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Numerical Modeling in Problems of Geophysical Fluid Dynamics.

Part 2.

Modeling of a Descending Lithospheric Slab: Induced Mantle Flow and Stress

Block-and-Fault Dynamics of the Lithosphere Beneath the Vrancea Region: Effect of Slab Descending

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Extended Abstract

The first part of the lecture addresses an application of a numerical viscous model to study evolution of descending lithospheric slab beneath the Vrancea region. The second part concerns an introduction of the slow mantle flow induced by the descending slab into a model of block-and-fault dynamics and a study of the latter model.

The earthquake-prone Vrancea region is situated at a bend of the Eastern Carpathians and bounded on the north and northeast by the Eastern European platform, on the east and south by the Moesian platform, and on the west by the Transylvanian and Pannonian basins. The epicenters of mantle earthquakes in the Vrancea region are concentrated within a very small area (less than $1° \times 1°$, Fig. 1), and the distribution of the epicenters 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 (see Fig. 1) shows a seismogenic body in the form of a parallelepiped about 100 km long, about 40 km wide, and extending to a depth of about 180 km. Beyond this depth the seismicity ends suddenly: a seismic event represents an exception beneath 180 km.

As early as 1949, Gutenberg and Richter (1954) drew attention to the remarkable source of shocks in the depth range of 100 km to 150 km in the Vrancea region. According to a historical catalogue, there have been 16 large intermediate-depth shocks with magnitudes $M_s > 6.5$ occurring three to five times per century. In this century, large events in the depth range 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 (Oncescu and Bonjer, 1997).

There are several geodynamic models for the Vrancea region. McKenzie (1972) suggested that large events in the Vrancea region occur in a vertical relic slab sinking within the mantle and now overlain by continental crust. He believed that the origin of this slab is the rapid southeast motion of the plate containing the Carpathians and the surrounding regions toward the Black Sea plate. The Vrancea region was also considered (Fuchs et al., 1979) as a place where an oceanic slab detached from the continental crust is sinking gravitationally. Oncescu et al. (1984) proposed a double subduction model for Vrancea on the basis of the interpretation of a 3-D seismic tomographic image. In their opinion, the intermediate-depth seismic events are generated in a vertical zone that separates the sinking slab from the immobile part of it rather than in the sinking slab itself. Linzer (1996) proposed that the nearly vertical position of the Vrancea slab represents the final rollback stage of a small fragment of oceanic lithosphere. On the basis of the ages and locations of the eruption centers of the volcanic chain and also the thrust directions, a migration path of the retreating slab was restored between the Moesian and East-European platforms.

According to these models, the cold (hence denser and more rigid than the surrounding mantle) relic slab beneath the Vrancea region sinks due to gravity. The active subduction ceased about 10 Ma ago; thereafter only some slight horizontal shortening was observed in

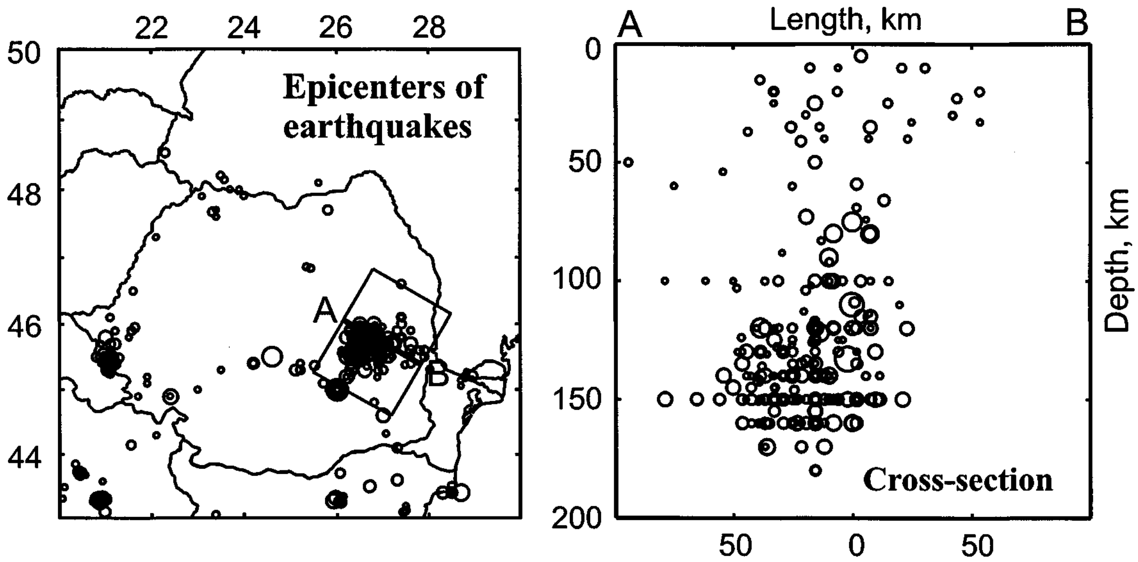

Figure 1: Epicenters and hypocenters of Romanian earthquakes with magnitude greater than 4 which occured from 1990 to 1996.

the sedimentary cover (Wenzel et al., 1998). 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 with one principal axis directed downward. Earthquakes occur in response to this stress.

We examine the effects of viscous flow on the stress field of a relic slab to explain the intermediate-depth seismic activity in the Vrancea region. A 2D finite-element model of a slab gravitationally sinking in the mantle predicts (1) nearly horizontal compression in the slab as inferred from the stress axes of earthquakes (see Fig. 2), (2) a very narrow area of the maximum stress, and (3) the maximum stress occurring in the depth range of 80 km to 180 km (see Fig. 3). We analyze effects of the geometry of the lithopsheric slab and of slab delamination on stress pattern in the slab. 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 in the slab.

The next step in numerical modeling is to introduce the slow mantle flow a model of block-and-fault dynamics. To do it, we model the Vrancea region by a system of absolutely rigid blocks separated by infinitely thin plane faults. The interaction of the blocks along the fault planes and with the surrounding medium is assumed to be a viscoelastic. The displacements of the block system are caused by motions of boundary blocks. The velocities of the motions are found from a model of mantle flows induced by a sinking slab beneath the Vrancea region. When a ratio of stress to pressure for some portion of a fault plane exceeds a certain strength level, a stress-drop ('earthquake') occurs. As a result of the numerical simulation a catalog of synthetic earthquakes is produced. Several numerical experiments for various model parameters show that the spatial distribution of synthetic

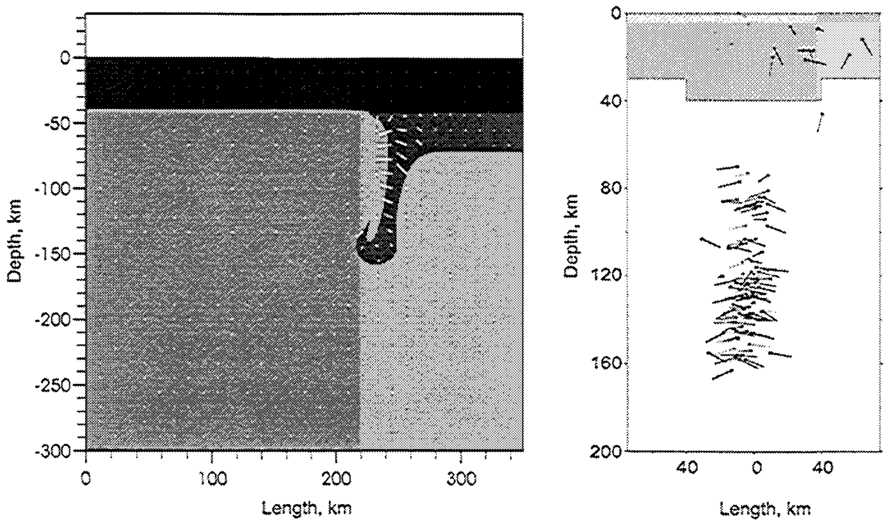

Figure 2: Compression axes predicted by the model (left panel) and observed (right panel).

events is significantly sensitive to the directions of the block movements. The results of the analysis show that the catalogs obtained by the simulation of the block structure dynamics have certain features similar to those of the real earthquake catalog of the Vrancea region. A most exciting result of the model is that large synthetic events are located at the right boundary of the block containing the slab; the model boundary corresponds to the lower plane of the Benioff double seismic zone. The recent seismotomographic study revealed the intermediate-depth earthquakes to occur to the south-east of the high-velocity body; the resutls confirm our model prediction (Fig. 4).

The attached reprint of the article *"Stress in the descending relic slab beneath the Vrancea region, Romania"* by Ismail-Zadeh, Panza and Naimark (1) describes a numerical model of the descending slab in an attempt to explain the observed distribution of earthquakes; (2) presents of the results on the study of influence of the basalt-eclogite phase transition within the slab on the stress in the surrounding rocks; and (3) discusses a possible role of the dehydration of rocks on the stress release within the descending Vrancea slab.

The other attached reprint of the article *"Numerical modelling of earthquake flow in the southeastern Carpathians (Vrancea): effect of a sinking slab"* by Ismail-Zadeh, Keilis-Borok and Soloviev describes a dynamical model of block structure, containing a sinking slab, by using results of geodynamic modelling of mantle flows beneath the SE-Carpathians.

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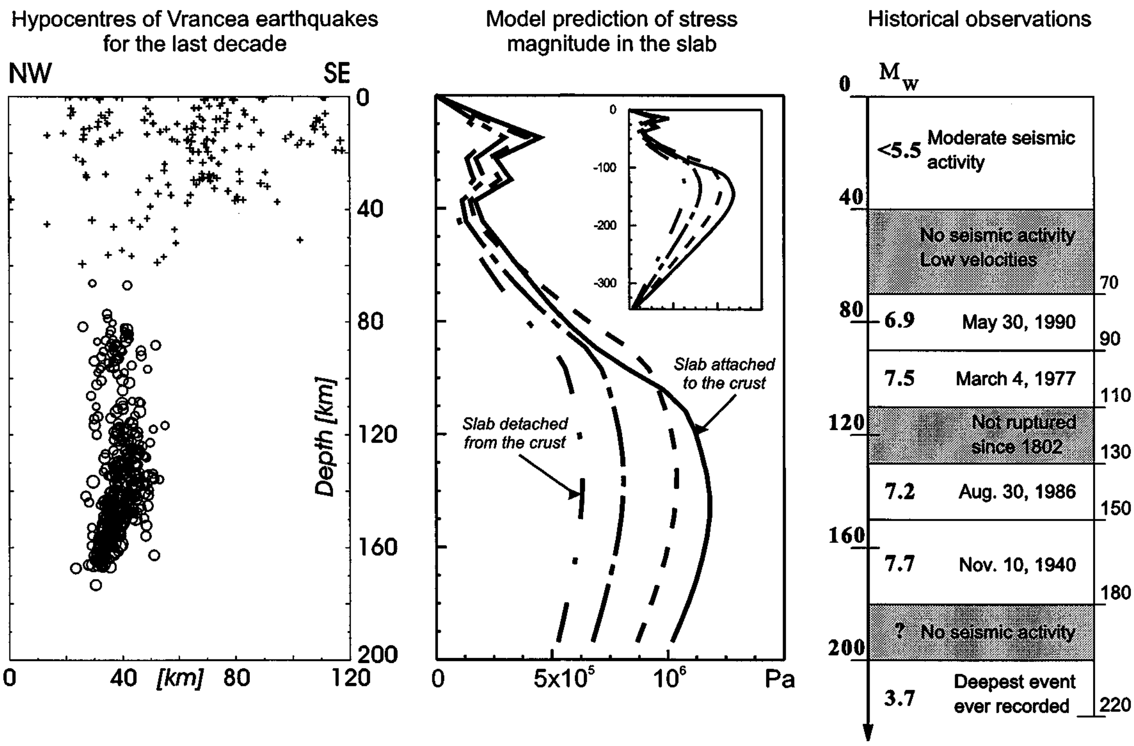

Figure 3: Stress in the descending slab (central panel) as compared to the hypocenters' distribution of the Vrancea earthquakes (left panel) and historical observations (right panel).

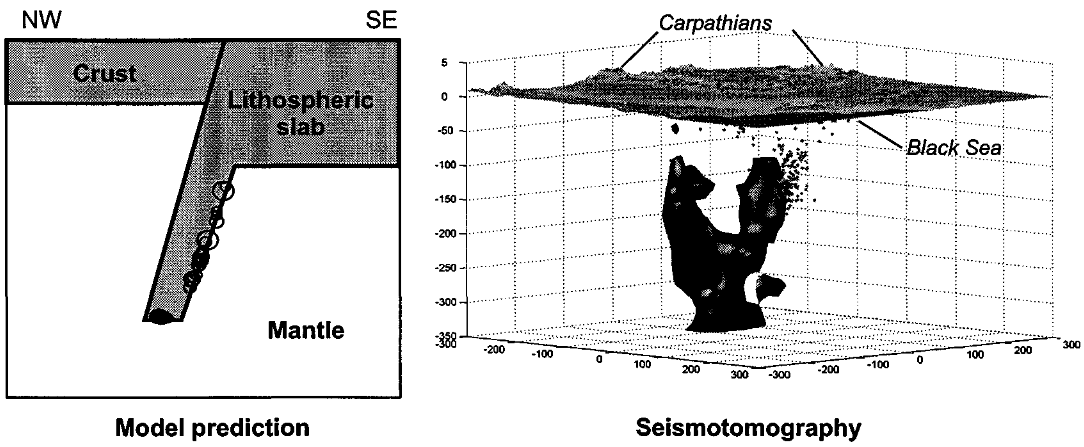

Figure 4: Large synthetic earthquakes predicted by the model of block-and-fault dynamics (left panel) and high seismic velocity body beneath the Vrancea revealed by the tomographic study and distribution of observed seismic events (right panel).

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Pure and Applied Geophysics

Stress in the Descending Relic Slab beneath the Vrancea Region, Romania

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Abstract—We examine the effects of viscous flow, phase transition, and dehydration on the stress field of a relic slab to explain the intermediate-depth seismic activity in the Vrancea region. A 2-D finite-element model of a slab gravitationally sinking in the mantle predicts (1) downward extension in the slab as inferred from the stress axes of earthquakes, (2) the maximum stress occurring in the depth range of 70 km to 160 km, and (3) a very narrow area of the maximum stress. 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 in the slab. Estimations of the cumulative annual seismic moment observed and associated with the volume change due to the basalt-eclogite phase changes in the oceanic slab indicate that a pure phase-transition model cannot solely explain the intermediate-depth earthquakes in the region. We consider that one of the realistic mechanisms for triggering these events in the Vrancea slab can be the dehydration of rocks which makes fluid-assisted faulting possible.

Key words: Stress, slab, Vrancea, numerical modelling.

Introduction

The earthquake-prone Vrancea region is situated at a bend of the Eastern Carpathians and bounded on the north and northeast by the Eastern European platform, on the east and south by the Moesian platform, and on the west by the Transylvanian and Pannonian basins (Fig. 1). The epicenters of mantle earthquakes in the Vrancea region are concentrated within a very small area (less than $1° \times 1°$, Fig. 2a), and the distribution of the epicenters 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 (Fig. 2b) shows a seismogenic body in the form of a parallelepiped about 100 km long, about 40-km wide, and extending to a depth of about 180 km. Beyond this depth the seismicity ends suddenly: A seismic event represents an exception beneath 180 km (TRIFU, 1990; TRIFU, *et al.*, 1991; ONCESCU and BONJER, 1997).

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As early as 1949, GUTENBERG and RICHTER (1954) drew attention to the remarkable source of shocks in the depth range of 100 km to 150 km in the Vrancea region. According to a historical catalogue (Table 1), there have been 16 large intermediate-depth shocks with magnitudes $M_s > 6.5$ occurring three to five times per century (KONDORSKAYA and SHEBALIN, 1977). In this century, large events in the depth range 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 $M_w = 6.9$ (ONCESCU and BONJER, 1997).

Using numerous fault-plane solutions for intermediate-depth shocks, RADU (1967), NIKOLAEV and SHCHYUKIN (1975), and ONCESCU and TRIFU (1987) show that the compressional axes are almost horizontal and directed SE-NW, and that the tensional axes are nearly vertical, suggesting that the slip is caused by gravitational forces.

There are several geodynamic models for the Vrancea region (e.g., MCKENZIE, 1970, 1972; FUCHS *et al.*, 1979; RIZNICHENKO *et al.*, 1980; SHCHYUKIN and DOBREV, 1980; CONSTANTINESCU and ENESCU, 1984; ONCESCU 1984; ONCESCU *et al.*, 1984; TRIFU and RADULIAN, 1989; KHAIN and LOBKOVSKY, 1994; LINZER, 1996). MCKENZIE (1970, 1972) suggested that large events in the Vrancea region occur in a vertical relic slab sinking within the mantle and now overlain by continental crust. He believed that the origin of this slab is the rapid southeast motion of the plate containing the Carpathians and the surrounding regions toward the Black Sea plate. The overriding plate pushing from the northwest has formed

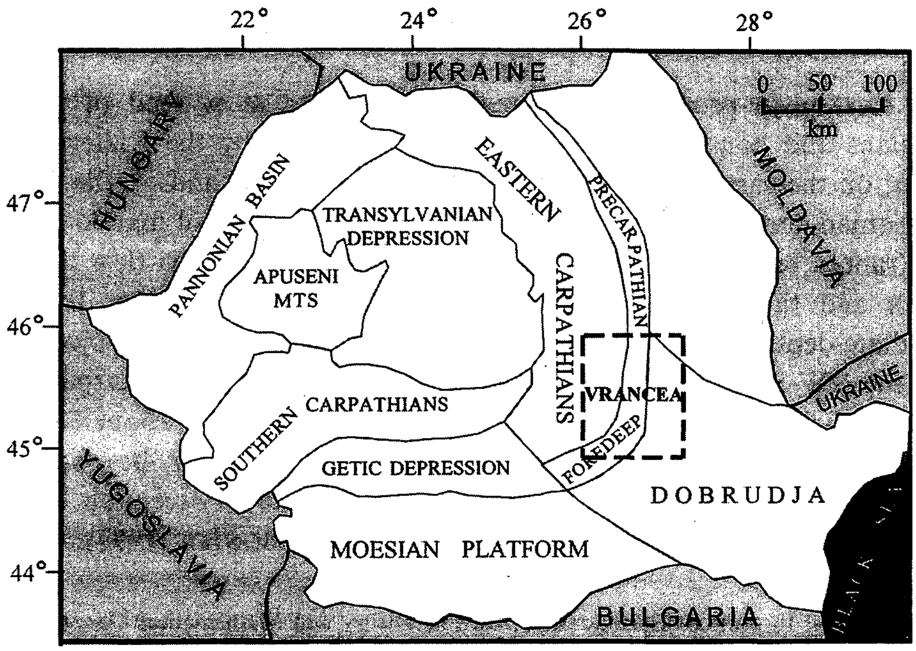


Figure 1
Tectonic sketch of the Carpathian area (modified after RĂDULESCU *et al.*, 1996).

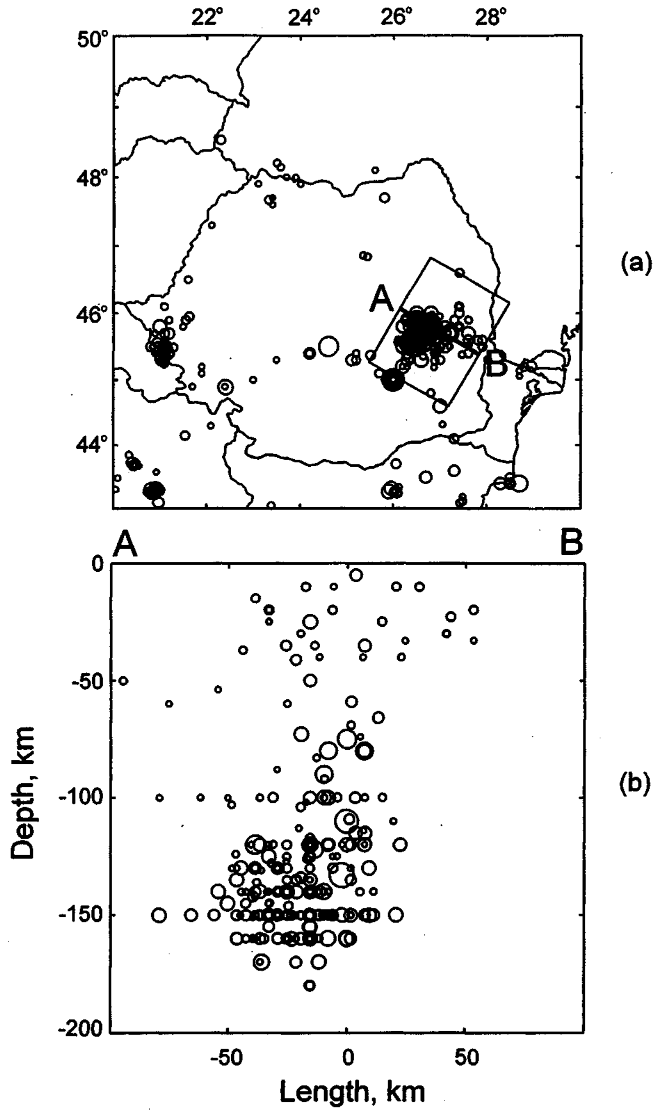


Figure 2
Map of the observed seismicity in Vrancea. (a) Epicenters of Romanian earthquakes with magnitude greater than 4 which occurred from 1900 to 1996. (b) Hypocenters of the same Romanian earthquakes projected onto the vertical plane AB along the NW-SE direction. Several catalogs have been combined to prepare the figure (VOROBIEVA *et al.*, 1996).

the Carpathian orogen, whereas the plate dipping from southeast has evolved the Pre-Carpathian foredeep (RIZNICHENKO *et al.*, 1980). SHCHYUKIN and DOBREV (1980) suggested that the mantle earthquakes in the Vrancea region are to be related to a deep-seated fault descending steeply. The Vrancea region was also considered (FUCHS *et al.*, 1979) as a place where an oceanic slab detached from the continental crust is sinking gravitationally. ONCESCU (1984) and ONCESCU *et al.* (1984) proposed a double subduction model for Vrancea on the basis of the interpretation of a 3-D seismic tomographic image. In their opinion, the intermediate-depth seismic events are generated in a vertical zone that separates the sinking slab from the immobile part of it rather than in the sinking slab itself. TRIFU and RADULIAN (1989) proposed a model of seismic cycle based on the existence of two active zones in the descending lithosphere beneath the Vrancea between 80- and 110-km depth and between 120- and 170-km depth. These zones are marked by a distribution of local stress inhomogeneities and are capable of generating large earthquakes in the region. KHAIN and LOBKOVSKY (1994) suggested that the lithosphere in the Vrancea region is delaminated from the continental crust during the continental collision and sinks in the mantle. Recently LINZER (1996) proposed that the nearly vertical position of the Vrancea slab represents the final rollback stage of a small fragment of oceanic lithosphere. On the basis of the ages and locations of the eruption centers of the volcanic chain and also the thrust directions, LINZER (1996) reconstructed a migration path of the retreating slab between the Moesian and East-European platforms.

According to these models, the cold (hence denser and more rigid than the surrounding mantle) relic slab beneath the Vrancea region sinks due to gravity. The active subduction ceased about 10 Ma ago; thereafter only slight horizontal shortening was observed in the sedimentary cover (WENZEL, 1997). The hydrostatic buoyancy forces help the slab to subduct, however viscous and frictional forces resist the descent. At intermediate depths these forces produce an internal stress with one principal axis directed downward (SLEEP, 1975). Earthquakes occur in response to this stress. These forces are not the only source of stress that leads to

Table 1

Strong intermediate-depth earthquakes in Vrancea since 1600

No.	Date m/d/y	Magnitude M_s
1	9/01/1637	6.6
2	9/09/1679	6.8
3	8/18/1681	6.7
4	6/12/1701	6.9
5	10/11/1711	6.7
6	6/11/1738	7.0
7	4/06/1790	6.9
8	10/26/1802	7.4
9	11/17/1821	6.7
10	11/26/1829	6.9
11	1/23/1838	6.9
12	10/06/1908	6.8
13	11/01/1929	6.6
14	3/29/1934	6.9
15	11/10/1940	7.4
16	3/04/1977	7.2
17	8/30/1986	6.9
18	5/31/1990	6.7

seismic activity in Vrancea; the process of slab descent may cause the seismogenic stress by means of mineralogical phase changes and dehydration of rocks, which possibly leads to fluid-assisted faulting.

The purpose of this paper is: (1) to study a numerical model of the descending relic slab in an attempt to explain the observed distribution of earthquakes; (2) to examine the influence of the basalt-eclogite phase transition within the slab on the stress in the surrounding rocks; and (3) to discuss a possible role of the dehydration of rocks on the stress release within the descending Vrancea slab.

Viscous Stress in the Descending Slab

Introduction to the Model

Numerical models of subducting slabs have been intensively studied by VASSILIOU *et al.* (1984) and VASSILIOU and HAGER (1988) to explain the global depth variation of Benioff zones of seismicity. MAROTTA and SABADINI (1995) showed that the shape of a slab sinking due to its own weight alone differs substantially from the shape of a slab pushed by active convergence. Here, to study the stress distribution and mantle flows beneath the Vrancea region, we construct a model of the evolution of a relic oceanic slab sinking gravitationally beneath an intracontinental region.

We assume that, keeping all the other parameters fixed, the number of earthquakes occurring in Vrancea at intermediate depths is related to the level of viscous stress in the slab. We consider a simple model for the relic slab evolution and calculate the stress therein, assuming that the earth's mantle behaves as a viscous fluid at the geological time scale, and the regional tectonic processes are associated with mantle flows regulated by Newtonian rheology.

The geometry and boundary conditions for the two-dimensional numerical model used in the analysis are shown in Figure 3. A viscous incompressible fluid with variable density and viscosity fills the model square ($0 \leq x \leq L$, $-H \leq z \leq h$) divided into four subdomains: atmosphere above $z = 0$, crust, slab, and mantle. These subdomains are bounded by material interfaces where density ρ and viscosity η are discontinuous, but are constant within each subdomain. The interface $z = 0$ approximates a free surface, because the density of the upper layer equals zero, and the viscosity is sufficiently low compared to that in the lower layer. The slab is modeled as being denser than the surrounding mantle, and therefore tends to sink under its own weight.

To test the stability of our results to variations of the density contrast, we consider the value of 0.7×10^2 kg m^{-3}, based on thermal models of the slab (SCHUBERT *et al.*, 1975) and used in numerical modelling of a subducting slab by VASSILIOU *et al.* (1984), and the value 0.4×10^2 kg m^{-3}, suggested by modelling

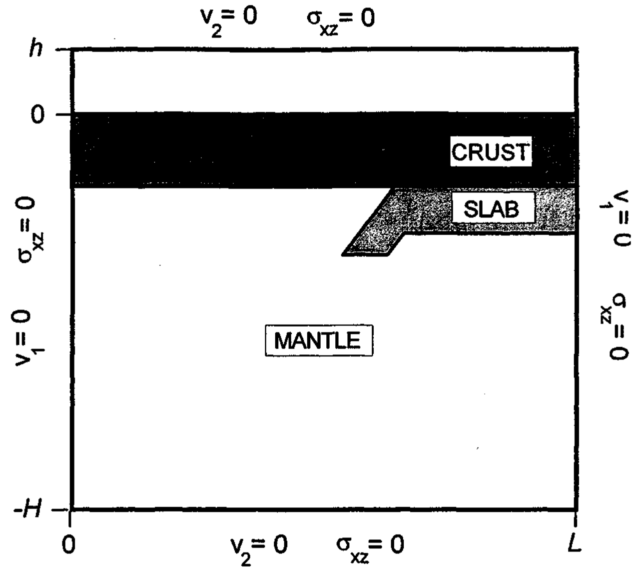


Figure 3
Geometry of the model with the boundary conditions used in the calculations. The z-axis is upward ($z = 0$ approximates the earth's surface), and the x-axis is from left to right.

the long wavelength component of Bouguer anomalies related to the lithospheric roots in the Alps and in the Apennines (WERNER and KISSLING, 1985; MUELLER and PANZA, 1986; MARSON *et al.*, 1995). We also consider several values of the viscosity ratio between the slab and the mantle: 5, 10, and 50, keeping the density contrast equal to 0.4×10^2 kg m^{-3}.

We solve Stokes' equation, which takes the following form in terms of the stream function ψ

$$4 \frac{\partial^2}{\partial x\, \partial z} \eta \frac{\partial^2 \psi}{\partial x\, \partial z} + \left(\frac{\partial^2}{\partial z^2} - \frac{\partial^2}{\partial x^2}\right) \eta \left(\frac{\partial^2 \psi}{\partial z^2} - \frac{\partial^2 \psi}{\partial x^2}\right) = -g \frac{\partial \rho}{\partial x}$$

where g is the acceleration due to gravity; $u = \partial \psi / \partial z$, $v = -\partial \psi / \partial x$, $\mathrm{v} = (u, v)$ is velocity. We assume impenetrability and free-slip boundary conditions:

$$\psi = \partial^2 \psi / \partial x^2 = 0 \quad \text{at} \quad x = 0 \quad \text{and} \quad x = L$$

$$\psi = \partial^2 \psi / \partial z^2 = 0 \quad \text{at} \quad z = -H \quad \text{and} \quad z = h.$$

These boundary conditions keep the model as a closed system, however since the Vrancea oceanic lithosphere is considered as a relic slab sinking in the mantle due only to gravitational forces (MCKENZIE, 1970), we can assume that the external forces are negligible. VASSILIOU *et al.* (1984) studied numerical models of a subducting plate with and without external forces applied to the plate. They showed that minor changes of stress distribution occurred in the plate (and in the system as a whole) due to the forces applied.

The time-dependence of ρ and η is described by the transfer equation

$$\frac{\partial A}{\partial t}=\frac{\partial \psi}{\partial x}\frac{\partial A}{\partial z}-\frac{\partial \psi}{\partial z}\frac{\partial A}{\partial x}$$

where A stands for ρ or η. The position of the material interfaces as functions of time are governed by the following differential equations:

$$dX/dt=\partial\psi/\partial z, \quad dZ/dt=-\partial\psi/\partial x$$

where the points (X, Z) are on the initial interfaces at $t=0$. The initial distributions $(t=0)$ of ρ and η and the positions of the material interfaces are known.

To solve the problem, that is, to compute the dependence of density, viscosity, material interfaces, velocity and stress on time, we employ an Eulerian finite element technique described in detail by NAIMARK and ISMAIL-ZADEH (1995), ISMAIL-ZADEH *et al.* (1996), and NAIMARK *et al.* (1998). The model region is divided into rectangular elements: 49×47 in the x and z directions. We use dimensionless variables, whereas in presenting the results for stress and velocity we scale them as follows: the time scale t^*, the velocity scale v^*, and the stress scale σ^* are taken respectively as $t^*=\eta^*/[\rho^* g(H+h)]$, $v^*=\rho^* g(H+h)^2/\eta^*$, and $\sigma^*=\rho^* g(H+h)$ where $\eta^*=10^{20}$ Pa s is a typical value of mantle viscosity (PELTIER, 1984), $\rho^*=3.3\times 10^3$ kg m^{-3} is a typical value of mantle density (TURCOTTE and SCHUBERT, 1982).

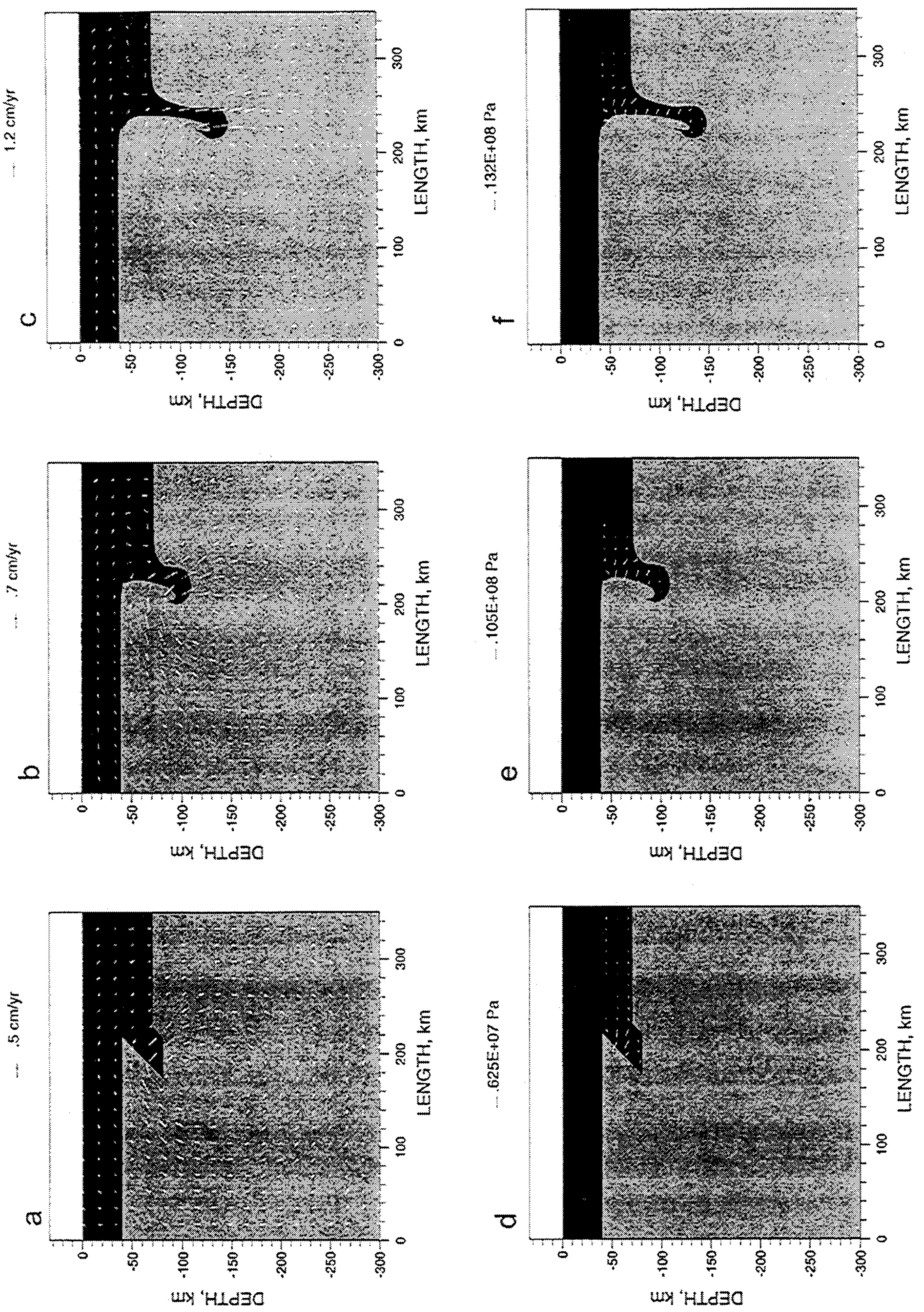
Numerical Results

The parameter values used in the numerical modelling are listed in Table 2. The deep structure of the crust and uppermost mantle of the Vrancea and surrounding regions is complex. The Moho discontinuity is at about 25–30 km in the basin areas, 30–36 km in the Moesian platform, 38–44 km in the Pre-Carpathian foredeep, and 45–56 km in the Eastern Carpathians (SHCHYUKIN and DOBREV, 1980; ENESCU, 1987). The thickness of the crust in the epicentral region is estimated at 43–44 km from DSS data (RĂDULESCU and POMPILIAN, 1991). As for the underlying mantle, the thickness of the lithosphere varies between less than 100 km within the Carpathian arc and about 150–200 km in the platform areas (SHCHYUKIN and DOBREV, 1980; CHEKUNOV, 1987). In the numerical model we assume that the initial thicknesses of the crust and the slab are 40 km and 30 km, respectively. We choose 45° for the dip of the slab at $t=0$; changes ($\pm 15°$) in the initial dip of the slab yield results similar to those we describe here. The stress magnitude σ is given by

$$\sigma=[0.5(\tau_{xx}^2+\tau_{zz}^2+2\tau_{xz}^2)]^{1/2}=\eta\left[4\left(\frac{\partial^2\psi}{\partial x\,\partial z}\right)^2+\left(\frac{\partial^2\psi}{\partial z^2}-\frac{\partial^2\psi}{\partial x^2}\right)^2\right]^{1/2}$$

where τ_{ij} $(i, j=x, z)$ are the components of the deviatoric stress.

The evolution of the slab that sinks under its own weight in the absence of external forces is displayed in Figure 4 for a density contrast 0.7×10^2 kg m^{-3} and


a
b
c
d
e
f
.5 cm/yr
.7 cm/yr
1.2 cm/yr
.625E+07 Pa
.105E+08 Pa
.132E+08 Pa
DEPTH, km
LENGTH, km
0
-50
-100
-150
-200
-250
-300
100
200
300

a viscosity ratio 10. The subducting slab gives rise to two mantle flows (Figs. 4a–c). The flow on the left moves clockwise, contributing to the evolution of the Transylvanian basin and the folded arc. The other rotates counterclockwise and possibly affects the development of the Pre-Carpathian foredeep and the Moesian platform. The shape of the slab is controlled by the circulation of mantle material. The mantle flows induced by the slab sinking gravitationally make the slab dip at a higher angle (Fig 4c). Figures 4d–f show the axes of compression of the deviatoric stress. The axes of tension are perpendicular to the axes of compression, and the magnitudes of tension and of compression are the same. The maximum viscous stress is reached within the slab, and the axes of compression are close to the horizontal direction. Based on the JHD method providing most relative locations of hypocenters, TRIFU (1990) and TRIFU *et al.* (1991) showed that the hypocentral projection of Vrancea intermediate-depth earthquakes onto the vertical plane along the NW-SE direction are nearly vertical and extended downward over the whole depth range. Most recently, ONCESCU and BONJER (1997) relocated the best recorded microearthquakes in the Vrancea region during 1982–1989 and

Table 2

Model parameters

Notation	Meaning	Value
g	acceleration due to gravity, m s^{-2}	9.8
h	height over the surface, km	33
h_c	initial thickness of the crust, km	40
h_s	initial thickness of the slab, km	30
$H+h$	vertical size of the model, km	333
L	horizontal size of the model, km	350
t^*	time scale, yr	300
v^*	velocity scale, m yr^{-1}	1.1×10^3
η^*	typical value of viscosity, Pa s	10^{20}
η_{air}	viscosity over the surface, Pa s	10^{15}
η_c	viscosity of the crust, Pa s	10^{22}
η_m	viscosity of the mantle, Pa s	10^{20}
η_s	viscosity of the slab, Pa s	10^{21}
ρ^*	typical value of density, kg m^{-3}	3.3×10^3
ρ_{air}	density over the surface, kg m^{-3}	0
ρ_c	density of the crust, kg m^{-3}	2.9×10^3
ρ_m	density of the mantle, kg m^{-3}	3.3×10^3
ρ_s	density of the slab, kg m^{-3}	3.37×10^3 and 3.34×10^3
σ^*	stress scale, Pa	1.1×10^{10}

Figure 4

Flow fields (a–c) and deviatoric compression axes (d–f) for the evolution of the slab subject to gravitational forces only: (a, d) $t = 16$ Ma BP. (b, e) $t = 10$ Ma BP, (c, f) present-day. The maximum values of flow velocity and stress magnitude are shown at the top of the figures.

showed (a) again the nearly vertical distribution of hypocenters of the events and (b) very narrow zone of the seismic activity (about 10-km wide). The numerical results, indicating a maximum stress in the narrow and subvertical region of the model, are in agreement with the observations.

The same computations made with a density contrast of 0.4×10^2 kg m^{-3} produce a nearly identical pattern. The numerical results indicate that variations of the viscosity ratio lead to changes in the stress distribution and in the velocity of the descending slab. If the viscosity ratio between the slab and the surrounding mantle is as small as 5, then the stress in the slab is not large enough. A high viscosity ratio (50) causes a slow descent of the slab (about 0.3 cm yr^{-1}), while the stress is now sufficiently large to give rise to seismic activity. Our computations show that a viscosity ratio of 10 is more suitable for the Vrancea region, because in this case the velocity of slab descent is about 1–2 cm yr^{-1}, which agrees with the regional geological inferences (BLEAHU *et al.*, 1973) and with the rate of subduction predicted from the thermal model of lithosphere in the Vrancea (DEMETRESCU and ANDREESCU, 1994).

The depth distribution of the average stress magnitude in the slab for the two density contrasts considered is presented in Figure 5. To compare the stress distribution resulting from the model with regional observations, we plot annual average energy released in earthquakes E versus depth. To do this, we use a combined catalog of earthquakes in the Vrancea region (VOROBIEVA *et al.*, 1996). This catalog consists of the subcatalogs of RADU (1979) for 1932–1979, earthquakes in the USSR from 1962–1990 (computer data file, 1992) for 1962–1979,

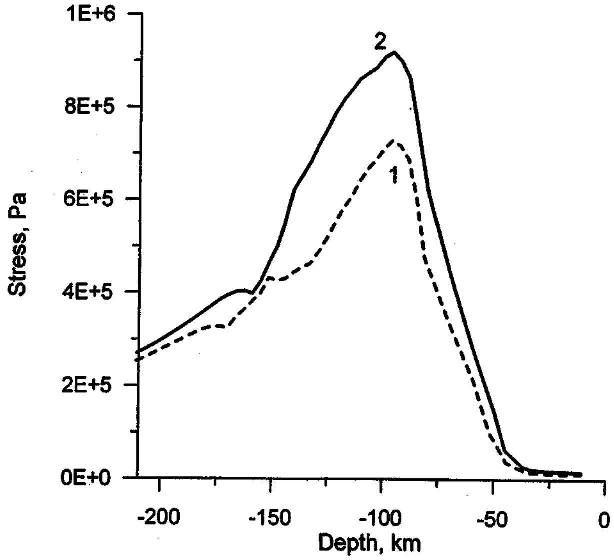


Figure 5
Depth distribution of the average stress in the model for density contrasts 0.4×10^2 kg m^{-3} (1) and 0.7×10^2 kg m^{-3} (2).

TRIFU and RADULIAN (1991) for 1980–1991, and world hypocenter data file USGS-NEIC for 1991–1996. However, we should note that the RADU catalog (1979) contains no depths. Accordingly, we analyze the distribution of earthquakes over magnitude and depth for 1962 to 1996. To calculate annual average energy E, we employ the GUTENBERG and RICHTER (1954) relation between E and magnitude M_s: $\log E = 1.5\ M_s + 11.8$. The two computed curves in Figure 5 show that the stress is the largest in the depth range from about 70 km to 150 km and has a shape similar to that of bar charts of $\log E$ versus depth (Fig. 6). A close inspection of the curves in Figure 5 and of the graph in Figure 6 reveals that the maximum viscous stress is reached at a depth of about 90 km, whereas the maximum energy released by earthquakes is observed at a depth of about 110 km. There is the second peak in energy distribution at a depth of about 150 km. The existence of stress heterogeneities responsible for earthquake occurrence send us to consider other faulting processes at intermediate depths.

Intermediate-depth Faulting Processes

Large earthquakes in the Vrancea region occur within a relic slab sinking in the mantle. It is less obvious that the observed time-space distribution of the large Vrancea events might be explained solely by viscous stress release. High-pressure faulting processes at intermediate depths in the Vrancea slab can also be activated

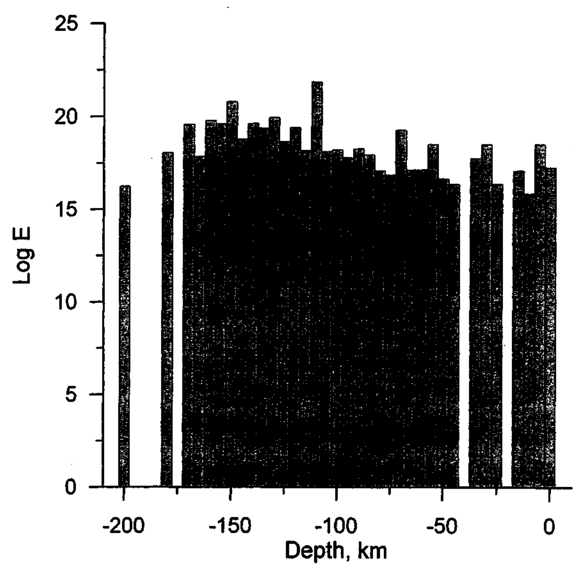


Figure 6
Distribution of the annual average seismic energy released E (measured in J) in 5-km depth intervals in the Vrancea region for the period 1932 to 1996.

by the stress produced by heterogeneities in the volume change due to phase transitions, and/or by the dehydration of rocks, which possibly leads to fluid-assisted faulting.

Phase Transition, Seismic Moment, and Volume Change

Slab metamorphism plays a crucial role in faulting processes at high pressures. Many authors have considered intermediate-depth earthquakes as a result of phase changes from basalt to eclogite in the slab (e.g., COMTE and SUÁRES, 1994). There are two main effects of these exothermic phase transitions (with a small positive Clapeyron slope): deflections of the phase boundary from its normal position and release of latent heat. As for the latter, it slightly changes the temperature of the surrounding material (S. Karato and S. Sobolev, personal communication, 1995) and hence the buoyancy forces. Deflection of the phase boundary depends upon the lateral temperature difference occurring in a relatively cold slab sinking into a hot mantle. The effects of phase transitions in the slab have two implications for the state of stress: (1) the volume change results in a contraction in the direction of the maximum principal stress and in increased compressive stress; and (2) the denser phase acts as an additional load that pulls down the slab and causes an increase of the viscous stress. As a volume within a rock mass undergoes transformation to a denser phase, contraction occurs in the direction of the maximum compressive stress, and large deviatoric stresses are generated within the neighboring rocks, leading to seismic failure.

To estimate the effect on the Vrancea seismicity due to the volume change associated with the basalt-eclogite phase transition, we employ the relation suggested by MCGARR (1977)

$$\sum_{n=1}^{N} M_0^n = \mu l T v_s \frac{\rho_1 - \rho_0}{\rho_1}$$

where M_0^n, is the seismic moment of the nth event caused by the volume change, μ is the shear modulus, l is the length of the slab along strike, T is the thickness of the oceanic crust, v_s is the velocity of descent of the slab, ρ_0 is the density of rocks prior to the phase transition, and ρ_1 is the density of transformed rocks. Given $\mu = 6.5 \times 10^{10}$ Pa (TURCOTTE and SCHUBERT, 1982), $l = 10^5$ m, $T = 10^4$ m (the thickness of a typical oceanic crust), $v_s = 2 \times 10^{-2}$ m yr^{-1}, $\rho_0 = 2.92 \times 10^3$ kg m^{-3} (a typical density of wet basalts), $\rho_1 = 3.5 \times 10^3$ kg m^{-3} (a typical density of dry eclogites), we obtain the annual cumulative seismic moment of about 2×10^{17} N m yr^{-1}.

To estimate the observed seismic moment rate (OSMR) for events in Vrancea in the depth range from 60 km to 170 km, we used the Harvard University Centroid-Moment Tensor Catalog (a computer file, 1977–1995). This catalog contains events with $M \geq 5$, and occasionally with lower magnitudes; the eight largest shocks are listed in Table 3. OSMR is found to be about 1.6×10^{19} N m yr^{-1} for the region. We consider a time period of 19 years that includes most of the largest earthquakes occurring in the region during the last century. In the evaluation of OSMR, the time period considered should be long enough to provide a representative sample of large earthquakes in the region. If the time interval is too short and does not include the largest shocks, it can result in an underestimate of OSMR and, conversely, one may overestimate the moment rate, if the time window encloses an unusual sequence of large events.

If we extend the time window to 1900 in the estimation of the annual OSMR, we must include the 1940 earthquake, with $M_w = 7.7$, a focal depth of 150 km and seismic moment, M_0 of 5.1×10^{20} (ONCESCU and BONJER, 1997). Hence, for this century, we get an OSMR of at least 8×10^{18} N m yr^{-1}. This value can be representative of a longer period of time, considering that the large earthquakes that have occurred since 1600 seem to follow a regular pattern (PURCARU, 1979; RIZNICHENKO *et al.*, 1980; NOVIKOVA *et al.*, 1995).

Thus the cumulative annual seismic moment associated with the volume change due to the phase transition is lower than that obtained from observations, so that a pure phase-transition model cannot explain the intermediate-depth seismicity in Vrancea.

Dehydration-induced Faulting

According to the subduction model for the thermal structure of the Eastern Carpathians, the seismogenic Vrancea zone lies above the 800°C isotherm, which approximately marks the brittle/ductile transition for ultramafic materials (DEMETRESCU and ANDREESCU, 1994). The strength envelop calculated for the Vrancea region points to a strong upper lithosphere where the tensional stress can range up to about 1000 MPa (LANKREIJER *et al.*, 1997).

Table 3

Subcatalog of strong intermediate-depth earthquakes in Vrancea beginning with 1977 event

No.	Date	Time	Latitude	Longitude	Depth	M_0
	m/d/y	h:m:s	°N	°E	km	N m
1	3/04/77	19:21:54	45.77	26.76	84	1.99×10^{20}
2	10/02/78	20:28:53	45.72	26.47	154	4.75×10^{16}
3	5/31/79	07:20:06	45.54	26.32	114	7.26×10^{16}
4	9/11/79	15:36:54	45.56	26.29	143	6.23×10^{16}
5	8/01/85	14:35:03	45.74	26.50	103	7.96×10^{16}
6	8/30/86	21:28:36	45.54	26.29	133	7.91×10^{19}
7	5/30/90	10:40:06	45.86	26.67	74	3.01×10^{19}
8	5/31/90	00:17:48	45.79	26.75	87	3.23×10^{18}

Despite the fact that rocks in the subducting slabs have considerably more strength compared with the surrounding material, the frictional processes resulting from pressure prevent brittle failure. At pressures above 3 GPa (about 100 km of depth), and even at a temperature of 20°C, brittle failure of rock is impossible in the absence of fluids (GREEN and HOUSTON, 1995). On the basis of experimental investigations, RALEIGH and PATERSON (1965) demonstrated that serpentinites (serpentinized peridotites) become brittle as a result of dehydration at high pressures such for which unhydrous rocks are plastically deformed.

It is well known from fracture mechanics that microcracks in rock are generated during brittle failure due to a tensile process (e.g., BRACE and BOMBOLAKIS, 1963; SCHOLZ, 1990; ROTWAIN *et al.*, 1997). The fluid released by dehydration fills the cracks and the pore fluid contributes, together with the stress, to the opening of microcracks by filling them. As macroscopic stress continues to rise, the tensile strength is exceeded and, finally, in some local region the rock becomes fractured so that it loses its ability to support the compressive load, with the resulting formation of a small fault within this region. The fault is bounded by a zone with a high density of tensile microcracks. This zone filled by fluid thus becomes the principal seat of the pore pressure generation that is necessary for fault growth.

Consequently, if a source of volatiles is available, there is a possibility of high-pressure faulting in the slab beneath Vrancea. Obviously, H_2O is carried down with the sediments covering the uppermost part of the slab, and the hydrated oceanic crust contains about 2% of H_2O at 3.0 GPa and 700°C. Moreover, results of recent experimental studies (ULMER and TROMMSDORFF, 1995) show that the subduction of serpentinites containing about 13% of H_2O may transport large quantities of water to depths of the order of 150–200 km. VANYAN (1997) believes that the reaction of dehydration occurring in the sinking slab can easily be detected as zones of electrical conductivity anomalies. In the Vrancea region the electrical resistivity drops below 1 Ω m (STĂNICĂ and STĂNICĂ, 1993) and indicates the upper limit of a conducting zone that correlates with the Carpathian electrical conductivity anomaly (PINNA *et al.*, 1992). Thus, the dehydration-induced faulting in the depth range of 70 to 170 km can contribute to the increase of stress and consequently to the intermediate-depth seismicity observed in Vrancea. This is mainly a qualitative inference; a quantitative estimate of the seismic moment rate associated with the dehydration of minerals in the slab is to be the subject of other specific research.

Discussion and Conclusions

There are essential distinctions between the intermediate-depth seismicity in intracontinental regions and the ordinary Benioff zones. The Pacific seismic zone is a linear extended structure several thousands of km in length and hundreds of km in width. Earthquakes with focal depth up to 60 km dominate these regions. At the same time, the earthquakes in the Circum-Pacific belt clearly concentrate on a nearly continuous circle along the subduction zones, while the seismicity of the Alpine-Himalayan orogenic belt is diffuse and does not correlate with active subduction zones. According to KHAIN and LOBKOVSKY (1994) the intermediate-depth events are observed in southern Spain, Calabria, Hellenic arc, Vrancea, Caucasus, Zagros, Pamir-Hindu Kush, and Assam (Fig. 7).

SPAKMAN (1991) and DE JONGE *et al.* (1994) used seismic tomography to reveal oceanic slabs sinking beneath the Alboran (southern Spain), Calabrian, and southern Aegean regions. The Vrancea and Pamir-Hindu Kush regions are particularly remarkable in that mantle seismicity is concentrated within very narrow zones in the sinking slabs. The intermediate-depth earthquakes in the Caucasus are likely to be associated with a relic Benioff zone dipping under the Greater Caucasus (KHALILOV *et al.*, 1987; GODZIKOVSKAYA and REYSNER, 1989). Therefore, the distinguishing feature of the Alpine-Himalaya seismic belt is its intermediate-depth events in paleosubducted slabs.

Studying the K_2O/SiO_2 ratio for magmatic rocks, BOCCALETTI *et al.* (1973) and BLEAHU *et al.* (1973) suggested that the Vrancea slab was subducted during Neogene time and reached depths of about 160 km where it partially melted and generated calc-alkaline magmas which erupted behind the Carpathian folded arc, building up the magmatic arc. They also believe that the persisting subduction caused an active stretching of the Transylvanian basin and eruption of basaltic magma in the Quaternary. The finite-element model of a descending relic slab allows us to explain the seismic activity in Vrancea: the axes of compression and tension are close to the horizontal and vertical directions, respectively; the maximum viscous stress is found to be at depths of 70 km to 160 km; the model predicts a very narrow area of maximum stress. The simplified numerical model explains, although roughly, the intermediate-depth seismicity in the region, if the seismic energy release depends exponentially on stress. Considering that hypocenters of large earthquakes in Vrancea fall in the narrow area (TRIFU, 1990; TRIFU *et al.*, 1991; ONCESCU and BONJER, 1997), a 3-D modelling of sinking slab seems to be more appropriate for the Vrancea region. Nevertheless the analyzed 2-D model reproduces the main features of spatial distribution of stress in the region.

The seismic moment rate due to the volume change associated with the effect of the basalt-eclogite phase transition in the descending slab is much lower (about 40 times) than that obtained from the events in Vrancea in the depth range of 60 km to 170 km. This suggests that the volume reduction is not likely to significantly contribute to the stress buildup at intermediate depths in Vrancea. Alternatively, the generation of a pore fluid by dehydration of hydrous minerals in the slab may give rise to dehydration-induced faulting. Thus, viscous flows due to the sinking relic slab together with the dehydration-induced faulting can be considered as a plausible triggering mechanism explaining the intermediate-depth seismicity in Vrancea.

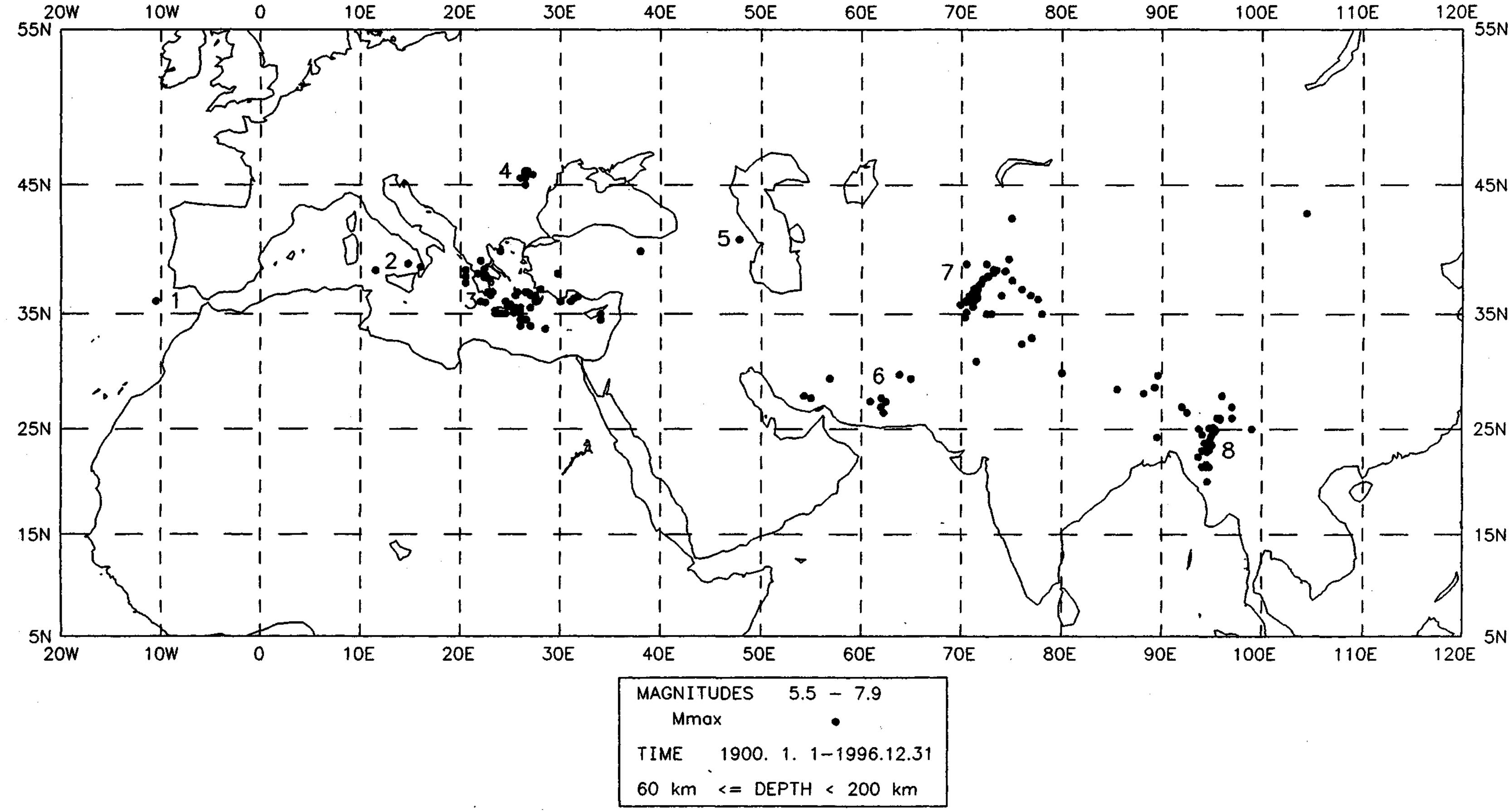


Figure 7

Spatial distribution of intermediate-depth earthquakes with $M_s > 5.5$ in the Alpine-Himalaya seismic belt. (1) Southern Spain; (2) Calabria; (3) the Hellenian arc; (4) Vrancea; (5) Caucasus; (6) Zagros; (7) Pamir-Hindu Kush; (8) Assam.

At the same time, the suggested model and hypotheses of stress generation should not be overestimated, for they still have many limitations and assumptions. The numerical model of a sinking slab cannot explain two separated zones of distinct seismicity in the Vrancea lithosphere at depths of 80 to 110 km and 120 to 170 km as suggested by TRIFU and RADULIAN (1989). The hypothesis of phase changes at the intermediate depths does not support the existing focal mechanism solutions for these earthquakes. The model of stress generation due to dehydration still remains conceptual, because a quantitative estimation of the rate of seismic moment associated with dehydration-induced faulting is required. Hence the model of stress generation in the Vrancea region must be improved to better understand and explain the origin of the intermediate-depth earthquakes.

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Numerical modelling of earthquake flow in the southeastern Carpathians (Vrancea): effect of a sinking slab

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Abstract

The earthquake-prone Vrancea region is modelled as a system of perfectly rigid blocks separated by infinitely thin plane faults. The interaction of the blocks along the fault planes and with the surrounding medium is assumed to be a viscous–elastic. The displacements of the block system are caused by motions of boundary blocks. The velocities of the motions are found from a model of mantle flows induced by a sinking slab beneath the Vrancea region. When a ratio of stress to pressure for some portion of a fault plane exceeds a certain strength level, a stress-drop ('earthquake') occurs. As a result of the numerical simulation a catalog of synthetic earthquakes is produced. Several numerical experiments for various model parameters show that the spatial distribution of synthetic events is significantly sensitive to the directions of the block movements. Small variations in a slab rotation control the pattern of the synthetic seismicity. The results of the analysis show that the catalogs obtained by the simulation of the block structure dynamics have certain features similar to those of the real earthquake catalog of the Vrancea region.

Keywords: Vrancea; Dynamics of rigid blocks; Sinking slab; Synthetic seismicity

1. Introduction

The Vrancea region is situated in the southeastern Carpathians and controls the seismicity of Central and Eastern Europe. It is bounded on the north and northeast by the Eastern European platform, on the east and south by the Moesian platform, and on the west by the Transylvanian and Pannonian basins. The epicenters of mantle earthquakes in the Vrancea region are concentrated within a very small area (about 30×60 km^2, Fig. 1a), and their distribution 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 (Fig. 1b) shows a seismogenic body with length of about 100 km, width of about 60 km, and extending to a depth of about 170 km. Beyond this depth nearly no seismicity is observed: the $M_w = 3.7$ event represents an exception beneath 180 km (Oncescu and Bonjer, 1997).

The updated combined Vrancea region catalog of earthquakes was used in the study (Vorobieva et al., 1996). This catalog consists of the subcatalogs of

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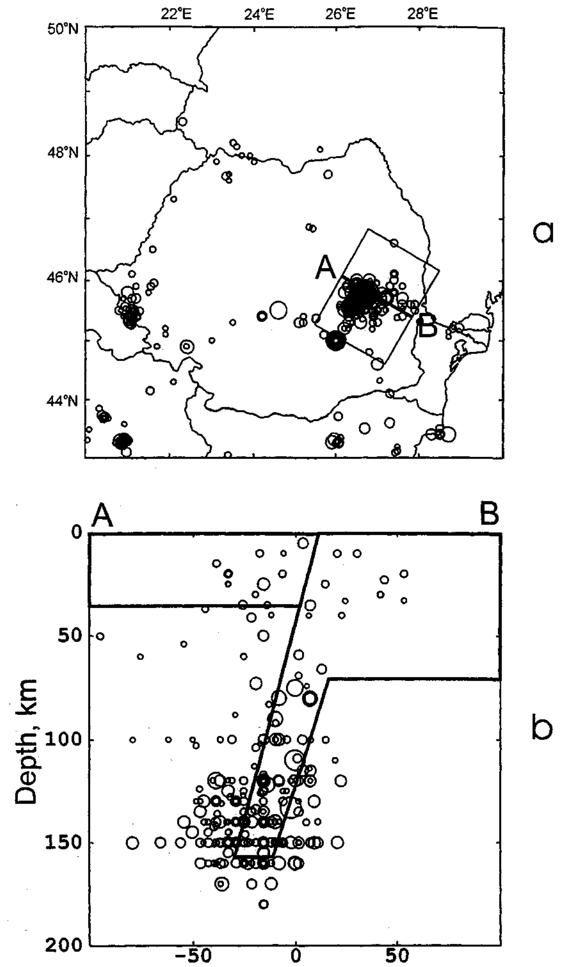

Fig. 1. Map of the observed seismicity in Vrancea. (a) Epicenters of Romanian earthquakes from 1900 to 1996. (b) Hypocenters of the same Romanian earthquakes projected onto the vertical plane AB along the NW–SE direction. Several catalogs have been combined to prepare the figure (Vorobieva et al., 1996).

Radu (1979) for 1932–1979, Earthquakes in the USSR from 1962–1990 (computer data file, 1992) for 1962–1979, Trifu and Radulian (1991) for 1980–1991, and world hypocenter data file USGS-NEIC for 1991–1997. However, we should note that the catalog by Radu (1979) contains no depths. Accordingly, we analyse the distribution of earthquakes over magnitude and depth from 1962 to 1996.

According to a historical catalog (Table 1), there have been 16 large intermediate-depth shocks with magnitudes $M_s > 6.5$ occurring three to five times per century (Kondorskaya and Shebalin, 1977; Purcaru, 1979). In this century, large events in the depth range of 70 to 170 km occurred in 1940, 1977, 1986, and 1990 with moment magnitude, M_w, of 7.7, 7.5, 7.2, and 6.9, respectively (Oncescu and Bonjer, 1997). Using numerous fault-plane solutions for intermediate-depth shocks Radu (1967), Nikolaev and Shchyukin (1975), and Oncescu and Trifu (1987) show that the compressional axes are almost horizontal and directed SE–NW, and that the tensional axes are nearly vertical, suggesting that the slip is caused by gravitational forces.

McKenzie (1970) suggested that large events in the Vrancea region occur in a vertical relic slab sinking within the mantle and now overlain by continental crust. The overriding plate pushing from northwest has formed the Carpathian orogen, whereas the plate dipping from southeast has evolved the Pre-Carpathian foredeep (Riznichenko et al., 1980). Shchyukin and Dobrev (1980) suggested that the mantle earthquakes in the Vrancea region are to be related to a deep-seated fault going steeply down. The Vrancea region was also considered by Fuchs et al. (1979) and Khain and Lobkovsky (1994) as a place where an oceanic slab detached from the continental crust is sinking gravitationally. Oncescu et al. (1984) proposed that the intermediate-depth seismic events were generated in a vertical zone that sepa-

Table 1
Strong intermediate-depth earthquakes in Vrancea since 1600

No	Date (m/d/y)	Magnitude (M_s)
1	9/01/1637	6.6
2	9/09/1679	6.8
3	8/18/1681	6.7
4	6/12/1701	6.9
5	10/11/1711	6.7
6	6/11/1738	7.0
7	4/06/1790	6.9
8	10/26/1802	7.4
9	11/17/1821	6.7
10	11/26/1829	6.9
11	1/23/1838	6.9
12	10/06/1908	6.8
13	11/01/1929	6.6
14	3/29/1934	6.9
15	11/10/1940	7.4
16	3/04/1977	7.2

rates the sinking slab from the immobile part of it rather than in the sinking slab itself.

The active subduction of the slab ceased about 10 Ma ago; thereafter, only some slight horizontal shortening was observed in the sedimentary cover (Wenzel, 1997). 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 with one principal axis directed downward. Earthquakes occur in response to this stress. These forces are not the only source of stress that leads to seismic activity in Vrancea; the process of slab descent may cause the seismogenic stress by means of mineralogical phase changes and dehydration of rocks, which possibly leads to fluid-assisted faulting (Ismail-Zadeh et al., 1998).

The purpose of this paper is to numerically study a dynamical model of block structure, containing a sinking slab, by using results of geodynamic modelling of mantle flow beneath the SE-Carpathians. This model allows the production of a catalog of synthetic earthquakes. The features of this catalog can be compared with those of the real seismicity. It could allow the determination of the properties of an earthquake flow which can be derived from simple assumptions about the processes in the lithosphere.

2. Formulation of block model

2.1. Introduction to the model

We consider the lithosphere to be a hierarchical structure of blocks separated by fault zones where major deformations and most earthquakes occur (e.g., Alekseevskaya et al., 1977). In the model of block dynamics a seismic region is represented by a system of perfectly rigid blocks divided by infinitely thin plane faults (Gabrielov et al., 1990; Gorshkov et al., 1997; Keilis-Borok et al., 1997). 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. The parts of the fault planes where the failures have occurred are in a state of creep immediately after the earthquake for some time, while the stress remains below the certain stress threshold. As a result of the numerical simulation a catalog of synthetic earthquakes is produced.

Panza et al. (1997) 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 catalogs. Ismail-Zadeh and Naimark (1997) and Ismail-Zadeh et al. (1998) developed a finite-element model of a slab sinking gravitationally in the mantle beneath the Vrancea region and showed that the mantle flow induced by the sinking slab controls the shape of the slab, and the depth distribution of the annual average seismic energy released in earthquakes correlates with the depth distribution of stress in the slab. Here we study a dynamical model of block structure, the principal part of which is a sinking slab.

2.2. Geometry of block structure

We consider a layer bounded by two vertical planes (A) and (B) (Fig. 2). A structure of blocks is a limited and simply-connected part of this layer. The horizontal boundaries of the blocks separating distinct rheologically heterogeneous media, such as crust/mantle or slab/mantle boundary, 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.'

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

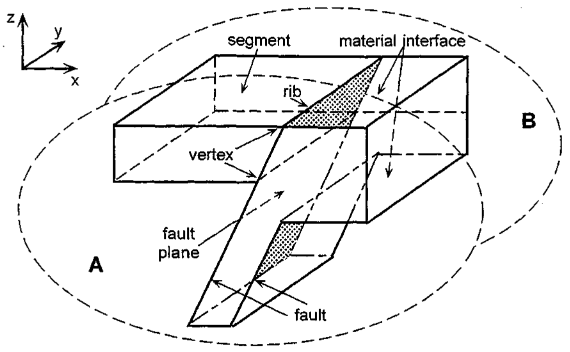

Fig. 2. Geometry of block structure and definitions used in the model.

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 trapezoid. The common part of the block with plane (B) is a polygon and is called 'block flank.'

2.3. 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 found from the geodynamic model of a sinking slab (Ismail-Zadeh and Naimark, 1997). 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 quasi-static 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

$$\sigma_e = K(\Delta \boldsymbol{r} - \delta \boldsymbol{r}) \qquad (1)$$

where $\Delta \boldsymbol{r}$ and $\delta \boldsymbol{r}$ 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 $\Delta \boldsymbol{r}$ are represented by

$$\Delta x = \boldsymbol{x}_i - \boldsymbol{x}_j - (Z - Z_c^i)\varphi_i + (Z - Z_c^j)\varphi_j,$$

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

where X_c^i, Z_c^i, X_c^j, and Z_c^j are the coordinates of the geometrical centers of the block flank; $(\boldsymbol{x}_i, z_i)$ and $(\boldsymbol{x}_j, z_j)$ are the translation vectors of the blocks; φ_i and φ_j are the angles of rotation of the blocks around the geometrical centers 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 $\delta \boldsymbol{r}$ at the point is described by

$$\mathrm{d}\delta \boldsymbol{r}/\mathrm{d}t = W\sigma_e. \qquad (2)$$

The coefficients K and W in Eqs. (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 trapezoid, each fault (boundary) segment is divided into small trapezoids called 'cells'. The values of $\Delta \boldsymbol{r}$ and $\delta \boldsymbol{r}$ 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. We introduce the following ratio:

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

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 $\sigma_e{}^{n}$ is a component of the elastic stress σ_e normal to a fault on plane (A), and α is an angle of a fault plane to plane (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

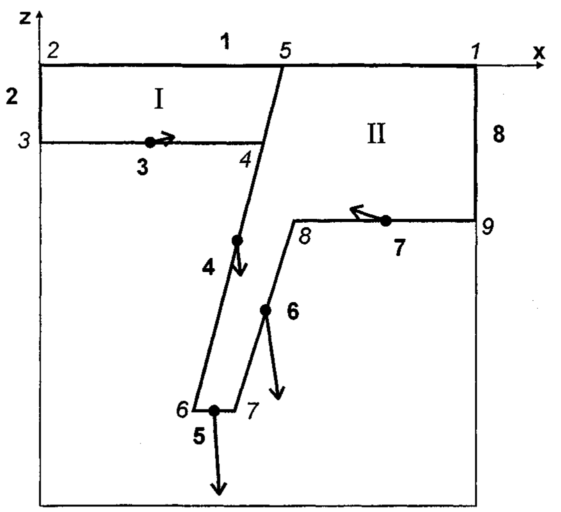

Fig. 3. The block structure used in numerical simulations; the numbers of the vertices (1–9), faults (1–8), and blocks (I and II) are indicated. The arrows stand for velocities of movements of boundary faults.

reaches the level (B), a failure ('earthquake') occurs. The failure is such an abrupt change of the inelastic displacements δr 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.

3. Results of numerical modelling

The configuration of blocks and faults on the vertical plane (A) used in the model is presented in Fig. 3. We consider a simple model of two rigid blocks: the continental crust (block I) and the sinking slab overlain by the continental crust (block II). The z-axis is pointing upward from the roof 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 coordinates (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 2. 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 2. These velocities are found from the numerical model of sinking slab (Ismail-Zadeh and Naimark, 1997). All deformations occur on these faults. We assume the horizontal thickness of blocks to be 60 km which is close to that observed, 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

Table 2
Model parameters of faults

Fault no.	Vertices	K (bar/cm)	W (cm/(bar s))	α (grad)	V_x (cm)	V_z (cm)	ω		
							Case 1	Case 2	Case 3
1	1, 5, 2	0	0	90	0	0	0	0	0
2	2, 3	0	0	85	0	0	0	0	0
3	3, 4	1	0.1	90	0.20	0.07	0	0	0
4[a]	5, 4, 6	1	0.05	85	4.73	−8.82	0	−0.063	−0.126
5	6, 7	1	0.05	90	1.82	−17.93	0	−0.057	−0.114
6	7, 8	1	0.05	85	15.63	−19.61	0	−0.322	−0.644
7	8, 9	1	0.1	90	−0.74	0.13	0	0	0
8	9, 1	0	0	85	0	0	0	0	0

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

and Seki (1954), and S is the sum of the squares of the cell (in km) included in the earthquake.

The synthetic earthquake catalog 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-stabilization of stress. We consider only the stable part of the synthetic catalog. The synthetic catalog contains 96442 events with magnitudes between 5 and 7.1.

To examine an effect of slab rotation on the seismicity, we produce three synthetic catalogs for the different values of angles of fault rotation ω (in 10^{-6} radians) around the origin of the coordinates. Case 1: $\omega_i = 0$ on faults 4 ($i = 4$), 5 ($i = 5$), and 6 ($i = 6$); case 2: $\omega_4 = -0.0631$, $\omega_5 = -0.0571$, and $\omega_6 = -0.3225$; case 3: the angles are increased by a factor of two as compared with case 2 (Table 2). Fig. 4 shows the distributions of the focal depths of the synthetic events (with magnitudes greater than 6.8) for the three cases. The distribution of earthquake hypocenters in the synthetic catalog for case 1 (Fig. 4a) is in good agreement with that in the real catalog (Fig. 1). Inspecting Fig. 4, we conclude that the small variations in the rotation angles result in changes of seismicity. Large synthetic earthquakes occur on faults 5 and 6 in case 1. The slab rotation tends to reduce earthquake magnitudes on fault 6 and to concentrate larger events on fault 5.

The frequency-of-occurrence plots for the observed seismicity and for the synthetic catalogs are represented in Fig. 5. 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 curves corresponding to the synthetic catalog for case 1 (dashed line) and that obtained from the model of Panza et al. (1997) (dot-dashed line) are almost linear, and they have 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 catalog. The gap seems to

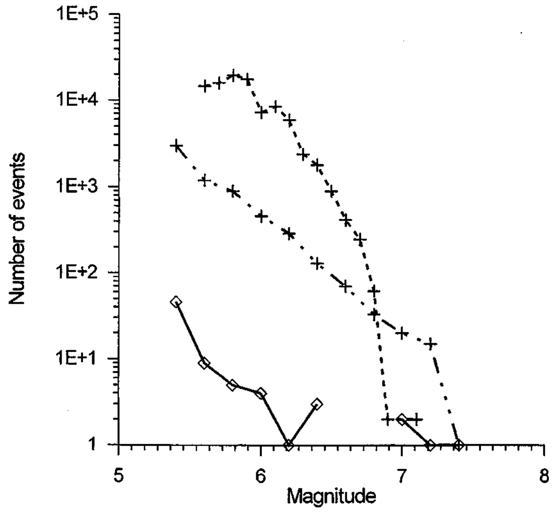

Fig. 5. Frequency-of-occurrence plots for the real catalog (solid line) and for synthetic catalogs obtained with the fault movements without rotation (dashed line) and from the model of Panza et al. (1997) (dot–dashed line).

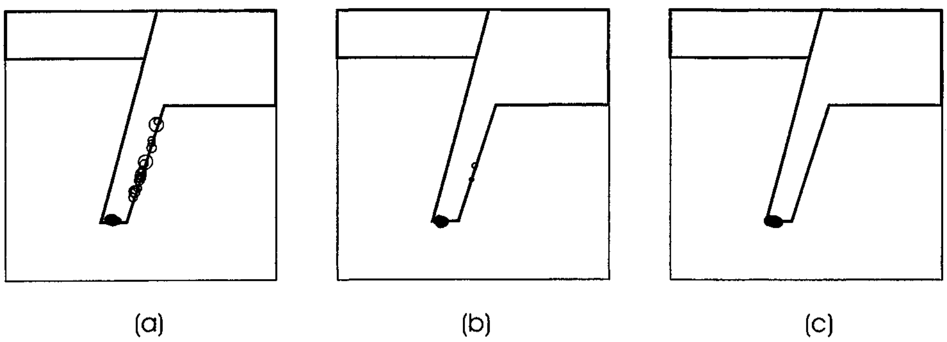

Fig. 4. Maps of the synthetic seismicity of the modeled region obtained from the simulation of the block-structure dynamics: Case 1 (a); case 2 (b); case 3 (c).

be caused by a short time interval for which relevant observations are available.

4. Conclusions

The results of the analysis show that synthetic catalogs obtained by simulations of the block structure dynamics have features similar to those of the real earthquake catalog. Several numerical experiments for various model parameters show that the spatial distribution of synthetic events is significantly sensitive to directions of block movements. Changes in synthetic seismicity due to small variations in slab rotation are in overall agreement with the hypothesis of Press and Allen (1995) which states that small changes in the direction of plate motion control the pattern of seismic release.

The maximum value of magnitude in the synthetic catalog is 7.1, whereas there were events with larger magnitudes in the Vrancea region. It should be noted that the magnitude depends on the number of cells included in a synthetic earthquake. Since the spatial parameters of the seismogenic body are considered in the model to be close to those observed in the region, and the synthetic events can occur on fault segments, we suggest that the temporal–spatial distribution of large Vrancea events cannot be explained solely by the shear stress release. Examination of the seismic moments of the intermediate-depth earthquakes in the region indicates that a realistic mechanism for triggering these events in the Vrancea slab can be the dehydration of rocks, which makes fluid-assisted faulting possible (Ismail-Zadeh et al., 1998).

The observed seismicity shows some clusters of earthquakes which are absent in the synthetic catalogs. This is not surprising since only a few main seismic faults of the Vrancea region are included in the model. Obtaining a more realistic distribution of the synthetic events requires the development of more detailed 3D structures of blocks containing additional fault planes (Soloviev et al., 1996). Nevertheless, the analysed structure, containing only two blocks, reproduces the main features of spatial distribution of the real seismicity.

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