MODELLING OF STRESS AND SEISMICITY IN THE SOUTH-EASTERN CARPATHIANS

A Basis for Seismic Risk Estimation

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1. Introduction

The vulnerability of the human civilisation to natural disasters is growing due to proliferation of high-risk objects, clustering of population, and destabilisation of large cities. Today a single earthquake may take up to a million lives, cause material damage up to several billions EURs with chain reaction expanding to world-wide economic depression, and trigger major ecological catastrophe (e.g. several Chernobyl-type calamities at once). In many developing countries the damage from earthquakes consumes all the increase in the GNP.

Problems of estimating risks of natural catastrophes are becoming highly important. In the last few decades a number of concepts of risks of natural catastrophes have been suggested and a number of international projects on safety and risk management have been conducted. Serious difficulties in decision making in these fields are concerned with strong uncertainties in data and limitations in using mathematical tools for carrying out the historical analysis and forecasting.

Seismic risk is a measure of possible damage from earthquakes. An estimation of seismic risk may facilitate a proper choice in a wide variety of seismic safety measures, ranging from building codes and insurance to establishment of rescue-and-relief resources. Different representations of seismic risk require different safety measures. Most of the practical problems require to estimate seismic risk for a territory as a whole, and within this territory separately for the objects of each type: areas, lifelines, sites of vulnerable constructions, etc. The choice of the territory and the objects is determined by the jurisdiction and responsibility of a decision-maker.

Each specific representation of seismic risk is derived from the primary models of geodynamics, stress generation and earthquake occurrences, strong motions caused by a single earthquake, the territorial distribution of population, property, and vulnerable objects, and the damage caused by an episode of strong motion.

In this study I focus on models of stress generation and earthquake occurrence. Stress accumulation and its release in earthquakes are governed by non-linear hierarchical systems, which have a number of degrees of freedom and, therefore, cannot be understood by studying them piece by piece [1]. Since an adequate theoretical base has yet not been well elaborated, theoretical estimation of statistical parameters of earthquake flows is still a highly complex problem. Studying seismicity using the statistical and phenomenological analysis of real earthquake catalogues has a disadvantage that instrumental observations cover, usually, too short time intervals compared to the duration of the tectonic processes responsible for seismic activity. The patterns of earthquake occurrence identifiable in a real catalogue may be apparent and may not be repeated in the future. Moreover, the historical data on seismicity are usually incomplete and do not cover uniformly a region under consideration. Numerical modelling of seismogenic processes allows to overcome these difficulties. Synthetic earthquake catalogues formed via numerical simulations may cover very long time intervals and, therefore, provide a basis for reliable estimates of the parameters of the earthquake flows [2, 3].

In section 2 I discuss the specific features of seismicity and geodynamics in the SE-Carpathians. Several large earthquakes in the XXth century occurred in the region. Section 3 presents the study on models of mantle flow and tectonic stress induced by the descending Vrancea slab. In section 4 a model of block-and-fault dynamics developed for the Vrancea region is described, and results of numerical simulations of the model are presented. Section 5 discusses the model results and presents conclusions.

2. Seismicity and Geodynamics of the SE-Carpathians

Repeated deep large earthquakes of the SE-Carpathians (Vrancea) strike “without warning”, cause destruction in Bucharest and shake the central and eastern European cities at distances of several hundred kilometres away from the hypocentres of the events. The earthquake-prone Vrancea region is situated at the bend of the SE-Carpathians and bounded on the north and north-east by the Eastern European craton (EEC), on the east and south by the Moesian platform (MP), and on the west by the Transylvanian basin (TB).

The epicentres of mantle earthquakes in the Vrancea region are concentrated within a very small area (Fig. 1), and the distribution of the epicentres is much denser than that of intermediate-depth events in other intracontinental regions. The projection of the foci on the NW-SE vertical plane across the bend of the Eastern Carpathians (section AB in Fig.1) shows a seismogenic volume about 100 km long, about 40 km wide, and extending to a depth of about 180 km. The body is interpreted as a lithospheric slab descending in the mantle. Beyond this depth the seismicity ends suddenly: a seismic event beneath 180 km represents an exception. A seismic gap at depths of 40-70 km led to the assumption that the lithospheric slab is already detached. According to a historical catalogue of Vrancea events, large intermediate-depth shocks with magnitudes $M_S > 6.5$ occur three to five times per century. In the XXth century, large events at depths of 70 to 170 km occurred in 1940 with moment magnitude $M_W = 7.7$, in 1977 $M_W = 7.4$, in 1986 $M_W = 7.1$, and in 1990 $M_W = 6.9$ [4].

The 1940 earthquake gave rise for the development of a number of geodynamic models for this region. McKenzie [6] suggested this seismicity to be associated with a relic slab sinking in the mantle and now overlain by continental crust. The 1977 disastrous earthquake and later the 1986 and 1990 earthquakes brought again up the discussion about the nature of the earthquakes. The Vrancea region was considered [7] as a place where the sinking oceanic slab was already detached from the continental crust. Oncescu [8] proposed that the intermediate-depth events are generated in a zone that separates the sinking slab from the neighbouring immobile part of the lithosphere rather than in the sinking slab itself. Linzer [9] explained the nearly vertical position of the Vrancea slab as the final rollback stage of a small fragment of oceanic lithosphere. Gibracea and Frisch [10] assumed the break-off of the slab to affect only its crustal portion followed by horizontal delamination of the lower portion of the slab. Sperner *et al.* [5] suggested a model of Miocene subduction of oceanic lithosphere beneath the Carpathian arc and subsequent gentle continental collision, which transported cold and dense lithospheric material into the mantle.

Figure 1. Location map of observed seismicity in SE-Carpathians with magnitude $M_w \geq 3$.
(a) Epicentres of Vrancea earthquakes. (b) Hypocentres of the same earthquakes projected onto the vertical plane AB along the NW-SE direction.

The active subduction ceased about 10 Ma ago [11]. Subsequently, the initial flat subduction began to steepen to its present-day nearly vertical orientation. Now the cold slab (hence denser than the surrounding mantle) beneath the Vrancea region sinks due to gravity. The hydrostatic buoyancy forces help the slab to subduct, but viscous and frictional forces resist the descent. At intermediate depths these forces produce an internal stress, and earthquakes occur in response to this stress. Ismail-Zadeh *et al.* [12] showed that the maximum stress in a descending slab occur in the depth range of 70 km to 160 km in a very narrow area and the depth distribution of the annual average seismic energy released in earthquakes has a shape similar to that of the depth distribution of the stress magnitude in the slab.

Figure 2. Seismic tomographic image of the Vrancea slab and hypocentres of intermediate-depth seismicity [14].

One question to be addressed in this paper concentrates on the pattern of earthquake hypocentres within the slab. Seismic tomographic studies revealed a body of high P -wave velocities beneath the Vrancea region, which was interpreted as a slab descending in the mantle [11, 13]. Its dimensions exceed the seismogenic volume by far.

In 1999 an international tomographic experiment with 120 seismic stations was realised in SE-Romania [14]. During the field experiment 160 local events with magnitude $M_l \geq 2.0$ and 450 teleseismic events with magnitude $M_b \geq 5.0$ were recorded. The station distance ranged from 15-20 km (the Vrancea region) to 25-30 km (outer margins of the network) covering a region of about 350 km in diameter. First preliminary results were achieved through an inversion of the teleseismic data. Data inversion reveals a high-velocity body with maximum P -wave velocity perturbations of +3.0 to +3.5% in comparison with the background model (see Fig. 2). This high-velocity body is interpreted as the descending lithospheric slab. It reaches a depth of at least 350 km which is in good agreement with results of previous low-resolution seismic tomography studies [15]. The high-resolution seismic tomographic image of the body (Fig. 2; after [14]) shows that Vrancea intermediate-depth earthquakes are located at the opposite side of the slab (or lower surface of the descending slab) as compared to zones of active subduction, where seismicity is associated with the upper surface of subducting lithosphere.

3. Stress Evolution – a Corner Flow Model

In this section I consider a fluid dynamical model which provides explanation for the observed distribution of seismicity in the Vrancea region. The Vrancea slab, which is

believed to sink beneath the SE-Carpathian arc, separates the mantle into two portions (or two corner sub-domains). Considering that stresses release in earthquakes is related to the level of shear stress, shear stress distributions are calculated in the each corner sub-domain by using an analytical model of the corner flow [16]. McKenzie [17] used the model to study dynamics of active subduction zones and causes of plate motions. Later Stevenson and Turner [18] and Tovish *et al.* [19] use the model to investigate the torque balance on the slab and angle of subduction for Newtonian and non-Newtonian rheologies of the mantle, respectively.

The descending slab must induce stresses within the surrounding mantle. Its motion will therefore govern the flow of the mantle. The principal forces determining the motion are a gravity force, normal forces on the upper and lower surfaces of the slab (due to pressure variations in the surrounding mantle), and resistance forces. Although the latter forces can contribute to the estimation of shear stresses on the slab, I follow McKenzie [17] and Tovish *et al.* [19] and omit them from the consideration in the section. Inside the mantle there are also body forces, caused by lateral density variations, however, they are neglected in this section, because the density is assumed to be constant in the model. Another assumption of the model is that flow in the mantle is governed by a viscous constitutional relationship, although it was shown that the shear stresses on the slab are reduced insignificantly, if the mantle behaves as a non-Newtonian fluid [19]. It is also assumed that the viscosity is constant in each corner sub-domain neglecting the effect of temperature on the viscosity in this model. Thus several of these assumptions are unlikely to be valid for mantle flow, but they enable to obtain analytical solutions.

3.1. GEOMETRY OF THE MODEL

The corner flows are assumed to be two-dimensional. Figure 3 illustrates how the descending slab divides the mantle into two corners where flows are induced by the motion of the slab.

Figure 3. Geometry and applied velocities of the model of corner flow induced by the descending slab beneath the Vrancea region.

The Vrancea region is located in the model at the origin of co-ordinates $x_1=0$, $x_2=0$. Axes Ox and Oy are directed leftward and downward, respectively. Surfaces $x_2=0$, $x_1<0$ and $x_2=0$, $x_1\geq 0$ move towards the trench ($x_1=0$) with constant velocity U_1 and $-U_2$,

respectively. The descending slab extends from the origin of co-ordinates downward at the dip angle α to positive x_1 axis. The slab moves with constant velocity U_3 and/or constant vertical velocity U_4 . The model slab divides the viscous flow into two corners: “Transylvanian basin” corner (TB corner) and “East-European craton” corner (EEC corner). The applied velocities induce a viscous flow, and the flow and tectonic shear stress are determined within the corners.

3.2. BASIC EQUATIONS

The velocity components (v_1, v_2) of the mantle flow and maximum tectonic (deviatoric) shear stress $\tau_{\max}$ in each corner can be found from the following expressions

$$v_1 = -(A_i x_1 + B_i x_2) \frac{x_1}{x_1^2 + x_2^2} - B_i \arctan \frac{x_2}{x_1} - D_i,$$

$$v_2 = -(A_i x_1 + B_i x_2) \frac{x_2}{x_1^2 + x_2^2} + A_i \arctan \frac{x_2}{x_1} + C_i,$$

$$\tau_{\max} = 2\mu_i \frac{|A_i x_2 - B_i x_1|}{x_1^2 + x_2^2},$$

where A_i, B_i, C_i , and D_i are constants, and $i=1$ and $i=2$ correspond to TB and EEC corners respectively. Their values are determined by boundary conditions.

The boundary conditions for the TB corner are $v_1 = -U_2, v_2 = 0$ at $x_2 = 0, x_1 > 0$ (or $\arctan(x_2/x_1) = 0$) and $v_1 = U_3 \cos \alpha, v_2 = U_3 \sin \alpha + U_4$ at $x_2 = x_1 \tan \alpha$ (or $\arctan(x_2/x_1) = \alpha$). An application of these boundary conditions to the equations for velocity leads to the following expressions for constants A_1, B_1, C_1 , and D_1 :

$$A_1 = \frac{-U_2 \sin^2 \alpha + U_3 \alpha \sin \alpha + U_4 (\alpha + \sin \alpha \cos \alpha)}{\alpha^2 - \sin^2 \alpha},$$

$$B_1 = \frac{-U_2 (\alpha - \sin \alpha \cos \alpha) - U_3 (\alpha \cos \alpha - \sin \alpha) + U_4 \sin^2 \alpha}{\alpha^2 - \sin^2 \alpha},$$

$$C_1 = 0, \quad D_1 = -A_1 + U_2.$$

The boundary conditions for the EEC corner are $v_1 = U_1, v_2 = 0$ at $x_2 = 0, x_1 < 0$ (or $\arctan(x_2/x_1) = \pi$) and $v_1 = U_3 \cos \alpha, v_2 = U_3 \sin \alpha + U_4$ at $x_2 = x_1 \tan \alpha$ (or $\arctan(x_2/x_1) = \alpha$). Substituting the boundary conditions into the equations for velocity I obtain the following expressions for constants A_2, B_2, C_2 , and D_2 :

$$A_2 = \frac{U_1 \sin^2 \alpha - U_3 (\pi - \alpha) \sin \alpha - U_4 (\pi - \alpha - \sin \alpha \cos \alpha)}{(\pi - \alpha)^2 - \sin^2 \alpha},$$

$$B_2 = \frac{-U_1 (\pi - \alpha + \sin \alpha \cos \alpha) - U_3 (\cos \alpha (\pi - \alpha) + \sin \alpha) + U_4 \sin^2 \alpha}{(\pi - \alpha)^2 - \sin^2 \alpha},$$

$$C_2 = -\pi A_2, \quad D_2 = -A_2 - \pi B_2 - U_1.$$

3.3. MODEL RESULTS

The viscosity of cooled mantle material beneath the old EEC ($\mu_1 = 2 \times 10^{20}$ Pa s) was assumed to be only five times greater than that of the mantle beneath the young TB ($\mu_2 = 10^{21}$ Pa s). High temperature and fluids beneath the TB may decrease the viscosity drastically, and hence the viscosity ratio between the EEC and TB would be even larger.

Three subsequent phases of the evolution of the descending lithosphere beneath the Vrancea region are considered: (i) active subduction ($\alpha = 30^\circ$, $U_1 = U_3 = 5$ cm yr⁻¹); (ii) slab steepening due to gravity and slab roll-back ($\alpha = 60^\circ$, $U_2 = U_4 = 5$ cm yr⁻¹); and (iii) gravity-driven slab sinking ($\alpha = 85^\circ$, $U_4 = 5$ cm yr⁻¹). Figure 4 shows the flow field and contours of constant shear stress for the model.

Figure 4. Modelled tectonic shear stress and flow in the mantle induced by a slab descending beneath the Vrancea region for three phases of slab evolution: (a) active subduction, (b) slab steepening, and (c) slab sinking due to gravity. Flow is indicated by the arrows, the shading represents the magnitudes of the shear stresses. IDE, intermediate-depth earthquakes

According to Sperner *et al.* [5] the dip angle of the Vrancea subduction in Miocene times was about 25° . Figure 4,a illustrates the pattern of mantle flow and distribution of stress during the active subduction of the Vrancea lithosphere. The pattern of the flow and shear stresses coincide with that of the McKenzie model [17]. Namely, the

maximum shear stresses are concentrated at the upper surface of the descending slab. The model predictions are in good agreement with the locations of earthquake hypocentres within the so-called Wadati-Benioff zones associated with the active subduction in other seismic belts (e.g., [20]).

When the subduction terminated (about 10 Ma ago), rollback movement of the slab resulted in a redistribution of shear stress in the mantle. The maximum shear stresses are shifted from the upper to lower surface of the slab (Fig.4,*b*). This effect is amplified during the final phase of slab evolution when the lithospheric plate sinks into the mantle driven only by gravity (Fig.4,*c*). The lower the viscosity of the TB corner, the greater the magnitude of shear stress at the EEC corner. The area of the maximum shear stresses in the model roughly coincides with the depth range of intermediate-depth events in SE-Carpathians.

Although our model presented here is based on simplified assumptions, it illustrates how changes in the dynamics of descending slab result in a significant redistribution of shear stresses and hence in spatial changes of seismicity.

4. Model of Block-and-Fault Dynamics

The purpose of this section is to numerically study a dynamical model of block structure, containing the Vrancea slab, by using results of modelling of mantle flow beneath the SE-Carpathians. This model allows producing a catalogue of synthetic earthquakes. The features of this catalogue can be compared with those of the real seismicity. In the model of block dynamics a seismic region is represented by a system of absolutely rigid blocks divided by infinitely thin plane faults ([3], [21]). The blocks interact between themselves and with the surrounding medium in response to the prescribed motion of the boundary blocks. Displacements of the blocks are assumed to be infinitesimal in relation to their geometric size. Therefore the geometry of the block structure does not change during a numerical simulation and the structure does not move as a whole. As the blocks are rigid, all deformation occurs in the fault zones and at interfaces separating the blocks and the surrounding medium. The appropriate stress depends on the relative displacement of the blocks. When the ratio of stress to pressure is exceeded in some part of a fault plane, the stress drops, possibly resulting in failures on other parts of the fault planes, and the failures are considered as earthquakes. Immediately after the earthquakes the parts of the fault planes where the failures have occurred are in a state of creep for some time, while the stress remains below the certain stress threshold.

Panza *et al.* [22] studied a model of block structure dynamics of the Vrancea region where the block system moves due to prescribed horizontal motion of the boundary blocks and of the medium underlying the blocks and showed similar features of real and synthetic catalogues. Here I present a dynamical model of block structure, the principal part of which is a sinking slab (see [2] for more details).

4.1. GEOMETRY OF BLOCK STRUCTURE

Consider a layer bounded by two vertical planes **A** and **B** (Fig.5). A structure of blocks is a limited and simply-connected part of this layer. The horizontal boundaries of the

blocks separating the crust, mantle, and slab are called 'material interfaces'. The other boundaries of the block structure are called 'fault planes'. The fault planes have arbitrary dip angles. The intersection lines of fault planes and material interfaces with vertical plane **A** are referred to as 'faults'. A common point of two faults is called 'the vertex'.

Figure 5. Geometry of block structure and definitions used in the model.

The fault planes and material interfaces intersect with the vertical plane **B** and thus in this plane there are faults and vertices corresponding to those in the vertical plane **A**. The vertex on plane **A** is connected with the corresponding vertex on plane **B** by a segment ('rib') of the intersection line of the corresponding fault planes or material interfaces. The part of a fault plane (or a material interface) between two ribs corresponding to successive vertices on the fault is called 'the fault segment' (or 'the boundary segment'). The shape of the fault and boundary segments is a trapezium. The common part of the block with plane **B** is a polygon and is called 'block flank'.

4.2. BASIC EQUATIONS

The movements of the boundaries of the block structure are assumed to be caused by an external force acting on the structure. The rates of these movements are prescribed. Dimensionless time is used in the model, and all quantities containing time are referred to one unit of the dimensionless time. At each time the structure of blocks is to be in a quasistatic equilibrium state. The blocks interact with each other along the fault planes separating them, and the interaction is viscous-elastic.

At time t , at some point (X, Z) of a fault plane separating two blocks the elastic stress σ_e along the fault plane is defined by

$$\sigma_e = K (\Delta \mathbf{r} - \delta \mathbf{r}), \quad (1)$$

where $\Delta \mathbf{r}$ and $\delta \mathbf{r}$ are the vectors of relative elastic and inelastic displacements of the blocks along the fault plane, respectively. The components Δx and Δz of the vector $\Delta \mathbf{r}$ are represented by

$$\Delta x = x_i - x_j - (Z - Z_c^i) \varphi_i + (Z - Z_c^j) \varphi_j,$$

$$\Delta z = z_i - z_j - (X - X_c^i) \varphi_i + (X - X_c^j) \varphi_j,$$

where X_c^i , Z_c^i , X_c^j , and Z_c^j are the co-ordinates of the geometrical centres of the block flank; (x_i, z_i) and (x_j, z_j) are the translation vectors of the blocks; φ_i and φ_j are the angles of rotation of the blocks around the geometrical centres of their flanks. Indexes i and j refer to the blocks on the left and right of the fault, respectively. The evolution of the inelastic displacement $\delta \mathbf{r}$ at the point is described by

$$d\delta \mathbf{r} / dt = W \sigma_e. \quad (2)$$

The coefficients K and W in (1) and (2) are, respectively, proportional to the shear modulus and inversely proportional to the viscous coefficient of the fault zone. The values of K and W can be different for different faults.

To simulate the dynamics of the block structure, a discrete representation of the plane surfaces is needed. Being a trapezium, each fault (boundary) segment is divided into small trapezia called 'cells'. The values of $\Delta \mathbf{r}$ and $\delta \mathbf{r}$ are supposed to be the same for all points of a cell. The state of the block structure is considered at discrete times.

Earthquakes are simulated according to a 'dry friction' model. The following ratio is introduced:

$$\kappa = |\sigma_e| / (P - p_0),$$

where P is a model parameter which can be interpreted as the difference between the lithostatic and hydrostatic pressure, assumed to be equal for all the faults; p_0 is the reaction force per unit area defined by

$$|p_0| = |\sigma_e^n \tan \alpha|,$$

where σ_e^n is a component of the elastic stress σ_e normal to a fault on plane $\mathbf{A}$, and α is an angle of a fault plane to plane $\mathbf{A}$. The value of p_0 is positive in the case of extension and negative in the case of compression.

For each fault the following three levels of κ are considered $B > B_f \geq B_s$. Initial conditions for a simulation of block structure dynamics satisfy the inequality $\kappa < B$ for all cells of the fault (boundary) segments. If at some time in any cell the value of κ reaches the level B , a failure ('earthquake') occurs. The failure is such an abrupt change of the inelastic displacements $\delta \mathbf{r}$ in the cell that the value of κ is reduced to the level B_f . The cells of the same fault plane in which a failure occurs at the same time generate a single event. Immediately after the earthquake, it is assumed that the cells in which failure has occurred are in the creep state as long as $\kappa > B_s$. When $\kappa \leq B_s$, the cells return to the normal state.

4.3. RESULTS OF NUMERICAL MODELLING

The configuration of blocks and faults on the vertical plane **A** used in the model is presented in Fig. 6.

Figure 6. The block structure used in numerical simulations; the numbers of the vertices (1-9), faults (1-8), and blocks (I and II) are indicated. The arrows stand for velocities of movements of boundary faults.

A simple model of two rigid blocks is considered: the continental crust (block I) and the sinking slab overlain by the continental crust (block II). The z -axis is pointing upward from the left upper corner of the model ($z=0$), the x -axis points to the right ($0 \leq x \leq 350$ km). The vertices of the block structure with numbers 1-9 have the following co-ordinates (in km): (350; 0), (0; 0), (0; -33.3), (227.5; -33.3), (240; 0), (181; -160), (206; -160), (240; -66.6), (350; -66.6). The block structure contains eight faults. The values of the model parameters are shown in Table 1.

TABLE 1. Model Parameters of Faults

Fault No.	Vertices	K , Bar/cm	W , cm/(bar s)	α deg	V_x cm	V_z cm
1	1, 5, 2	0	0	90	0	0
2	2, 3	0	0	85	0	0
3	3, 4	1	0.1	90	0.20	0.07
4*	5, 4, 6	1	0.05	85	4.73	-8.82
5	6, 7	1	0.05	90	1.82	-17.93
6	7, 8	1	0.05	85	15.63	-19.61
7	8, 9	1	0.1	90	-0.74	0.13
8	9, 1	0	0	85	0	0

* V_x , V_z , and ω are prescribed for the part of fault 4 confined between vertices 4 and 6.

Fault **1** is an artificial one corresponding to the earth's surface; faults **2** and **8** are 'passive' because no shocks are observed there. The faults **1**, **2**, and **8** are immobile, $K = 0$ for them, and, therefore, all forces are equal to zero in these faults. The faults **3**, **5**, **6**, **7**, and the part of fault **4** confined between vertices **4** and **6** move with prescribed velocities (V_x , V_z) specified in Table 1. These velocities are found from the numerical model of the descending Vrancea slab [12]. All deformations occur on these faults. The horizontal thickness of blocks is assumed to be 60 km, and $P=2$ kb.

The magnitude of earthquakes is calculated by using the relationship: $M = D \lg S + E$, where the constants $D=0.98$ and $E=3.93$ are given by Utsu and Seki [23], and S is the sum of the squares of the cell (in km) included in the earthquake.

The synthetic earthquake catalogue is obtained as a result of the block-structure dynamics simulation for a period of 300 units of dimensionless time. The simulation starts from the initial zero condition and some time is needed for the quasi-stabilisation of stress. Only the stable part of the synthetic catalogue is considered. The synthetic catalogue contains 96442 events with magnitudes between 5 and 7.1.

Figure 7. Results of the model of block-and-fault dynamics. (a) Map of the synthetic seismicity. (b) Frequency-of-occurrence plots for the real catalogue (solid line marked by 'square') and for the synthetic catalogue (dashed line marked by 'cross').

Figure 7,a shows the distributions of the focal depths of the synthetic events with magnitudes greater than 6.8. The synthetic earthquake hypocentres are located at the lower surface of the modelled slab, and this is in a good agreement with the seismic tomographic models (e.g., [14]).

The frequency-of-occurrence plots for the observed and synthetic earthquakes are represented in Fig. 7,b. According to the Gutenberg-Richter law on the frequency-of-occurrence for the observed seismicity, the logarithm of the number of earthquakes depends linearly on magnitude. The curve corresponding to the synthetic catalogue (dashed line) is almost linear and has approximately the same slope as the curve corresponding to the observed seismicity (solid line) in the range of magnitudes from 5.5 to 6.5. The observed seismicity reveals a gap in magnitude interval $6.5 < M < 7.0$.

which is not visible in the synthetic catalogue. The gap seems to be caused by a short time interval for which relevant observations are available.

5. Discussion and Conclusions

The dramatic increase of losses due to natural and technological hazards in recent time entails the necessity of modelling of catastrophic events. Among other reasons it is explained by a lack of reliable observation data on catastrophic phenomena. The problems of risks connected with catastrophic events are considered with the using of earthquakes as an example. Our principal objective was to understand a process of stress generation beneath the Vrancea region and stress release in large earthquakes. Such a knowledge of the stress regime in the lithosphere of earthquake-prone regions may assist in risk estimation.

The intermediate-depth seismicity in the SE-Carpathians is concentrated near and along the south-eastern margin of the high-velocity body (Fig. 2) which is considered to be a lower surface of the slab during its active subduction. The location of earthquakes is obviously not compatible with Wadati-Benioff zones of subducting lithosphere where earthquakes are concentrated near the upper surface of the slab. Using an analytical model of corner flow I showed here that the pattern of tectonic stress induced by a descending slab in active subduction zones differs from that in passive subduction zones. Maximum shear stress migrates from the upper surface of the descending slab to its lower surface due to changes in dynamics of the descending slab (from active subduction to passive sinking due to gravity). Hence I conclude that the seismicity pattern of the final stage of a descending lithospheric plate differs completely from the pattern familiar from Wadati-Benioff zones

Results of the model of block-and-fault dynamics show that synthetic earthquakes are located at the lower surface of the descending slab. It correlates well with the model of stress generation and with the observed location of seismic events with respect to the Vrancea slab. It is also shown that the synthetic catalogue has features similar to those of the catalogue of Vrancea earthquakes. This synthetic catalogue or its relevant segment could be used to predict the future behaviour of the seismicity in the region and therefore for seismic risk estimation.

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