through springs



An array of slider blocks pulled across a surface by a driver plate at constant velocity v.

Simulation algorithm

Stress inhomogeneities along the fault plane: asperities and barriers.

Asperity = hard region able to accumulate shear stress, surrounded by a softer region in which the stress drop is close to zero. The eq. initiates by asperity rupture and the failure spreads over the whole softer area.

Barrier = hard regions which cannot break. The shear stress accumulates over the whole source, while rupture and slippage occur only over the neighboring weak area.

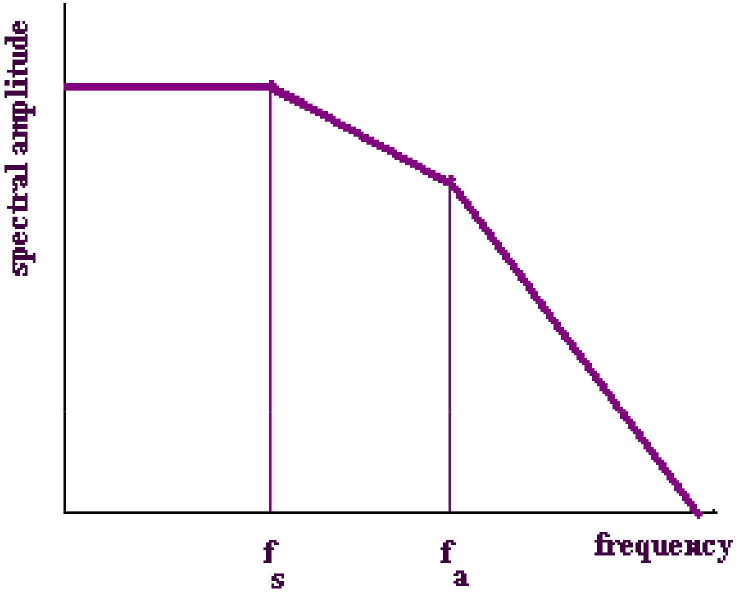
Lomintz-Adler (1985) postulated the existence of elementary fault areas, appropriate for small earthquakes and asperities. Moderate and large events were explained by the coupling of faultlets around the asperities.

Simulation algorithm

Trifu (1987) displacement spectra for 208 moderate size Vrancea earthquakes. Source characterized by two corner frequencies, one related to source dimension (r_s), the other related to asperity dimension (r_a).

The ratio r_a / r_s measures the source inhomogeneity (complexity). It decreases as the inhomogeneity level increases from 0.5 for M = 3 to 0.15 for M = 5.

The second corner frequency is found to be nearly magnitude independent



Two-corner displacement spectrum

Simulation algorithm

Definitions

Active zone = a distinct surface on the fault plane which is able to generate a major eq.

Crack-like failure = failure of a weak area surounded by barriers. Slip only over weak area.

Asperity-like failure = when surrounded by weak area the asperity fails due to the increase of the effective stress. Stress is released on asperity, while failure spreads over the whole softer area.

Major earthquake = the earthquake releasing the system at the end of a seismic cycle.

Simulation algorithm

Scholz and Aviles (1986): irregularities on the fault area are of the order of 0.1 – 1.0 km.

Trifu (1987): displacement spectra of Vrancea earthquakes show a second corner frequency of about 8-10 Hz. For a mean rupture velocity of $v = 0.8\ \beta$, with the shear wave velocity in the lower lithosphere $\beta = 4.5$ km/s, the asperity dimension is of the order of $v/f = 0.3\text{-}0.4$ km. This corresponds with the inhomogeneity range of Scholz and Aviles (1986).

The same dimension is obtained using the source complexity method (***Boatwright, 1984***).

Discrete structure means that an elementary characteristic surface characterizes asperity area (cell),

$$S_e = \pi r_a^2 = 0.38\ \text{km}^2$$

and every asperity-like eq. ruptures a finite number of elementary cells.

Izutani (1984) came to a similar conclusion for Japan.

Simulation algorithm

We postulate (ac. to ***Lomnitz-Adler, 1988***) the existence of three types of grid cells:

- cells of normal resistance (that we conventionally represent by ***white cells***)
- weak cells – ruptured cells by background earthquakes (that we conventionally represent by ***gray cells***)
- asperity cells – resistant cells that we conventionally represent by ***black cells***

Three characteristic rupture mechanisms are defined:

- ***crack-like type*** which rupture only white cells and release the stress on elementary areas (background seismicity)
- ***asperity-like type,*** which rupture asperities coupled with weak adjacent areas (moderate earthquakes)
- ***percolation type*** major earthquakes which broke major asperities coupled with percolation clusters.

Characteristic mechanisms

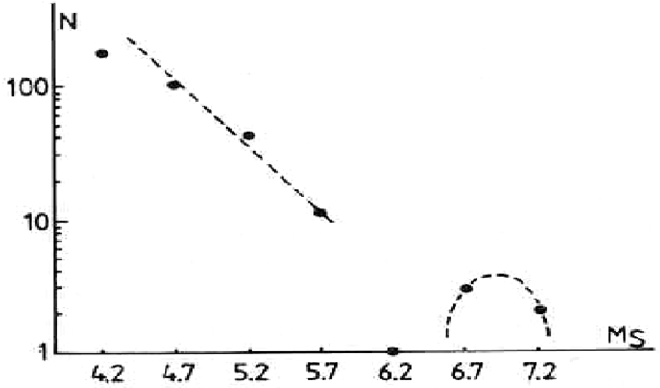


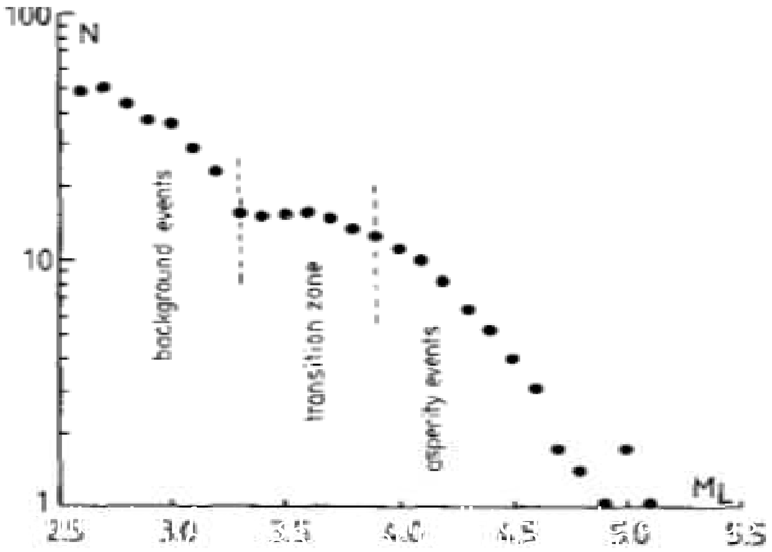
Figure 2
Noncumulative frequency-magnitude distribution of Vrancea intermediate depth earthquakes ($h >$ 60 km) occurred between 1936 and 1986.

- Deviations from self-similarity in the FMD.
- Three distinct parts:

(1) a linear decrease which characterizes the background seismicity;

(2) a relative bump, related to the threshold of the asperity-like eqs.;

(3) enhancement at largest magnitudes.



Typical distribution for Vrancea small-to-moderate eqs. 1 Oct. 1980 – 29 Aug. 1986 (after ***Radulian and Trifu, 1991***)

Simulation algorithm

Background seismicity

Small (single-cell) events of crack-like type are generated at constant rate randomly on the grid. They are characteristic for the first branch of the frequency-magnitude distribution.

The background activity generates single cells of weakness. During the cycle evolution they can link themselves in clusters and can link asperity cells.

Background earthquakes favor the transfer of effective stress on asperities.

Simulation algorithm

Asperity-like seismicity

Initially the asperity cells are distributed randomly in the grid. Single asperities and clusters of asperities are created this way. An index of strength is attributed to each asperity, function of its size.

The number of asperities injected in the grid should be enough to assure the production of the average asperity-like eqs. per cycle.

Simulation algorithm

Asperity-like seismicity

In case of cluster of asperities, the strength increases. Thus, in order to broke a cluster of N linked asperities, an adjacent area of weakness should be developed over a radius given by:

$$R(N) = \alpha\, 10^{\beta N}\, \Delta L$$

where α and β are constants, while ΔL is the linear dimension of the elementary surface.

The asperity strength decreases as stress free cells come in contact with it. The appearance of adjacent weakness areas leads to an increase of the effective stress on the asperity, equivalent with the decrease of its strength. The weakening mechanism considers the amount of stress-free area adjacent to the asperity cluster within a critical distance.

Simulation algorithm

Asperity failure

When the strength becomes zero, an asperity eq. is triggered with magnitude

$M = Me+3/2(\log(S/Se))/c,$

where S = sum of asperity cells + weak cells (contributing to the asperity failure, within the radius of action of the asperity - which increase with the size - measured from its centre of mass).

A background cell can contribute to the failure of more asperities (multiple event). In this case, the weak cells located within the intersection of circles of action are counted once.

Percolation theory

- Occupied surface (stress released surface) continuously increases in time.

- Grid-filling density = occupied surface/total surface

- Regardless of the grid type, there is a critical filling density (= 0.44) which implies a sudden transition from finite clusters to an infinite cluster (***Scher and Zallen, 1970***).

- Percolation – an intimate relation between small-scale ruptures, seismic area geometry and major shock.

Simulation algorithm

Healing procedure

We adopted in this stage a very simple procedure: after an asperity fails, the source area transforms into an white area (still able to be ruptured by small eqs.) and not gray area.

As concerns the gray areas, they remain stress-free areas all along the cycle interval. New insight in the seismicity pattern seems to indicate some healing process also at this scale.

This is an important constraint in the percolation process – otherwise the fusion of gray areas is too strong and the major shock is triggered too early.

The adopted healing procedure assures the *stability* of the eq. process simulation (tested using different parameters and random seeds).

Simulation algorithm

Major event triggering

A major event is ready to be produced when the gray cells can merge in avalanche covering the entire grid (domino effect).

A certain amount of time is required to get this critical state – which is an important parameter characteristic of each cycle.

Two conditions are required to trigger the major event:
(1) The percolation threshold is attained;
(2) The size of the triggered event is sufficiently high and increase with the time from beginning of the cycle

Major event = failure in avalanche of the resistance nuclei

Consequence: as the event is triggered later, as its size is larger.

Simulation algorithm

Model parametrization

- Seismic bidimensional active area
- Dimension and distribution of the elementary rupture cell
- Dimension and distribution of the elementary asperity cell
- Level of occupation with asperity cells at cycle initiation
- Average rate of generation of background seismicity
- Minimum clustering degree to broke an asperity cell
- Erosion of asperity cluster mechanism
- Strategy and average rate of healing

Simulation algorithm

Implementation for the lower segment

Depth range: 110 – 170 km

Zone area = 52 x 45 km^2

Liniar dimension of the elementary cell = 0.65 km

Number of elementary cells: 80 x 70 = 5600

Rate of background seismicity = 50 earthquakes/year

Number of asperities ~ 900

Threshold magnitude for asperity-type earthquakes = 3.9

Simulation algorithm

Simulation algorithm

Two kinds of seismicity:

-Background (3.-3.9) which develops randomly shear-free surfaces, with a constant rate (50 per year). Affects only an elementary surface;

-Asperity-like (~20 per year), resulting from rupture of harder areas, and requires a minimum, critical, low shear stress surfaces around

Seismic cycle begins with locking of the active zone following a major earthquake; initially the grid (70 x 80) contains only unbroken cells of weak resistance and asperity cells.

The initial number of asperity clusters has to be large enough to ensure that the number of asperity-like earthquakes in a cycle is around 850 which covers not only asperity-like earthquakes that Vrancea region requires for a cycle, but also possible simultaneous failures (multiple events) and asperities that remain unbroken after the major earthquake.

Simulation algorithm

Example of simulation

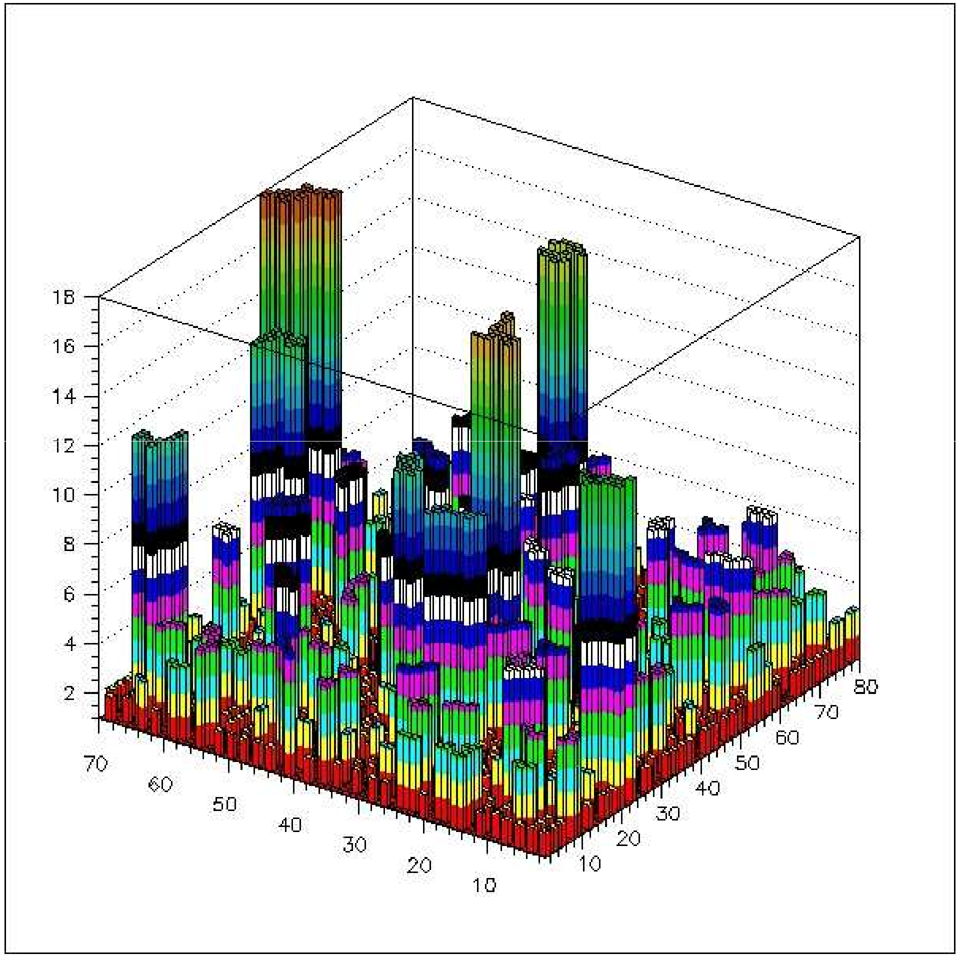
Cycle duration = 39 years.

Fusion of clusters is triggered when the critical density is 36% (as compared with 44% for a pure percolation process).

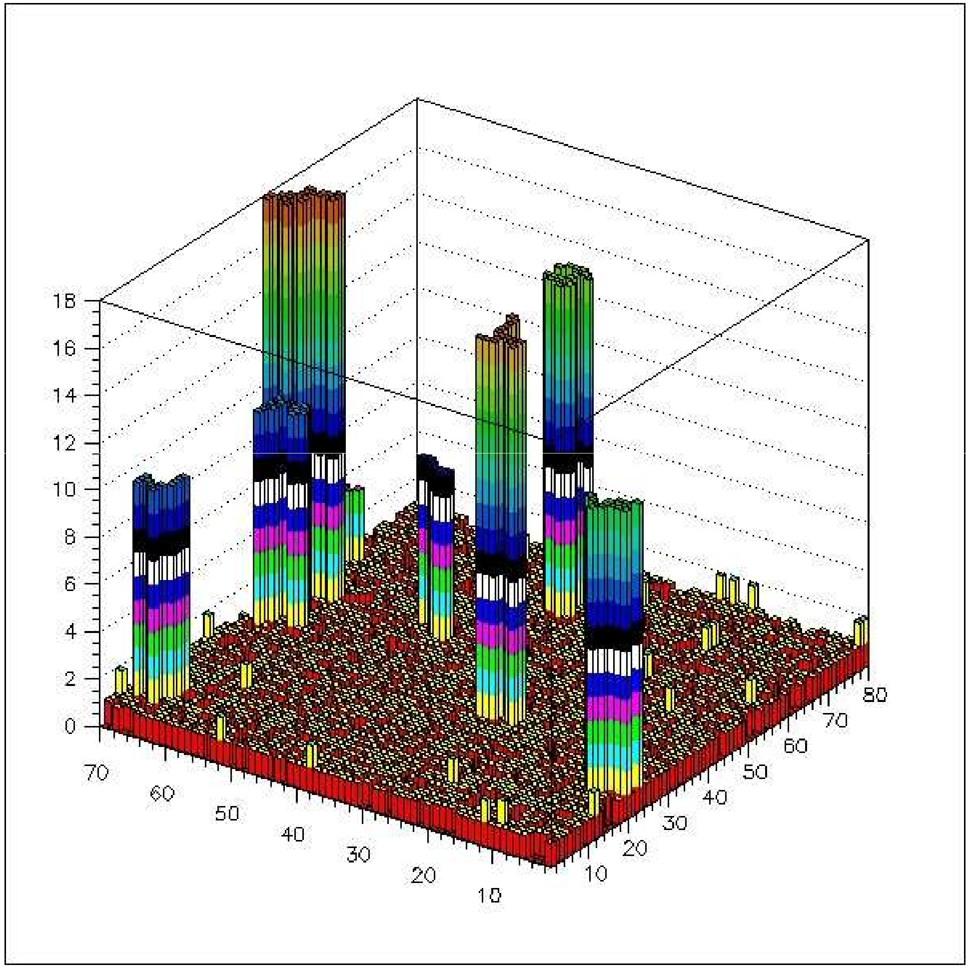
Simulated magnitude = 7.1 (triggered by the failure of a 10-cell asperity).

Large asperity clusters (of 13 and 14 cells) remain unbroken in this seismic cycle.

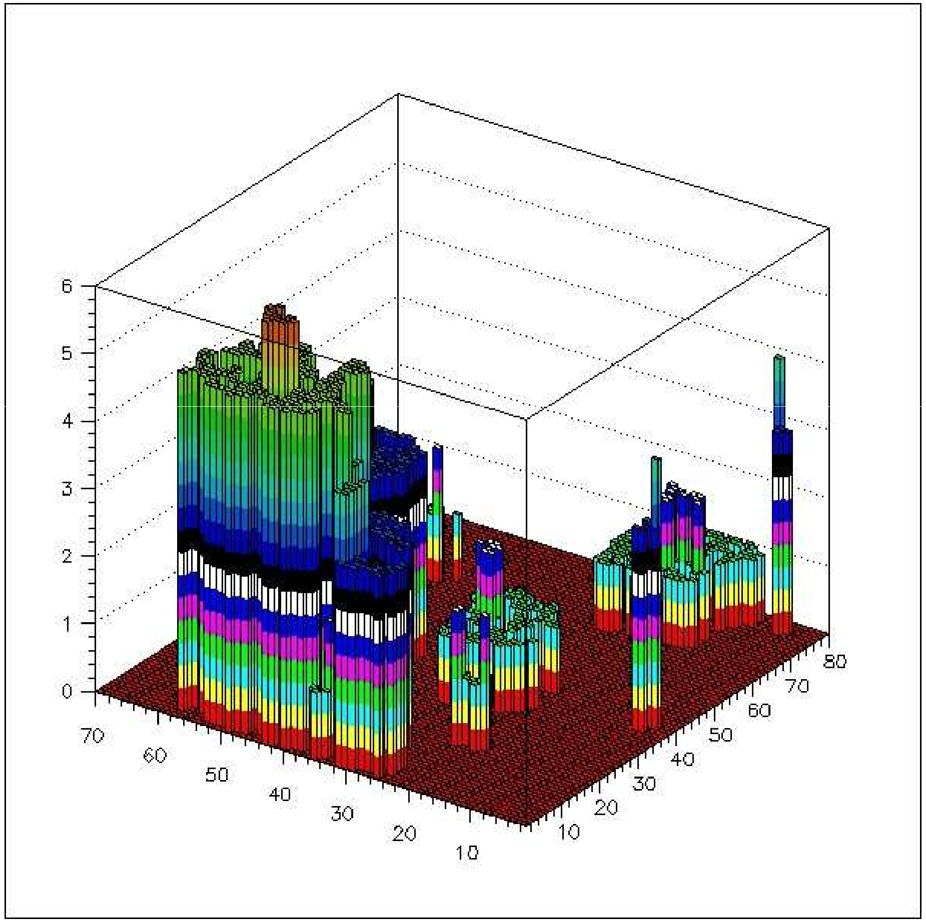
Sample initial grid configuration



Remaining asperity clusters



Major event and associated fore- and after-shocks



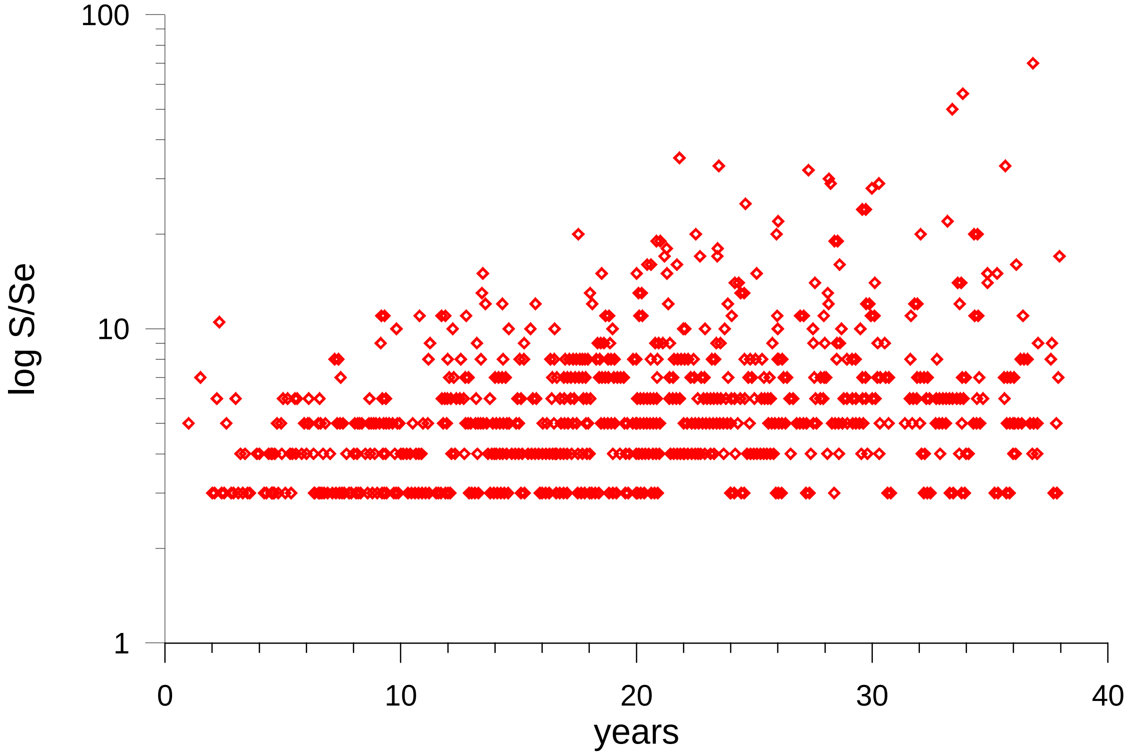
Simulation algorithm

Eq. size tends to increase in time as approaching the major eq. triggering.

Eq. deficit immediately after the previous major eq.

Sometimes asperity production tends to exhaust before the major eq. triggering.

Clearly this behavior depends on the way the asperity are broken and on the healing process.



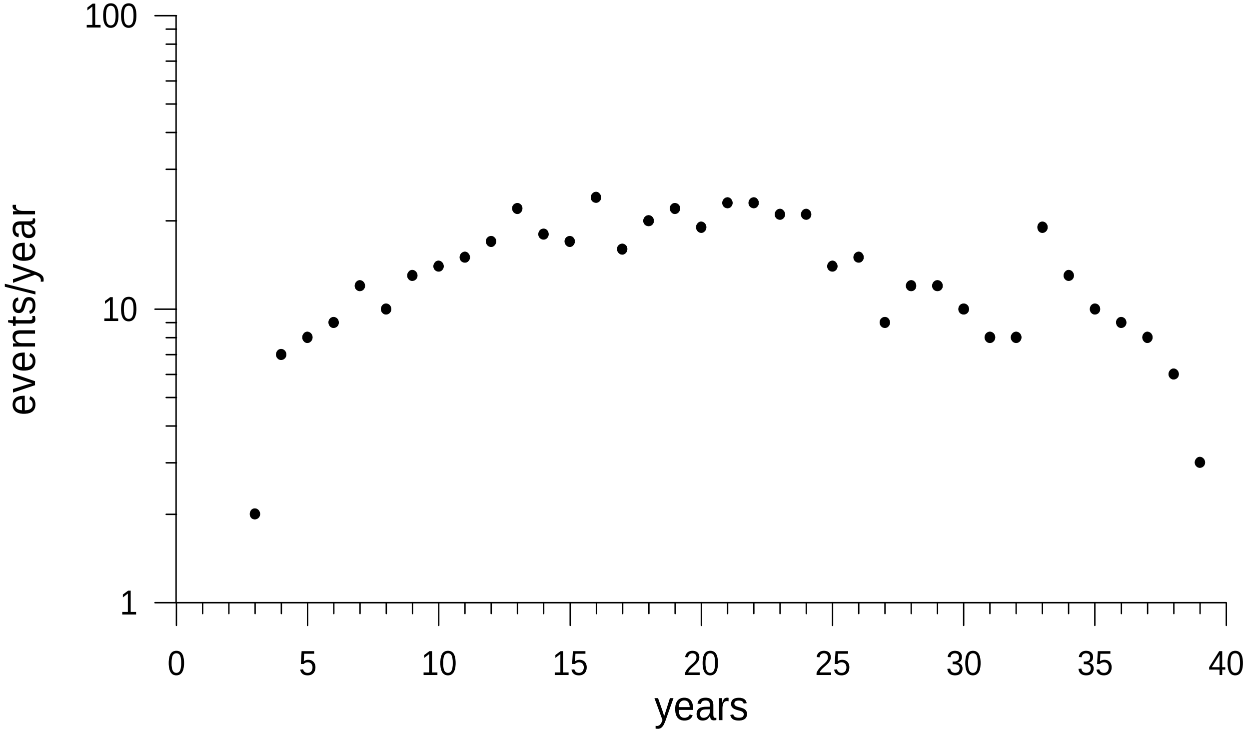
Asperity-like earthquake production along the simulated cycle (size/year)

Simulation algorithm

For a long time interval the rate of asperity-like events is rather constant (10-20 events/year).

A time interval of about 5-7 years is required to develop enough free surfaces to obtain the stationary regime.

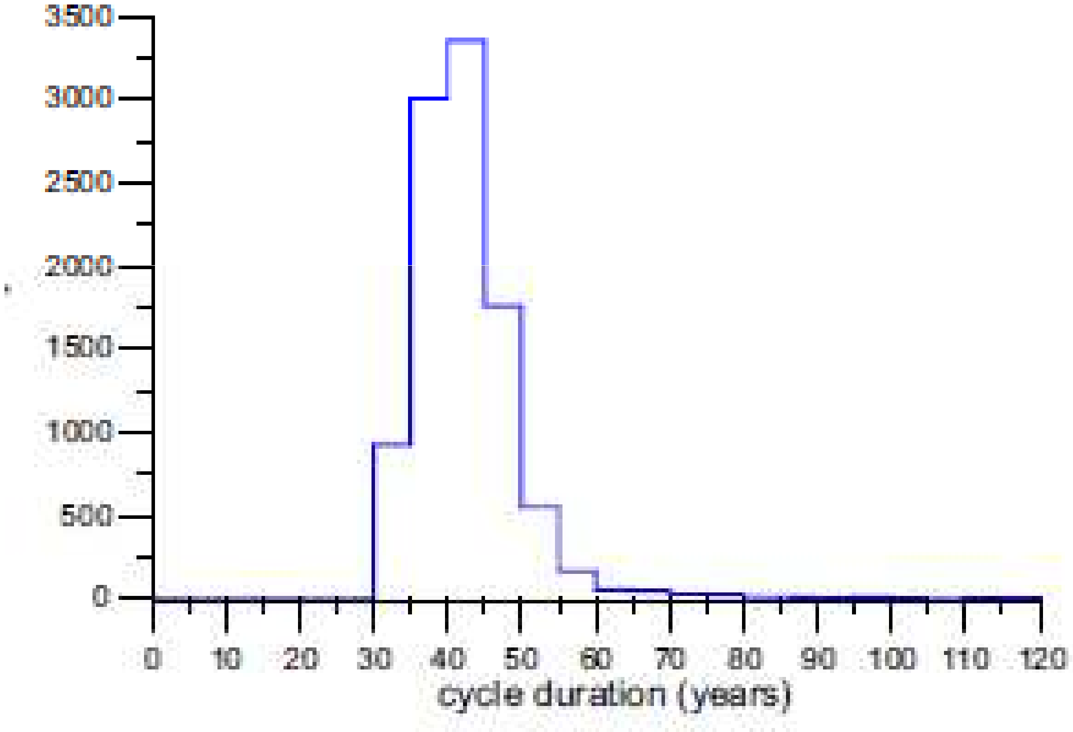
A deficit appears before major eq. occurrence. this seems to be qualitatively the real situation



Asperity-like earthquake production along the simulated cycle (number/year)

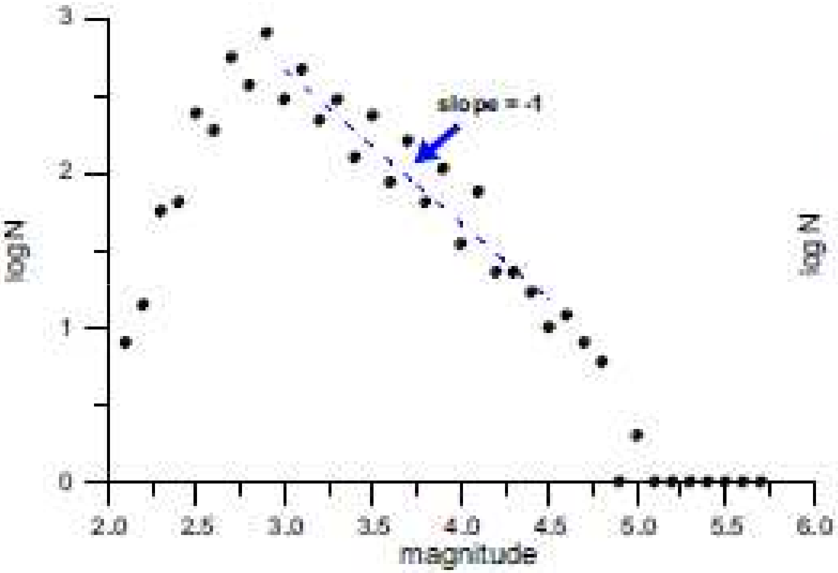
Simulation algorithm

Multiple simulations

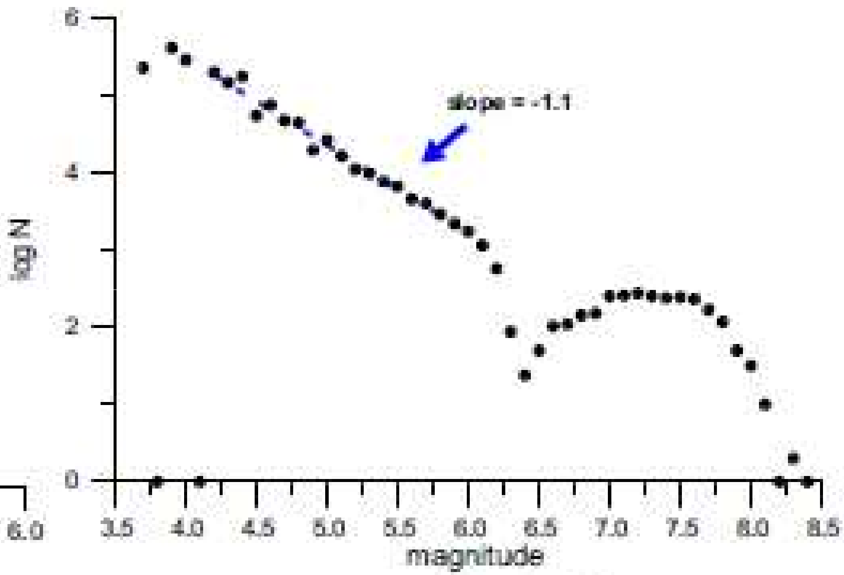


Simulation algorithm

Frequency-magnitude distribution



Real data



Simulated

Conclusions

Geometrical features

- hypocentre distribution delineates an approximate 2-D vertical structure oriented NE-SW, parallel to the Carpathians Arc Bend

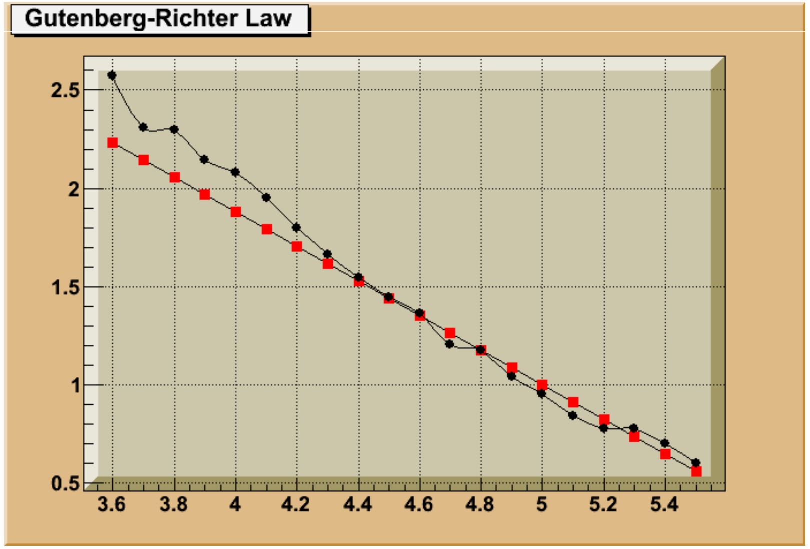
- refined investigation of the relocated events - a possible double fault structure with two vertical parallel planes in the upper and lower segments shifted a few km apart around 100 km depth

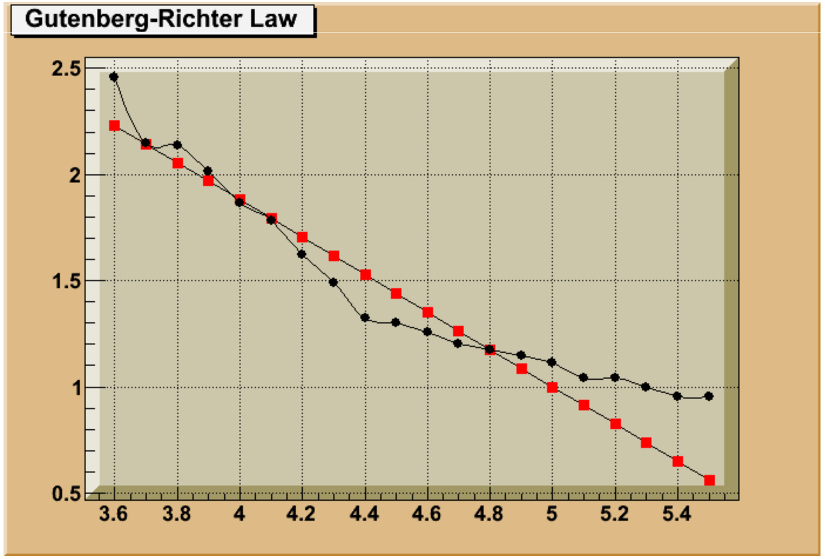
- correspondence between seismicity geometry and predominant faulting mechanism

Conclusions

Frequency-magnitude distribution

- non-linear distribution
- it follows Gutenberg-Richter law at small-to-moderate earthquakes
- seismicity deficit in the 6-7 magnitude range





Conclusions

Implementation of simulation algorithm

➢ A simulation 2D algorithm with percolation working in cascade: stress is gradually released during the seismic cycle: first on the weakest zones (by background seismicity), then on the stronger zones (asperities) and finally by the major earthquake (at the scale of the entire seismogenic zone).

➢ Basic hypotheses:
  - the generation mechanisms are qualitatively different;
  - existence of two seismic active segments;
  - existence of a critical minimum area to release the stress.

➢ The algorithm allows simulation of the seismic process for one cycle, or successive multiple cycles.

Conclusions

- Percolation occurs when a critical weak surface is developed on the seismogenic area. For the Vrancea source geometry, an eq. is generated by percolation starting with magnitude about 6.5.

- The average duration per cycle on the lower active segment is 40-50 years

- Simulation can generate or not precursory activity.

- The asperities remained unbroken at the end of the cycle continue to act in the next cycle.

- Simulation modeling allows the constrain the major ***magnitude range*** for a particular active zone and the range of corresponding return periods (40-100 years).

- The predicted ***maximum possible magnitude*** is $M_w = 7.6$ and $M_w = 7.8$ for the upper and lower active segment, respectively.

Implications

- Seismic cycle modeling: existence of two seismic active segments with somewhat independent activity and alternative triggering of major shocks

- A particular geometry of the seismicity pattern, which looks like to be time independent

- Existence of high density of foci indicates a fast healing process

- Generation process of major shocks is closely linked to the background seismicity space-time evolution

Future developments

- New tests to estimate the critical magnitude threshold in Vrancea
- Coupling between the active segments
- Calibration of healing process
- Reconsidering the historical information (macroseismic and instrumental)
- Modeling of aftershock activity
- Coupling from one cycle to the other