ATTACHED OR NOT ATTACHED: SLAB DYNAMICS BENEATH VRANCEA, ROMANIA

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ABSTRACT

On geological timescales the detachment of descending oceanic lithosphere is a short-term process and can be studied only at few localities on Earth today. The Vrancea region in the SE-Carpathians is one of these rare places. Here, Miocene subduction of oceanic crust of the Tethian Ocean was accompanied by rollback of the subduction zone and slab steepening in its final phase after continental collision had started in Mid Miocene. Seismic tomography determined that the high-velocity body beneath Vrancea extends to a depth of at least 350 km is a vertical position. Within the NE part of this high-velocity body strong earthquakes occur in a very limited seismogenic volume at intermediate-depth (70-180 km). These events are thought to be triggered by slab pull as indicated by the vertical extension axes from earthquake focal mechanism solutions. The SW part of the high-velocity body is aseismic and thus probably already detached from the overlying crust. We present an integrated 4D numerical model to (1) investigate the cause of stress concentrations in the very limited seismogenic volume, (2) test the hypothesis of stress triggering of the strong earthquakes sequence, and (3) quantify the degree of stress transfer from the slab into the crust. Our approach integrates (i) the feedback process of mass redistribution through erosion and sedimentation and its tectonic response, (ii) sources of the observed regional and local stress and strain pattern due to 3D density and strength contrasts including topography, and (iii) mantle processes including the down-sinking slab and stress transfer imposed by the strong earthquake sequence. First, but preliminary results are: (a) The slab is probably only attached in a very small area in the SW of the high-velocity body and the material connecting the slab to the crust is probably rather weak. (b) Static stress transfer can explain the sequence of strong earthquakes and might be an indicator for the location of the next strong event. (c) Lateral tear-off of the deeper, N-S striking part of the slab (> 200 km depth) imposes high shear stresses with vertical extension on the upper NE part of the slab where the strong earthquakes occur.

INTRODUCTION

A sequence of five strong earthquakes (Mw > 6.8) at intermediate depth in the past century near Bucharest initiated intense research activity in this SE part of the Carpathian arc [Oncescu and Bonjer, 1997; Wenzel et al., 1999; Wenzel et al., 2002]. This area is called the Vrancea area. It is bounded by the Trotus Fault and the Peceneaga-Carmena Fault to the NE, the Intra-Moesian Fault to the S and the Transylvanian Basin and the Focsani Basin to the NW and SE, respectively (Fig. 1). The Vrancea region marks the final stage of subduction of remnants from the Tethian Ocean that was subducted toward NW and W [e.g. Sperner et al., 2002; e.g. Stampfli and Borel, 2002]. This subduction ceased in the Vrancea area at c. 9 Ma followed by continental collision. As a consequence the slab steepened to its present vertical position. However, earthquakes below the crust only occur in a very limited

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seismogenic volume located in the NE part of the slab at intermediate depth (Fig. 1 and 2). The tectonic evolution of the Vrancea area as well as the degree of attachment of the slab to the crust is under controversial discussion [e.g. Cloetingh et al., 2004; Csontos, 1995; Gîrbacea and Frisch, 1998; Gîrbacea and Frisch, 1999; Gîrbacea et al., 1998; Gvirtzman, 2002; Martin et al., 2006; Matenco et al., 2007; Matenco et al., 2003; e.g. Sperner et al., 2004; Sperner et al., 2001]. One intriguing feature of the earthquakes in Vrancea is that they mark a relatively short geological time-window of the final stage of slab break-off that can be studied only in very few places on Earth.

![Figure 1](image-url)

**Figure 1.** Seismicity in the Vrancea area recorded 1996-2003. Black circles indicate seismicity at depth < 70 km. Blue and red circles are earthquake at depth > 70 km. The joint hypocenter determination from Radulian et al. [2007] reveals for earthquakes at depth > 70 km the existence of a vertical double seismic zone. Yellow stars mark the location of the October 27th, 2004 (Mw=5.8) and the September 27th, 2004 (Mw=4.7) earthquake, respectively. Black line in the map indicates the location of the depth profile of the inset. Blue dotted line is the 2.2% isoline of the p-wave velocity anomaly at 110 km depth from seismic tomography of Martin et al. [2006, see Fig. 2]. Orange line indicates the 500 m thickness isoline of Quaternary sediments in the Focsani Basin (FB). Thin black lines are the borders of the foreland and the accretionary wedge. Fault mapping and isoline of Quaternary deposit are from Matenco et al. [2007]. TF=Trotus Fault, IMF=Intra-Moesian Fault, PCF=Peceneaga-Carmena Fault. Note the concentration of intermediate-depth earthquakes (70-170 km) in a very confined area.

In 1996 and 1997 two closely collaborating research projects were established, the Romanian Group for Strong Earthquakes (RGVE) under the umbrella of the Romanian Academy (Bucharest) and the Collaborative Research Center (CRC) 461 ‘Strong Earthquakes: A Challenge for Geosciences and Civil Engineering’ at the Karlsruhe University as a project of the Deutsche Forschungsgemeinschaft (DFG). In both groups
scientists from different fields (geology, geophysics, civil engineering, operation research) make a multidisciplinary attempt towards earthquake risk mitigation. Key objectives of the joint research activities are (1) the understanding of the tectonic processes that cause the sequence of strong earthquakes at intermediate depth, (2) the development of realistic models for ground motion prediction, (3) the prognosis of the potential damage due to a strong earthquake, and (4) risk reduction by appropriate civil engineering concepts.

Figure 2. Topography and Moho layer and the isosurface of the 2.2% p-wave velocity anomaly of the Vrancea area from the seismic tomography work by Martin et al. [2006]. Spheres within the high-velocity body are the earthquakes. Red spheres mark the location of the strong earthquakes. Beachballs of the focal mechanism solutions are from map view; black indicates the compressional quadrant. Note the alternating depth of the strong earthquakes.

Our contribution to CRC 461 addresses the first of these four fundamental questions. In particular we focus on three key questions related to the geodynamics of the region: (1) What is the cause of the very limited seismogenic volume? (2) Is there a causal relationship between the intermediate depth strong earthquakes? Here we investigate the hypothesis of triggering of the strong earthquakes due to co-seismic stress transfer. (3) Is the slab still attached to the lithosphere and is there a substantial amount of stress transferred to the crust. We address these question by means of a 4D numerical finite element modeling that describes the contemporary evolution of the displacement and stress field. This 4D integrated model approach will give us new insights into the interdependencies of the processes which act on a wide range of spatial and time scales.

GEODYNAMIC MODEL

The Neogene tectonic evolution of the Carpathians is mainly driven by the NE- and later Eward retreat of a NW-, later W-dipping subduction zone (Fig. 3) [Csontos, 1995]. Subduction retreat pulled them into an oceanic embayment, the last remnant of the Alpine Tethys south of the European continent [Stampfli and Borel, 2002]. When the European continent started to enter the subduction zone, the buoyancy forces of the thick continental crust exceeded the slab pull forces and convergence stopped after a short period of continental thrusting. The age of the youngest thrusting in the fold-and-thrust belt of the accretionary wedge is from 13 Ma in the northern part and from 10 Ma in the south-eastern part [Jiricek, 1979]. This indicates that collision first took place in the northern part of the Carpathian arc while subduction was still going on for a short time in the eastern part (Fig. 3). Today the subducted lithosphere beneath the SE Carpathians, the so-called Vrancea region, is in a sub-vertical position as indicated by the distribution of intermediate-depth earthquakes (Fig. 1) and by the results of seismic tomography (Fig. 2) [Martin et al., 2006; Wenzel et al., 1998; Wortel and Spakman, 1992; Wortel and Spakman, 2000].
Figure 3. Tectonic evolution of the SE-Carpathians. Black line in the present-day map of the tectonic evolution indicates the position of the cross-section of Fig. 5. Note that subduction orientation changes at around 12 Ma (Sarmatian) from E-W to NW-SE probably initiating lateral tear-off.

Fig. 4 presents a WNW-ESE cross section of the geological units and the intermediate depth seismicity with respect to the position of the high-velocity body. Taking into account that the Focsani Basin is still subsiding [Bertotti et al., 2003; Matenco et al., 2007] an attached slab below the basin could be expected. However, this is in contrast to the regional pattern of kinematics observed by GPS [van der Hoeven et al., 2005] and the contemporary stress observations [Heidbach et al., 2007b]. A fully attached slab would result in a regional-wide consistent kinematic and stress pattern that is not seen (Fig. 5 in the following section). Other additional forces e.g. from lithospheric folding and far-field stresses must interact with the slab pull forces transferred to the crust [Bada et al., 1998; Buiter et al., 2002; Cloetingh et al., 1999; Matenco et al., 2007] in order to find a consistent explanation for the geological and geophysical observations. Furthermore, the role of the lateral variability of crustal strength and density contrast need to be taken into account to further develop the concept of tectonic evolution of the Vrancea area [Cloetingh et al., 2004; Heidbach et al., 2007b; Matenco et al., 2007].

Figure 4. Geological profile through the Vrancea region with proposed delamination of slab. Slab outline comes from seismic tomography of Martin et al. [2006] and position of the Miocene suture from geology (e.g. location of accretionary wedge) [Sperner et al., 2004]. LVZ= Low velocity zone as indicated by the seismic profile VRANCEA 2001 [Hauser et al., 2007] and the seismic tomography [Martin et al., 2006]. Note the location of the proposed Miocene suture zone and the present-day location of the high-velocity body (the slab) and the earthquakes within the slab.
DATA AND OBSERVATIONS

Vrancea Seismicity

The Vrancea area is affected by the occurrence of frequent and strong intermediate-depth earthquakes (Fig. 1 and 2). All these events occur within a narrowly confined seismogenic volume with a lateral extension of 30 x 70 km (Fig. 1) in an almost vertical stripe that extends from around 70 to 170 km in depth (inset Fig. 1). The observed focal mechanisms of Vrancea earthquakes [Oncescu and Trifu, 1987; Radulian et al., 2000] as well as the results of a stress inversion by Plenefisch [1996] indicate a thrust regime with thrust faulting regime, i.e. the maximum horizontal stresses are larger than the maximum vertical stress. Two types of focal mechanisms occur. The prevailing type is characterized by a NE-SW striking fault plane and perpendicular maximum compression. All events with $M_w \geq 7$ show this kind of mechanism. Fewer earthquakes have a NW-SE striking fault plane with maximum compression in the NE-SW direction. According to the tomography of Martin et al. [2006] seismicity is located within the cold core of the subducting lithosphere indicating that earthquakes can not be explained by a Wadati-Benioff zone (Fig. 1 and 2). However, the latest result of the joint hypocenter analysis from Radulian et al. [2007] indicates the existence of a vertical double seismic zone.

The rate of seismic moment release of the intermediate depth seismicity within the confined seismic volume is in the order of $0.8 \times 10^{19} \text{Nm yr}^{-1}$ which is comparable to the one from southern California [Wenzel et al., 1998]. This strain-rate is equivalent to c. 2.6 cm yr$^{-1}$ slab elongation. Taking into account that strain-rate localization might have occurred the timescale of the break-off remains an open question, but the high elongation rate indicates that break-off is in its very final stage in the Vrancea area.

Crustal stress observations

Within the framework of the CRC 461 stress information in Romania and adjacent areas have been increased by 108 data records in collaboration with M. Negut and A. Negut (pers. communication). This data are quality ranked according to the scheme of the World Stress Map project [Heidbach et al., 2007b; Sperner et al., 2003; Zoback and Zoback, 1991] and integrated into the WSM database release 2005 [Reinecker et al., 2005]. 98 of the 208 stress data records have A-C quality, i.e. the orientation of maximum horizontal compressional stress ($S_{HH}$) is accurate to within $\pm 25^\circ$. The stress pattern from this compilation does not show any regional trend (Fig. 5). This is in contrast to the results presented by Bada et al. [1998], which indicate a regional trend of WNW-ESE $S_{HH}$ orientation. There are three possible explanations for this enigma: (1) The stress data set used by Bada et al. [1998] probably also included focal mechanism solutions from sub-crustal earthquakes within the subducting slab at 70-130 km (whereas the WSM database only includes data within the upper 40 km of the earth). (2) The smoothing parameter applied by Bada et al. [1998] filtered only the first-order pattern on a plate-wide scale. (3) The smaller number of stress data records available at that time could not reveal the complicated local stress pattern.

The high variability of $S_{HH}$ orientations in our stress map (Fig. 5) is most likely the result of relatively isotropic and thus low far-field horizontal stress magnitudes in the SE Carpathians. Such low or isotropic far-field stress magnitudes allow small local stress effects to control the in-situ stress and thus result in a perturbed stress field. According to Sonder [1990], the net stress field is a superposition of local and regional stresses in dependence on the magnitudes of the regional principal stresses, the magnitudes of the local stress component as well as the angular difference of the regional principal stress directions to the stresses caused by the local stress source. Local additional stresses that are not parallel to the
regional stresses will a change of the orientations of the principal stresses and can also change the faulting style. Similar localized stress perturbations, thought to be due to low and/or isotropic horizontal stresses, are observed in the central and northern North Sea and Permian Basin [Tingay et al., 2006].

Figure 5. Crustal in situ stresses from the World Stress Map Project [Heidbach et al., 2007a; Reinecker et al., 2005]. Red lines on the grid represent the smoothed stress map. Smoothing has been proceeded using the quality- and distance-weighted method of Müller et al. [2003] with a search radius of 100 km for the grid. Note the variation in tectonic regime and the high deviations of the observed data with respect to the stress orientations of the smoothed stress field. Same legend as in Fig. 1.

From the diversity of $S_H$ orientations and the changes in the tectonic regime on short spatial scales in Romania (Fig. 6) we conclude that the contribution from plate boundary forces on the magnitude of tectonic stresses is small and that the stress tensor has similar eigenvalues, i.e. a stress state that is close to isotropic. This implies that second- and third-order sources have a large influence on both the $S_H$ orientation and the tectonic regime in the SE Carpathians [Heidbach et al., 2007b]. Possible local stress sources are topography, lateral density and strength contrasts (Focsani Basin with 11 km depth, foreland, Moesian platform), basin subsidence due to slab pull of a former subduction zone, and stress rotations at active fault tips. Superposition of these stress sources leads to a complex stress field with highly variable $S_H$ orientations and short-scale changes of the tectonic regime.

Furthermore, the high variation of the local stress pattern in Romania puts also an upper bounds to potential regional stress sources in the region such as the degree of coupling of the subducting Vrancea slab. We hypothesize that the slab beneath the Vrancea does not transfer large amounts of stresses to the crust and that the coupling is probably weak. A strong coupling would produce a large regional signal to the stress pattern which cannot be identified in the stress observations. However, this hypothesis still needs to be investigated in detail with a 4D numerical model in order to compare the differential stresses produce by the local stress sources and the ones superimposed from different slab coupling scenarios.
GPS observations

Starting in 1995 a dense GPS network was established in the SE-Carpathians. The first eight stations were installed as part of the CEGRN (Central European Geodynamic Regional Network) project. From 1997 on the network was extended by 28 stations in the framework of the CRC 461 (Geodetic Institute of Karlsruhe University, Faculty of Geodesy of the Technical University of Civil Engineering in Bucharest); in 2002 the Delft Institute for Earth-Oriented Space Research (DEOS) joined the team and 19 new stations were installed including five permanent stations [van der Hoeven et al., 2005]. Data processing and analyses was accomplished in two different ways by using different processing strategies by the Karlsruhe and the Delft groups [Schmitt et al., 2007]. Since the expected vertical and horizontal displacement signal is in the order of 1-5 mm/a the errors bars of the GPS stations are often larger than the signal.

Figure 6. Horizontal component of GPS observations derived in 1996-2006. Velocities are referenced to the East European Platform, that is defined by six permanent international GPS sites referenced in the ITRF 2000. Same legend as in Fig. 1.

Figure 7. Vertical component of GPS observations. Blue arrows indicate subsidence and red ones uplift. Same legend as in Fig. 1.
Fig. 6 displays the horizontal GPS displacement with respect to a fixed Eurasia Plate. In contrast to the work of van der Hoeven et al. [2005] no clear SE-movement of the block between the Intra-Moesian Fault and the Trotus and Peceneaga Fault is identified. Most of the stations within this block and in the foreland show displacements in the order of 1-2 mm yr\(^{-1}\). Exceptions are two stations in the centre of the Vrancea area located above the subducting slab, that show a SE-ward displacement of 4-5 mm yr\(^{-1}\). The vertical GPS observations displayed in Fig. 7 are partly in agreement with the results from other methods such as leveling, fission-track, and geomorphology. They show subsidence in the Focsani Basin, i.e. in the foredeep of the SE-Carpathians, and uplift in the Vrancea region, i.e. in the Neogene flysch nappes (accretionary wedge) of the SE-Carpathians.

However, both velocity fields, the vertical and the horizontal do not show a regional-scale pattern, but local-scale variations with small magnitudes of absolute displacement. Similar to the stress observations this indicates that at present no large-scale geodynamic process controls the deformation pattern, but a number of processes acting on small scale allowing for small scale changes.

**Tectonic geomorphology**

The study of river terraces in the SE Carpathians foreland aims to search for indications of Quaternary tectonic activity. The study uses the relative position of river terraces to determine displacement rates and patterns of vertical motions. This data is to be used for benchmarking of the crustal-scale FE model. In the foreland of the SE Carpathians river terraces of Quaternary age are exposed (Fig. 8). Along the Putna river, Necea et al. [2005] recently mapped terraces and determined their ages based on relative height positions. By means of a longitudinal profile along the river, the authors calculated uplift rates of 0.75 mm/a for the Early Pleistocene, 0.4 mm/a for the Middle Pleistocene and 0.2 mm/a from the Middle Pleistocene to recent.

![Figure 8. Map of river terraces in the foreland of the SE Carpathians (modified after Quaternary deposits map of Structural Geology and Basin Analysis Group, Dept. of Geology & Paleontology, University of Bucharest). Fault mapping and isolines of Quaternary deposits are from Matenco et al. [2007].](image-url)
The terrace study presented herein focused on the lower course of the Trotus river and the Siret river to the area of Focsani. On the basis of previous terrace mapping shown in Fig. 8, longitudinal profiles have been constructed along these rivers. First interpretations of these profiles provide uplift rates in the order of 0.5 mm/a for the Middle Pleistocene, which are in agreement with the results of Necea et al. [2005]. Ongoing work concentrates on determination of uplift rates of Late Pleistocene to Holocene terraces. Furthermore, the effects of movements along individual faults on the terrace levels in the entire Carpathians foreland are investigated. A second part of the geomorphology study focuses on the characteristics of the drainage system. Measurements of gradients along river profiles are used to determine the balance between erosional processes and the effects of faulting activity on the rivers. This data is to be used for comparison with the results of the surface process model.

INTEGRATED NUMERICAL MODEL

The numerical model simulates the evolution of the contemporary stress and strain pattern in order to address three key questions: (1) What is the cause of the limited seismogenic volume? (2) Is there a causal relationship between the intermediate depth strong earthquakes? (3) Is the slab still attached to the crust and is a substantial amount of stress transferred to the crust. Our aim is to link the 3D structural complexity of the crust with the mantle processes and the surface processes (erosion and sedimentation) and their mechanical response in an integrated model approach. In order to assess the seismic hazard we focus on the estimation of the present-day stress state, but still we need to incorporate model times in the order of $10^5$-$10^6$ years to receive a realistic background stress field.

Figure 9. Flowchart of the 4D model approach. (a) Topography, Moho and the 3D representation of the sinking slab with the $+2.2\%$ p-wave velocity anomaly beneath the Vrancea region from a tomography study of Martin et al. [2006]. Colored spheres indicate the earthquake hypocenter with size proportional to magnitude. (b) Discretization of the volume. Mantle elements are not shown.
The model takes into account the changes of density and rock strength of the major geological units such as the Focsani Basin, the basement, the Moho, and the shape of the slab (Fig. 9). It also incorporates the topography and the major active as contact surfaces where relative movement is allowed. The lateral dimensions of the model are 550 km x 380 km and the depth is 900 km. Boundary conditions are gravity, a free surface, co-seismic displacement of the strong earthquakes, and no displacement perpendicular to the model sides and its bottom. The rheology of the model will is non-linear visco-elastic where viscosity of the implemented dislocation creep is mainly controlled by the temperature field of the model.

A critical issue of modeling is always the availability of model independent observations in sufficient density and quality in order to narrow the model parameter space (Fig. 9). This enables us to investigate and assess which process contributes to the observations. Kinematic and stress data are the two major observations which are used for comparison. Seismicity indicates where rock strength is exceeded and provides information on the tectonic regime, seismic strain rates as well as density and temperature distributions. GPS observations measure the contemporary deformation of the Earth’s topography, but in contrast to geological strain release indicators, e.g. from fault-slip analysis, the GPS signal contains both, contemporary strain accumulation and strain release.

In seismogenic region such as the SE-Carpathians deterministic models can quantify the stress accumulation as well as its evolution in time. For the usage of GPS data as independent constraints for numerical model we need to quantify and separate the diversity of signals of the observed deformations. Contributions to the GPS signal originate from a wide range of sources acting on different spatial and time scales: (1) Plate boundary forces such as slab pull or ridge push, gravitational potential energy and mantle drag [Bird, 1998]; (2) Co-seismic displacements [Bürgmann et al., 2002]; (3) Post-seismic displacements such as visco-elastic relaxation of co-seismically induced stress changes [Hergert and Heidbach, 2006], after slip and after creep [Melbourne et al., 2002], silent slip [Douglas et al., 2005], and poroelastic rebound [Cocco and Rice, 2002]; (4) Surface processes: Mass redistribution due to deglaciation, sedimentation and erosion [Pysklywec, 2006]. In order to address the key questions raised in the introduction as well as to understand which geodynamic process contributes to the observed stress and strain pattern, we use the model in the first step to investigate several process. So far we investigated the feedback process of surface processes and tectonics (section 4.1), the co-seismic stress transfer (section 4.2), and the coupling degree of the slab to the crust (section 4.3).

**Coupling of surface processes to crustal tectonics**

It is now well known that the interaction between surface processes (i.e., erosion and sedimentation) and tectonic processes provides a critical feedback mechanism. This feedback controls the evolution of landscapes as well as processes in the interior of the Earth. For a fully coupled 4D numerical model of the Vrancea region this aspect has to be considered. We have developed a software tool called CASQUS that allows for a computation of this interaction. It integrates the erosion and sedimentation routines of the surface processes model CASCADE [Braun and Sambridge, 1997] into the finite element software package ABAQUSTM. CASCADE includes both long-range fluvial sediment transport and short-range hillslope processes (weathering, slope wash, mass wasting and soil creep).

Preliminary finite element modeling results for the region around the SE Carpathians are shown in Fig. 10. Here the coupling between surface processes and the mechanical response was computed for 60,000 a. The finite element model contains the crust and the upper mantle down to a depth of 80 km (cf. the plate that is drawn in Fig. 9. Its dimensions are 550 km from NNE to SSW times 380 km from WNW to ESE (Fig. 10). The vertical side
boundaries are fixed in normal direction. A horizontal plane in 80 km depth defines the fixed lower boundary of the model. No isostasy or viscous behavior is included yet. Both the crust and the mantle are purely elastic, with different tectonic blocks having different elastic material properties and different density. These density variations and the surface topography in combination with the application of gravity lead to stress variations and deformations in the crust.

As expected, the purely elastic response to surficial mass redistribution is negligibly small. The simulated values of the mean uplift or subsidence rate in 3 km below sea level range from +0.005 mm/a to -0.006 mm/a. A fully coupled model, however, that contains deeper parts of the mantle and also addresses viscous behavior and isostasy may give a more pronounced vertical surface uplift/subsidence signal. The integration of surface processes into the complete coupled 4D model will be done in the following months.

**Stress transfer from the slab into the crust**

In this section we investigate with the numerical model (as described in Fig. 9) the coupling degree of the slab to the crust. This is a key issue for most of the observations at the Earth’s surface as a strong and full coupling would be a major control for the kinematics as well as for the stress pattern. Furthermore, also a scenario where full break-off had happened recently would result in a broad scale pattern as e.g. observed in the Puglia region in southern Italy where slab break-off in the Pleistocene led to fast uplift and change of the stress pattern [Bertotti et al., 2001; Hippolyte et al., 1994]. Thus, both scenarios would result in a long wave-length of the stress and strain pattern at the surface. As neither is observed, we hypothesize that the slab is still attached, but that this coupling is rather weak due to strain localization and that the coupling is limited to a very small area.
We test two scenarios: Model B1 assumes that the slab is only attached in the SW of the area outlined by the 2.2\% isoline of the p-wave velocity anomaly (displayed as a dotted blue line in Figs. 1, 5, and 7). In a second scenario, model B2, we assume that the model is only coupled to the crust in the NE, i.e. the area above the intermediate depth seismicity. Both models simulate 100,000 yrs to allow for stationary sinking of the slab.

The results in Fig. 11 indicate that model B2 with coupling in the NE is not capable to reproduce the observed tectonic stress regime. It results into normal faulting where largest principal stress axis is vertical. In contrast to this, model B1 produces thrust faulting and thus favors coupling of the slab in the SW.
Earthquake triggering through co-seismic stress transfer

With our numerical model we test the hypothesis whether the sequence of six intermediate depth strong earthquakes could have been triggered due to co-seismically induced static stress changes. The sequence of these intermediate depth strong earthquakes has three aspects in common: (1) Similar fault planes orientation with thrust faulting regime. (2) The focal depth of the earthquakes is alternating. The first strong earthquake in 1940 occurred at 150 km depth (hypocenter) and was followed in 1977 by an event at 89 km. Subsequent earthquakes in 1986 and 1990 occurred at depths of 136 km and 90 km, respectively. The last earthquake of the sequence in 2004 was located at 97 km depth.

Within the model the earthquake rupture planes are implemented as so-called contact surfaces. On these the co-seismic displacements are described as boundary conditions. During the displacement on one rupture plane all others are kept locked. For the rupture planes we use the following boundary conditions: (1) we define the rupture plane size according to \( \text{Wells and Coppersmith} \) [1994] following: \( \log(A) = a + b M_w \) where \( A \) is the rupture area, \( a \) and \( b \) the regression coefficients, and \( M_w \) the moment magnitude, (2) we assume that the shape of the rupture planes are circles with their centre at the centroid position, and (3) we calculate the average displacement \( d \) by \( M_0 = \mu A d \) where \( M_0 \) is the seismic moment and \( \mu \) the shear modulus. To simulate the co-seismic slip of the rupture planes the hanging wall and footwall at the centroidal planes are displaced by half the average displacement in the rake direction. The summary of all values applied for the rupture plane geometry and the displacement are summarized in Table 1.

### Table 1. Earthquake parameters at the hypocenter of the six strong events in Vrancea.

<table>
<thead>
<tr>
<th>Date</th>
<th>( M_w )</th>
<th>strike ( \varphi )</th>
<th>dip ( \delta )</th>
<th>rake ( \lambda )</th>
<th>lat ( \varphi )</th>
<th>long ( \lambda )</th>
<th>depth ( [\text{km}] )</th>
<th>( M_0 ) ( [\text{N m}] )</th>
<th>( \mu ) ( [\text{GPa}] )</th>
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<th>displacet ( [\text{m}] )</th>
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<td>11.4</td>
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<td>69</td>
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<td>26.73</td>
<td>91.1</td>
<td>3.00E+18</td>
<td>67</td>
<td>5.2</td>
<td>0.53</td>
</tr>
<tr>
<td>2004</td>
<td>5.8</td>
<td>219</td>
<td>81</td>
<td>107</td>
<td>45.79</td>
<td>26.61</td>
<td>96.3</td>
<td>6.00E+17</td>
<td>67</td>
<td>3.0</td>
<td>0.33</td>
</tr>
</tbody>
</table>

As the numerical model solves the equilibrium of forces in 3D we compute from the six components of the resulting stress tensor \( \sigma_{ij} \) the shear and normal stress in order to calculate the Coulomb Failure Stress (CFS). CFS is defined as:

\[
\text{CFS} = |\tau| + \mu (\sigma_n + P) - S
\]  

(1)

where \( |\tau| \) is the magnitude of the shear stress resolved on a given failure plane (positive in the direction of fault slip), \( \sigma_n \) is the normal stress (positive for extension), \( \mu \) is the coefficient of friction, \( P \) is the fluid pressure, and \( S \) is the cohesion \([\text{e.g. Harris, 1998; e.g. Jaeger et al., 2007}]\). Under the assumption that cohesion and coefficient of friction remain constant, and neglecting a change in pore fluid pressure during the tectonic event, the change in CFS caused by stress perturbations induced by a nearby tectonic event can be expressed as:

\[
\Delta\text{CFS} = \Delta|\tau| + \mu (\Delta\sigma_n)
\]  

(2).

\( \Delta\text{CFS} \) only depends on the change in shear and normal stress on the rupture planes. In general, we calculate \( \Delta\text{CFS} \) caused by a tectonic event on the subsequent event in its rake direction on pre-existing rupture planes by assuming a coefficient of friction \( \mu=0.6 \).
The results displayed in Fig. 12 for the single event analysis of the hypocenter show that 4 out of 5 strong earthquakes occurred in areas where $\Delta$CFS is positive and has values in the order of 0.05 MPa at the hypocenter location. Only the 2004 event occurred in an area with negative $\Delta$CFS values in the order of 0.005 MPa. The results of the cumulative analysis show that for the hypocenter all events could have been triggered. All planes show positive $\Delta$CFS values $>0.1$ MPa. The same analysis for the centroid of the earthquakes resulted in moderate to large negative $\Delta$CFS values except for the 1990a event.

<table>
<thead>
<tr>
<th>Single Event</th>
<th>Cumulative Event</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hypocenter Centroid</td>
</tr>
<tr>
<td>EQ 1977</td>
<td><img src="image1" alt="Image" /></td>
</tr>
<tr>
<td>EQ 1986</td>
<td><img src="image3" alt="Image" /></td>
</tr>
<tr>
<td>EQ 1990a</td>
<td><img src="image5" alt="Image" /></td>
</tr>
<tr>
<td>EQ 1990b</td>
<td><img src="image7" alt="Image" /></td>
</tr>
<tr>
<td>EQ 2004</td>
<td><img src="image9" alt="Image" /></td>
</tr>
</tbody>
</table>

Figure 12. Co-seismic stress transfer. Single event analysis: For each event $\Delta$CFS is only calculated for the rupture plane of the subsequent event. 2. Cumulative event analysis: $\Delta$CFS is calculated from all preceding events. Note that hypothesis is only confirmed using the hypocenter location.

CONCLUSIONS

Seismic tomography in the Vrancea area revealed that the sequence of strong earthquakes is located within the NE part of a high-velocity body in a very limited seismogenic volume at intermediate depth (70-180 km). These thrust faulting events are thought to be triggered by slab pull as indicated by the vertical extension T-axes from earthquake focal mechanism solutions. The SW part of the high-velocity body is aseismic. From these observations one could intuitively conclude that the SW part of this high-velocity body is already detached from the overlying crust and that the NE is still coupled to the crust. Observations of the contemporary velocity field and the stress pattern show that no long-wave length stress or strain pattern exists. From this observation we conclude that stresses are close to isotropic. This implies that the magnitude of first-order stress sources such as plate boundary forces from the far-field (Adriatic push) and from slab pull of a fully attached slab must be rather small and local second- and third-order stress sources control the in-situ stress and the deformation pattern in the SE Carpathian.
From our presented 4D numerical model first, but preliminary results are: (a) The slab is probably only attached in a very small area in the SW of the high-velocity body and the material connecting the slab to the crust is probably rather weak. (b) Static stress transfer can explain the sequence of strong earthquakes and might be an indicator for the location of the next strong event. (c) Lateral tear-off of the deeper, N-S striking part of the slab (> 200 km depth) imposes high shear stresses with vertical extension on the upper NE part of the slab where the strong earthquakes occur.

ACKNOWLEDGEMENTS

This research is funded by Deutsche Forschungsgemeinschaft (DFG) through the Collaborative Research Centre 461 ‘Strong Earthquakes – A Challenge for Geosciences and Civil Engineering’ (CRC 461). Birgit Müller acknowledges the financial support of the Heidelberg Academy of Sciences and Humanities. In particular we would like to thank Karen Leevers, Sandra Mertens, Diana Necea, Corneliu Dinu, and Sierd Cloetingh for lively and fruitful discussion during two jointly organized Amsterdam-Karlsruhe workshops on the SE-Carpathians.

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