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Block-Structure Modeling of Vrancea (Romania): Study of Seismic Regime

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Introduction

The block structure modeling of geodynamics and seismicity is the powerful tool for the study of a number of problems.

The model is designed to study seismicity and its connection with geodynamics in the certain region. A seismically active region is modeled as a system of absolutely rigid blocks separated by infinitely thin plane faults (*Soloviev and Ismail-Zadeh*, *2003*). The system of blocks moves as a consequence of prescribed motion of the boundary blocks and of the underlying medium. As the blocks are absolutely rigid, all deformations take place in the fault zones and at the block base in contact with the underlying medium. Relative block displacements take place along the fault zones. The interaction of the blocks along fault zones is viscous-elastic ("normal state") so as far as the ratio of the stress to the pressure remains below a certain strength level. When the critical level is exceeded in some part of a fault zone, a stress-drop ("failure") occurs in accordance with the dry friction model, possibly causing failures in other parts of the fault zones. In our model the failures represent earthquakes. As a result of the numerical simulation a synthetic earthquake catalog is produced.

The model is regionally oriented: it allows taking into account realistic geometry of the fault network, including the depth and dip angles of faults as well as directions and velocities of the tectonic motions in the region under study. Model reproduces the whole ensemble: tectonic driving forces => geodetic movements => creep => earthquakes. The model allows to reproduce not only general features of seismicity like Gutenber-Richter law, but a number of regional details: space distribution of epicenters; relative level of seismic activity in the different faults; type of the fault plane solutions.

Input data for modeling are:

- Geometry of the block structure including the depth of layer and dip angles of the fault. The block structure can be outlined on the base of seismotectonic or morphostructural scheme of the region under study. Profiles and the seismicity data including fault plane solutions are useful as well for the determination of the depth of the layer and dip angles of the faults.
- Driving forces that are rates and directions of tectonic motions of boundaries of the block structure and of the underlying medium. Geodetic and GPS data can be used.
- Rheology: visco-elastic features of faults and block bottoms; conditions of earthquake occurrence.

Output:

- Movements of the blocks, including rotations.
- Synthetic earthquake catalog; each earthquake has origin time, coordinates of hypocenter, magnitude, fault plane solution.

Criteria of modeling quality depends on the task, but mainly it is reproducing of the directions of tectonic motions in the region and reproducing of main features of observed seismicity: epicenter distribution, location of the large events, type of the source mechanisms, Gutenberg-Richter relation.

The goal of the present work is studying temporal patterns of seismicity in the process of large earthquake preparation. The duration of instrumentally recorded earthquake catalogs is short, usually it does not exceed several decades. The reoccurrence time of large events in the same place is usually tens to thousand years. The numerical modeling of seismicity allows to generate long catalogs of synthetic events, that gives a possibility to estimate more reliable the parameters of seismic flow, to study the process of large earthquake preparation and to check the hypothesis in the earthquake prediction.

Seismoactive region of Vrancea (Romania)

The Vrancea is the one of the most seismically active regions in the Europe. It is characterized by small size of focal volume and high level of intermediate depth seismic activity. The distribution of epicenters for intermediate depth earthquake with magnitude M≥5.0 is shown in the Figure 1.

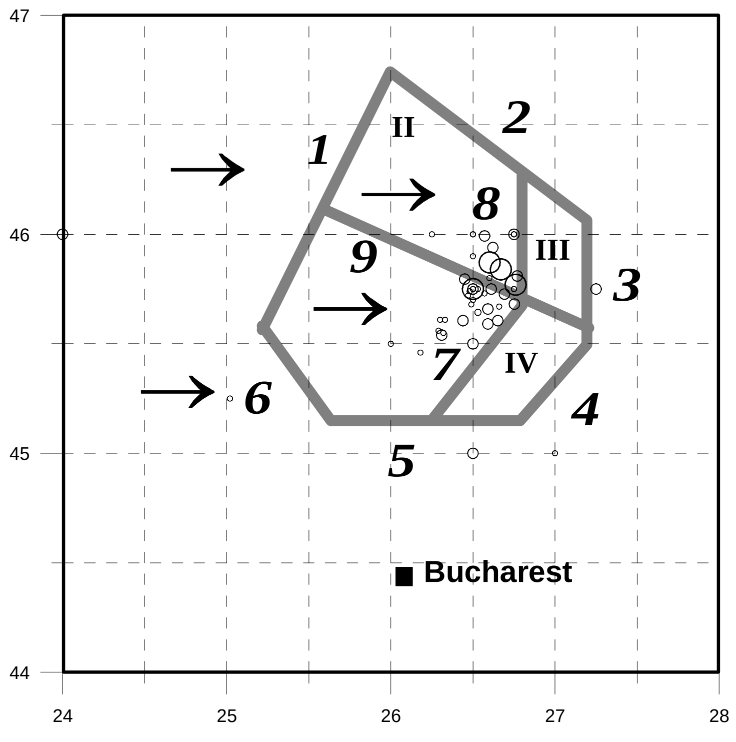

Figure 1. Observed seismicity of Vrancea and the block structure. ***1-9*** *– faults,* **I-IV** *– blocks, arrows – prescribed motions.*

The seismic activity of Vrancea is generated in paleosubduction of the lithospheric fragment from SE to NW (Constantinescu and Enescu, 1984). Four catastrophic earthquakes with a magnitude 7.0 and greater, occurred during XX century (Table 1).

Table 1. Large earthquakes in Vrancea from 1900.

Date	*latitude*	*longitude*	*depth*	*M*	*Fault plane solution Harvard catalogue (CMT, 1994)*		
					Strike	*Dip*	*Slip*
1940 11 10	45.80N	26.70E	133	7.4			
1977 03 04	45.78N	26.80E	110	7.1	235	62	92
1986 08 30	45.51N	26.47E	138	7.0	240	72	97
1990 05 30	45.83N	26.74E	90	7.0	236	63	101

These earthquakes caused heavy destructions not only in Romania, but in other European countries. Therefore the study of Vrancea seismic regime is extremely important, also considering the fact that in the territory, that can be shaken by such events several nuclear power plants are presently operating.

Another reason to choose the Vrancea region for the present study is its small volume: – sesmicity is concentrated in the area with linear size about half of degree. So we can content our self with studying of temporal patterns of seismicity and do not take into account the space distribution of earthquakes.

Block structure of Vrancea

The block structure of Vrancea seismoactive region was outlined on the base of the morphostructural scheme. It consists of four blocks delimited by nine faults; it is shown in Figure 1. The depth of the layer is 200 km, which corresponds to the deepest events in this area. Fault 1 represents the western edge of the Carpathians; fault 8 is the eastern edge. Fault 7 is the Vrancea sudduction. The dip angle for subduction is chosen 70^o. This value corresponds to the known fault plane solution of large Vrancea earthquakes (See Table 1). The western boundary of the structure moves in the eastern direction as well as the medium underlying blocks I and II.

Modeling of seismicity in the Vrancea region.

The general features of seismic regime in the model strictly depend not only on geometry of the structure and prescribed velocities of tectonic motions, but on the rheological features of the faults as well. There is information about the geometry of the fault network and tectonic motions in the region, while the rheological features are not so clear.

The task for the first stage of the investigation is to get synthetic seismicity with the features similar to the observed one; i.e. seismisity must be concentrated in the Vrancea subduction zone and have similar Gutenberg-Richter plot.

The numerical simulation was done for 200 unit of non-dimensional time. We vary the rheological features of the faults that represent the Vrancea subduction zone. In the model rheological features of fault are controlled by the rates of inelastic displacement in the normal state and after earthquake. As larger is the rate of inelastic displacement, as larger part of stress is realized by creep. This value also controls the redistribution of stress in the fault planes.

The earthquake sequences obtained for different rheology are shown in the Figure 2.

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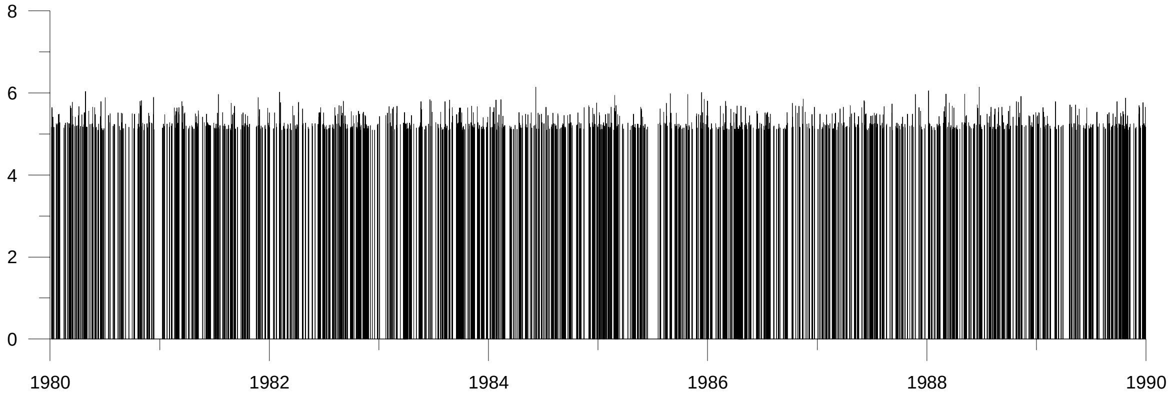

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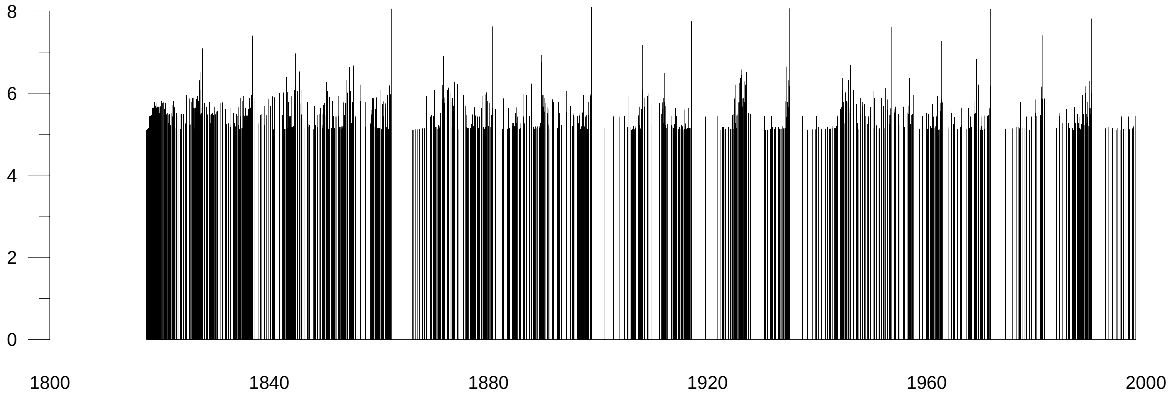

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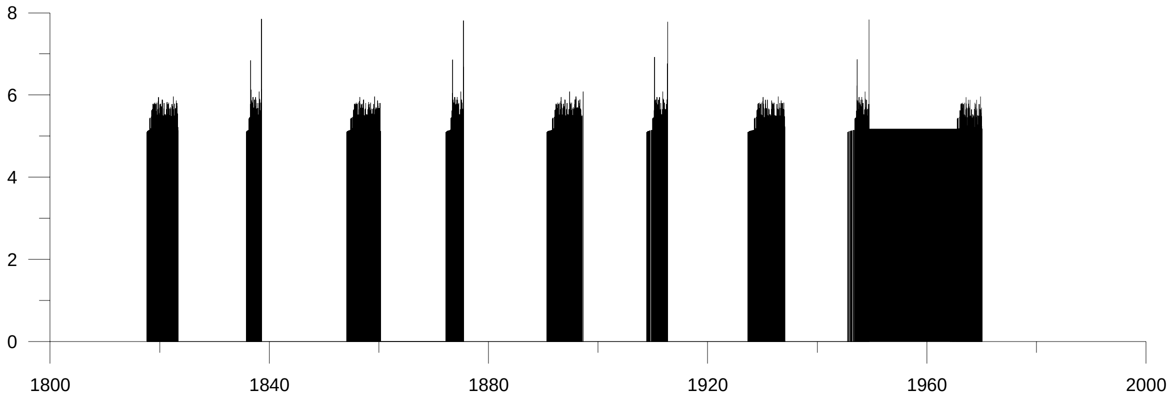

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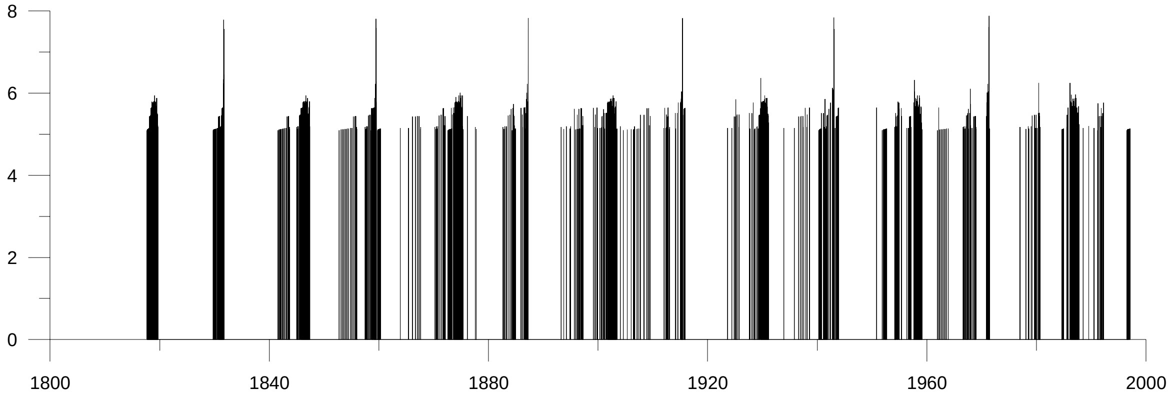

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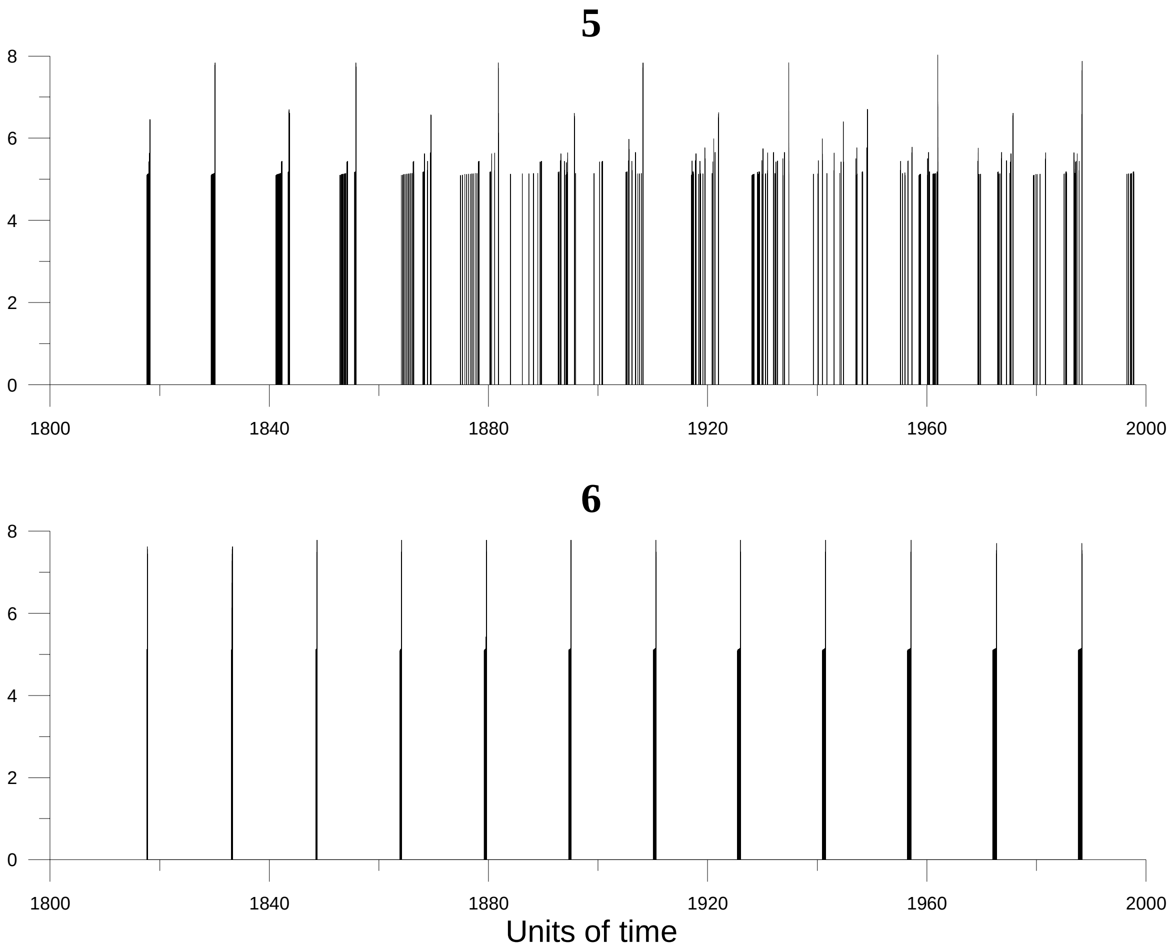

Figure 2. Temporal sequences of synthetic earthquakes generated for different rheology of the Vrancea subduction.

When the rate of inelastic displacement *W* is small the model produces very large number of earthquakes, but all of them are small (Figure 2.1). This can be explained by the fact that redistribution of stress is small, so the critical level of the stress can not be reached simultaneously in the large area that is a condition for large earthquake occurrence. With the growing of *W* the seismic regime changes: large events and periods of seismic quiescence appear. With the further growing of *W* model produces periodical sequence of very large earthquakes only. Among the obtained synthetic catalogs we chose the 5th one which has Gutenberg-Richter plot similar to the observed one (Figure 3).

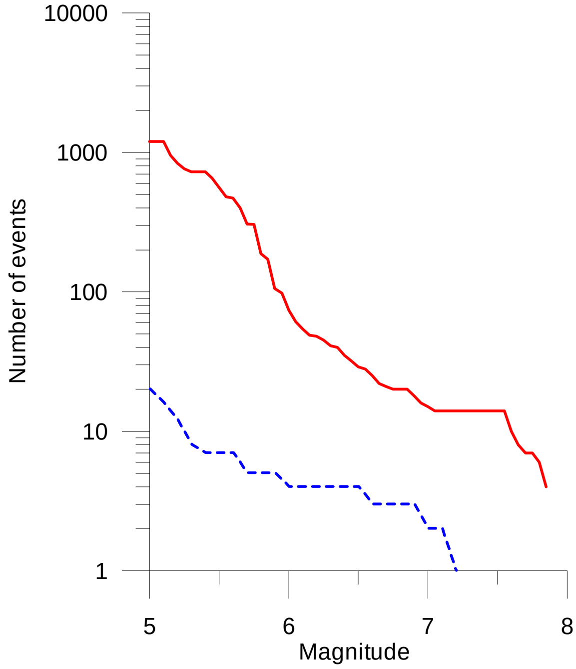

Figure 3. Gutenberg-Richter plot for synthetic (variant 5) and observed earthquakes.

The dashed line is the graph for the observed events. It is seen the presence of the characteristic earthquakes (*M*>7) in the model. The slope of the graphs in the linear part (6<M<7) is close and they have similar shape. The maximum magnitude of the synthetic earthquakes is 7.8; this is close to the maximum recorded magnitude 7.4. The distribution of the epicenters for the synthetic earthquakes is sown in Figure 4

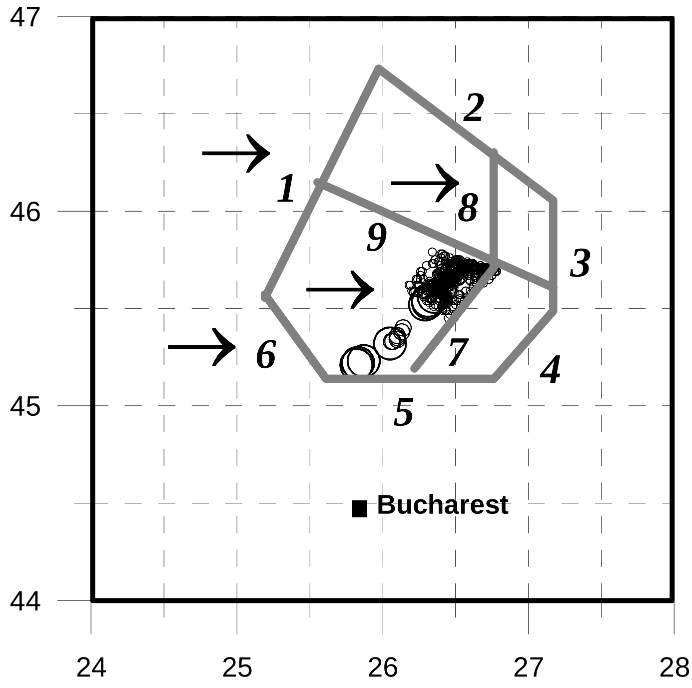

Figure 4. Epicenter distribution of synthetic seismicity.

It is close to the observed one shown in the Figure 1. The most active place is connected with the intersection of the faults 7, 8 and 9, that represent the Vrancea subduction zone.

Temporal patterns of synthetic seismicity before large earthquakes.

In the first stage of work the parameters of the model were fitted to recover integral features of the regional seismicity, like epicenter distribution and frequency of occurrence relation. In the present stage we study the temporal patterns of synthetic seismicity before large events. The numerical simulation is done for longer period - 2000 units of non-dimensional time. In the study, the second part of the catalog for the period 1000-2000 units of time has been used, to exclude the influence of the beginning stage of the simulation with zero initial stresses. The synthetic catalog contains about 6500 events with magnitude in the range 5.0 – 8.1. The moments of time when strong earthquakes with the magnitude 7.5 and more occurred are shown in Figure 5.

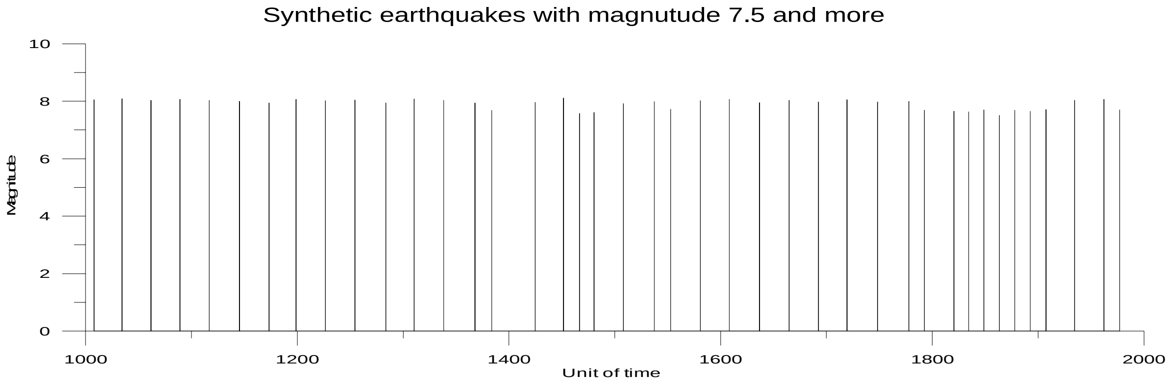

Figure 5. Synthetic earthquakes with M ≥ 7.5

It is seen, that they occur almost periodically, this periodicity breaks in the last part of the catalog. Nevertheless, the seismicity patterns before large earthquakes are different. The patterns before 3 large earthquakes are shown in the Figure 6.

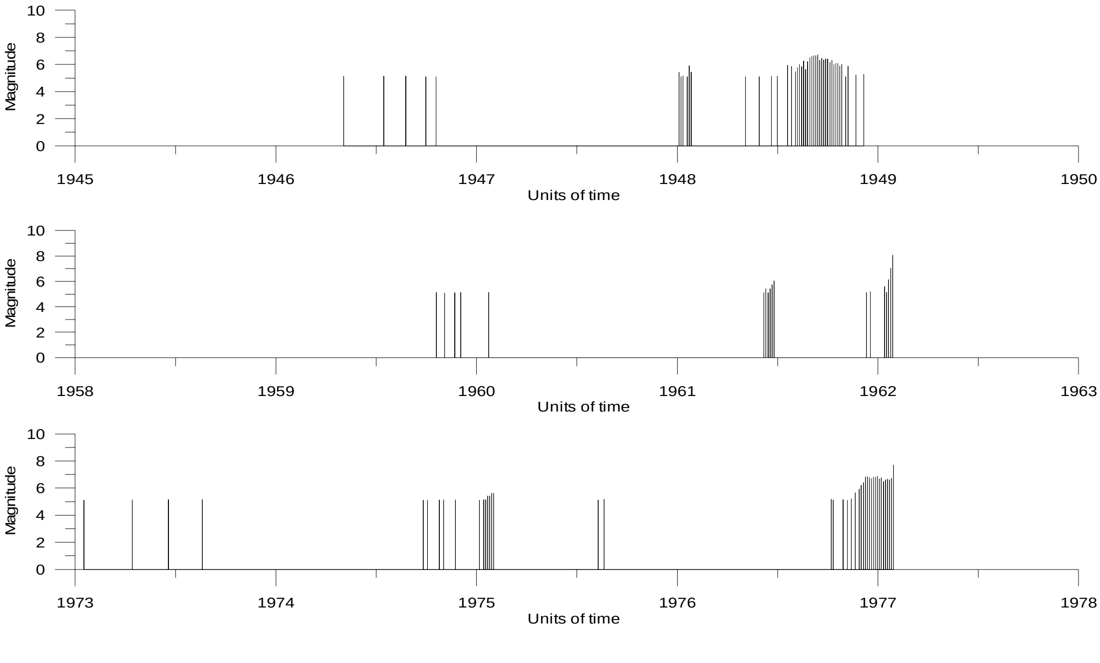

Figure 6. Temporal seismisity patterns before three large synthetic earthquakes in Vrancea

They are different but have some common features: in the beginning, in the background of the seismic quiescence single earthquakes appear, then clustering of events is observed, and then large earthquake occurs in the background of high seismic activity. These features appear before the most of large earthquakes in the synthetic catalog. The observed sequence of Vrancea earthquakes is shown in the Figure 7. One can see the similar patterns before observed large events.

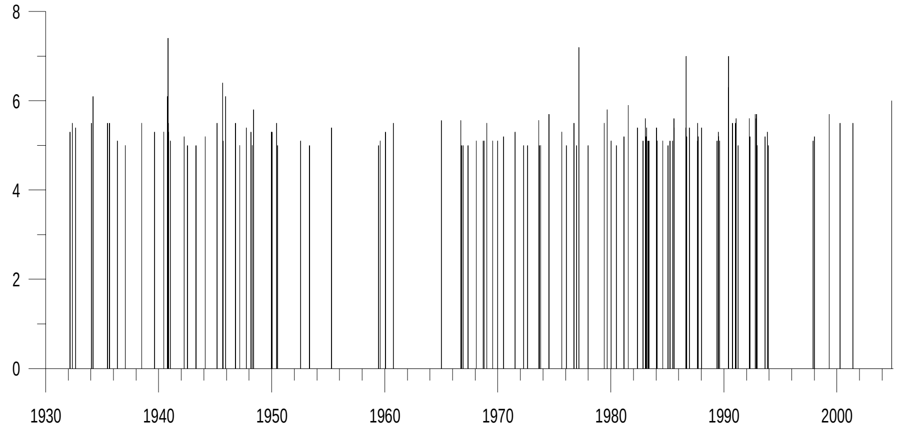

Figure 7. Temporal seismisity patterns before three large observed earthquakes in Vrancea

This scenario is in good agreement with the hypothesis of non-linear dynamics of the Earth. The behavior of many non-liner systems before collapse has similar features: the response to the small perturbation grows, that is reflected in the growing of activity, clustering, etc. In our case the non-linear system is the system of seismogenic faults, small earthquakes are the sources of the perturbation, the large earthquake represents the collapse of the system.

Prediction of large earthquake in the block-structure dynamics model

The intermediate term earthquake prediction algorithm CN was designed on the basis of the idea of non-linear dynamics of the Earth (Keilis-Borok & Rotwain, 1990). It was developed for prediction of the large earthquakes in California and Nevada and then was successfully applied in the number of other seismoactive regions of the world including Vrancea (Novikova et al., 1996).

We applied the CN algorithm to the synthetic seismicity of the Vrancea. We assign the one unit of non-dimensional time is equal to one year. In this time scale we have 300-350 earthquakes during 100 years, 4-6 of them are strong (magnitude more than 7.5). The standard CN algorithm uses the catalog of the main shocks, and the number of aftershocks is a very important characteristic of the preparation process of the large earthquakes. The block structure model of seismicity in general does not produce aftershocks; so we do not exclude aftershocks but use the whole catalog; the number of aftershocks is substituted by another characteristic of clustering: the number of events following the earthquake in the next 30 days. All the other functions of CN algorithm are standard. The last 100 units of time have been used for the learning, and then the algorithm has been tested considering the two previous periods, of 100 units each.

The result of learning is presented in Table 2. Four strong earthquakes occurred in the learning period, all of them were predicted, and the percentage of the alarm time was 28.8%.

The result of test is presented in Table 3. In the two test periods the strong earthquakes were 3 and 6, respectively, and the percentage of the alarm time were 30.2% and 23.9%, respectively. All 9 strong earthquakes were successfully predicted.
The results of CN application are also shown in Figure 8. Large earthquakes, $M \geq 7.5$, are marked by asterisk, true alarms are rose, and false alarms are dotted. One can see that many false alarms precede quite strong events with magnitude more than 7.

Table 2. Results of learning

Start of alarm	Large earthquakes Date	M	End of false alarm	Duration of alarm (months)
1. 3.1904	11. 5.1907	7.7		38.3
1. 5.1910			1. 5.1911	12.0
1. 1.1915			1.11.1918	46.0
1. 1.1920			1. 3.1925	62.0
1. 7.1928			1. 5.1932	46.0
1. 5.1934	25. 7.1934	8.0		2.8
1. 3.1948			1. 9.1952	54.0
1. 1.1961	3. 2.1962	8.1		13.1
1. 3.1975	1. 2.1977	7.7		23.0
1. 7.1988			1. 5.1991	34.0

Total number of strong earthquakes = 4
4 earthquakes have been predicted
Total duration of alarm time = 331.2 months (28.8% of total time)

Table 3. Results of tests

Start of alarm	Large earthquakes Date	M	End of false alarm	Duration of alarm (months)
1. 1.1706			1.11.1710	58.0
1. 1.1719	23. 8.1719	8.1		7.7
1. 7.1732			1. 9.1738	74.0
1.11.1745	10. 6.1748	8.0		31.3
1. 1.1758			1.11.1762	58.0
1. 3.1763			1. 9.1767	54.0
1.11.1771			1.11.1775	48.0
1. 9.1777	21.11.1777	8.0		2.7
1. 9.1792			1.11.1792	2.0
1. 9.1795			1. 9.1796	12.0

Total number of strong earthquakes = 3
3 earthquakes have been predicted
Total duration of alarm time = 347.7 months (30.2% of total time)

Start of alarm	Large earthquakes Date	M	End of false alarm	Duration of alarm (months)
1. 9.1806			1.11.1806	2.0
1. 9.1809			1. 9.1810	12.0
1. 1.1820	9. 9.1820	7.7		8.3

1. 9.1823			1. 9.1824	12.0
1. 7.1833	15. 9.1834	7.6		14.5
1. 9.1837			1. 9.1838	12.0
1.11.1846	2.11.1848	7.7		24.0
1. 5.1860	29. 4.1863	7.5		35.9
1. 5.1874	9.12.1877	7.7		43.3
1. 7.1886	28. 9.1892	7.7		74.9
1. 9.1895			1. 9.1896	12.0
1. 1.1898			1. 1.1900	24.0

Total number of strong earthquakes = 6
6 earthquakes have been predicted
Total duration of alarm time = 274.9 months (23.9% of total time)

Figure 8. Results of CN applying to the synthetic seismicity of Vrancea. Large earthquakes M≥7.5 are marked by asterisk, rose rectangles are true alarms, dotted rectangles are false alarms

Conclusions

The model of the block and faults structure dynamics is the powerful tool for study of the wide range of the geophysical problems. The model is able to generate very long synthetic earthquake catalog that recover not only general features of the seismicity, like Gutenberg-Richter relation, but demonstrates the number of regional details, like epicenter distribution, location of the large events, type of fault plane solution. The analysis of the temporal patterns of the synthetic seismicity demonstrates non-trivial behavior of the model. The scenario before large events occurrence is different, but has some common features, like premonitory growth of seismic activity, clustering of seismic events in time before large events. The similar changes of seismic flow were found out in the observation. This scenario is in good agreement with the hypothesis of non-linear dynamics of the Earth.

The successful application of the CN algorithm for prediction of the large synthetic earthquake demonstrates that the Block Structure Model is able to recover many subtle features of the observed seismicity. It gives a possibility for studying of seismic regime, reliable estimation of its parameters, and developing of the earthquake prediction methods.

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