SHALLOW SEISMIC ACTIVITY (< 55 KM) TRIGGERED ALONG THE MĂRĂŞEŞTI–GALAȚI–BRĂILA LINEAMENT IN RESPONSE TO THE MAJOR SUB-CRUSTAL EARTHQUAKES OF VRANCEA AREA*

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L'activité séismique de faible profondeur (<55 km) déclenchée sur l'alignement Mărăşeşti–Galați–Brăila par réponse aux tremblements de terre majeurs produits en dessous de la croûte terrestre dans la région de Vrancea. On a constaté que pendant les dernières 70 années, après chaque tremblement de terre destructif ($6.9 \le M_w \le 7.7$) produit á une profondeur intermédiaire ($180 > h > 70$ km) dans la région de Vrancea, on a aussi enregistré une notable activité séismique superficielle ($h < 55$ km) sur l'alignement tectonique Mărăşeşti–Galați–Brăila. Pour l'intervalle 1976–1995, pendant lequel les plus récents tremblements de terre destructifs de Vrancea ont eu lieu, cette corrélation entre l'activité séismique profonde et celle superficielle peut être illustrée par la similitude des courbes Benioff auto-normées construites pour chacun des domaines considérés. En revanche, c'est seulement en réconsidérant certaines données historiques qu'on a pu déduire que le tremblement de terre destructif du 10 novembre 1940 ($M_w = 7.7$) a été suivi à son tour par un important événement séismique superficiel ($M_w \approx 5$) localisé sur l'alignement tectonique Mărăşeşti–Galați–Brăila. On conclut qu'on se trouve en présence d'une situation typique, quand l'avènement d'un certain tremblement de terre majeur déclenche à grande distance (plusieurs dizaines de kilomètres en direction horizontale ainsi que verticale), et quelques mois / dizaines de mois plus tard, un tremblement de terre significatif, ou toute une série de tremblements de terre significatifs.

Key words: earthquake-triggering, crustal seismicity, macroseismic intensity, Benioff curve, Vrancea

1. INTRODUCTION

Earthquake triggering is the process by which stress changes associated with an earthquake can induce or delay seismic activity in the surrounding region, or trigger other earthquakes at great distances.

In the case of the *sub-crustal* seismogenic volume of Vrancea area, a Coulomb Failure Stress analysis has been performed by Wüstefeld (2003) and Wuestefeld *et al.* (2003), in order to determine whether the major ($6.9 \le M_w \le 7.7$) seismic events which had occurred in that region during the last 70 years had been independent, or if they had been triggered by the preceding large earthquakes. By considering the same domain, of the *intermediate-depth* Vrancea earthquakes, Radulian *et al.* (2007, 2008) have noticed that the corresponding hypocenters exhibited a non-random distribution – a setting which could not be explained by stress transfer associated to a simple mechanical rupture process. By performing a seismicity pattern analysis, the latter authors additionally inferred that the strong earthquakes located in the upper part of the Vrancea *sub-crustal* seismogenic volume (such as the 1977 earthquake, or the 1990 earthquake) could have been generated in response to the preceding large shocks having occurred below (in 1940 and in 1986, respectively), concluding that the seismicity configuration at shallower depths (including the

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crust) should correspond to that particular triggering mechanism.

In the following, we provide new evidence that at shallow (crustal) levels, a significant seismic activity was triggered in response to the major earthquakes generated at intermediate-depth in Vrancea area. The crustal region which we identified as being concerned by that seismic triggering processes is located along the so-called "Mărăşeşti–Galați–Brăila Lineament" (MGBL).

Our results should provide additional constraints for certain geotectonic models which advocate that a mechanical coupling presently still exists between the Vrancea seismogenic body, on the one hand, and the overlying crust, on the other. Consequently, a central question addressed by such models (for instance, among others, Mucuța *et al.*, 2006, and Enciu *et al.*, 2009) is how the *crustal* deformation in the Carpathians foreland area relates to the Vrancea *sub-crustal* seismic activity.

2. GEOTECTONIC SETTING

The crustal structures possibly concerned by the present-day deformation of the considered area include the stable East European and Moesian foreland units (Fig. 1), which were subject to subduction and continental collision against the Alcapa and Tisia–Dacia intra-Carpathian microplates (Mațenco and Bertotti, 2000). During the Miocene, the indicated subduction and collisional processes resulted in the emplacement of a complex pile of nappes, which consisted of northward-trending successions of Cretaceous–Neogene flysch deposits. The focal region of the Vrancea earthquakes, at the southeast Carpathians Arc bend, is located just beneath that nappes stack.

A NW–SE oriented system of regional crustal-scale fractures (Peceneaga–Camena fault, Trotuş fault) act as a boundary (Fig. 1) between the mechanically weak Moesian Platform and the more competent East-European/Scythian craton (Bertotti *et al.*, 2003). In particular, while the Moesian domain experienced Quaternary tilting (uplift in the thrust belt and subsidence in the foredeep – a setting which Leever *et al.* (2006), interpreted to be the result of crustal/lithospheric buckling induced by the Adriatic plate push), the indicated mechanical strength transition boundary represented by the Peceneaga–Camena–Trotuş faults system prevented the differential uplift and subsidence from being transferred further to the north-east, into the East-European/Scythian domain. At the same time, even nowadays, the Moesian domain appears to be subject to analogous differential vertical motions, as GPS observations (Schmitt *et al.*, 2007) suggest (Figs. 1, 2).

Two distinct patterns have been recognized in the seismicity of Vrancea zone:

- in a *sub-crustal* seismogenic volume, which extends significantly along the vertical (in the 70–180 km intermediate-depth range), being at the same time tightly confined laterally (50 × 20 km), strong and very strong earthquakes (instrumentally determined M_w up to 7.7) occur rather frequently;
- at *crustal* depths ($h < 55$ km) there occur, in contrast, only moderate magnitude earthquakes (instrumentally determined M_w up to about 5), whose epicenters are strewn across a much broader area: the latter domain surface projection essentially overlies the Vrancea *sub-crustal* earthquakes zone, yet also extending farther to the east and to the southeast, mainly in Carpathians foreland domain (Fig. 1).

By considering the unusual high rate of deformation in the *sub-crustal* seismogenic volume (6.3×10^{-15} s^{-1}; Wenzel *et al.*, 1998), and the persistence of reverse faulting mechanisms, with extension on the vertical direction and compression on the horizontal direction, Radulian *et al.* (2007) definitely favored the hypothesis of a subducting lithosphere which was still present beneath Vrancea zone and continued to be attached to the overriding crust. Moreover, in the latter authors' opinion, the very configuration of the crustal seismic activity in Vrancea area would indicate a coupling between the crust deformation and deformation occurring at sub-crustal levels. However, no slab-pull-related pattern could be identified in the recent crustal stress field (Sperner *et al.*, 2001; Heidbach *et al.*, 2007;

Müller *et al*., 2010). In addition, a key observation of Leever (2007) highlighted the fact that the Carpathian Bend zone is nowadays actively uplifting, being consequently decoupled from the presumed downward pull possibly induced by the Vrancea slab. It appears therefore that attempting to document explicit relationships which might exist between the *sub-crustal* and the *crustal* seismic activities of the Vrancea zone still remains a challenging task.

3. INVESTIGATION APPROACH

In an attempt to circumvent difficulties that former investigators encountered in addressing interactions presumed to exist between the sub-crustal and the crustal seismicity regimes of Vrancea area, we divided the broad *crustal* seismicity domain into smaller regions. We have adopted the Vrancea *crustal* seismicity domain subdivisions already suggested by previous investigators (Popescu, Radulian, 2001; Răileanu *et al*., 2007), namely (Figs. 1, 2): the *Râmnicu Sărat* area, the *Vrâncioaia* area, and the *Mărăşeşti-Galaţi-Brăila lineament (MGBL)*. We have specified, in addition, distinct boundaries for each subdivision. Our zonation was essentially based on a visual inspection of the epicenters clustering, while also taking into account the homogeneity of the seismic activity. There were considered the $M_w \geq 2.5$ seismic events with hypocentral depths < 55 km, which the ROMPLUS catalog (available at *http://infp.infp.ro/catal.php*) listed over the 20 years time-interval that spanned from 1976 to 1995; during that period there have occurred the three most recent destructive earthquakes (1977, 1986, 1990, with moment magnitudes 7.4, 7.1 and 6.9 respectively) of the intermediate-depth seismic region of Vrancea.

Next, the present study focused on the MGBL sub-zone. The reason was that the indicated sub-zone incorporated *all* the moderate-magnitude events ($M_w > 4.0$) which had occurred within the broad *crustal* seismicity domain of Vrancea over the considered time-interval (Figs. 1, 2). On the other hand, the two other sub-zones (Râmnicu Sărat and Vrâncioaia) had already been considered by previous investigators (Popescu and Radulian, 2001; Radulian *et al.*, 2007; Ţugui *et al.*, 2009), who yet managed to outline only a series of rather general correlations with the *sub-crustal* seismicity of Vrancea area.

In order to simultaneously compare the seismic activity time-pattern recorded in the MGBL *crustal* domain, with the corresponding time-pattern exhibited by the Vrancea *sub-crustal* earthquakes, we used a procedure analogous to the one proposed by Mantovani *et al*. (1987): the latter authors had noticed that alternating active and quiescent periods of seismicity on the eastern margin of the Adriatic plate boundary were significantly correlated with analogous periods recorded – with a few years time-lag – on the opposite (western) boundary of the same tectonic plate. The similarities in the corresponding seismic activity time-patterns had been documented by means of the so-called "Benioff curves". In devising such diagrams, a magnitude-based estimation of the "seismic release" (Chouliaras, 2009) is first considered:

$$log_{10}\,\Omega = cM_W + d \qquad (1)$$

where M_w is the moment magnitude, c and d are constants, and Ω is a measure of the "seismic release", so that:

– if Ω is the *seismic moment*, or the *seismic energy*, $c = 1.5$ and $d = 9.1$;

– if Ω is the "*Benioff strain release*" (the deformation release), the entire right side of (1) is divided by 2, and thus c and d are correspondingly reduced to half the above-indicated values.

There is next considered the *cumulative* "seismic release" ε at time t (Papadimitriou, 2008):

$$\varepsilon(t) \equiv \sum_{i=1}^{N(t)} \Omega_i \qquad (2)$$

where Ω_i is the seismic release measure associated to the i-th event, and $N(t)$ is the number of events up to the time t.

Finally, by plotting ε provided by (2) as a function of t, the "Benioff curve" is obtained.

We constructed the cumulative "Benioff strain release" diagram (the "Benioff curve", Fig. 3) for the MGBL *crustal* domain, by using the moment magnitudes (M_w) that the ROMPLUS catalog indicated for the earthquakes recorded in that crustal seismicity sub-zone.

An analogous "Benioff curve" has also been constructed for the Vrancea *intermediate-depth* earthquakes: in that case, from the ROMPLUS catalog there were retrieved the seismic events that complied with the hypocenter-depth requirement (≥ 55 km), and with the completeness criterion ($M_w \geq 2.8$) that Enescu *et al.* (2008) stipulated for the intermediate-depth Vrancea earthquakes catalog. As expected, the obtained Benioff curve (Fig. 3) was largely similar to that constructed by Scordilis (2006), who yet utilized a different, composite catalog, and addressed only intermediate-depth Vrancea earthquakes with $M_w \geq 4.8$.

A critical issue needing to be additionally addressed concerned the highly contrasting seismic energy release rates to which the two considered domains – the *crustal* MGBL domain, and the Vrancea *sub-crustal* earthquakes domain – were subject (Radulian *et al.*, 2007). Such a circumstance would have made direct comparison of their Benioff curves difficult. Therefore, the raw values of the cumulative strain have been divided, for each of the two distinct domains, with the corresponding cumulative strain value recorded by the end of the considered time interval (such diagrams were designated by Mantovani *et al.*, 1987, as "autonormalized").

In order to better constrain the periods when a strong seismic activity had occurred within the MGBL domain, earthquake catalogs other than ROMPLUS have also been considered: specifically, the catalog devised by Shebalin *et al.* (1998), the ISC catalog (available at *http://www.isc.ac.uk/search/bulletin/*), and the PDE (USGS-NEIC) catalog (available at *http://earthquake.usgs.gov/earthquakes/eqarchives/epic/epic_rect.php*). The rationale of this approach was that the records of those catalogs would be in principle restricted just to the strongest events (with magnitudes in excess of 3, or even 4) which had occurred in the considered domain.

It eventually proved that of the three catalogs considered in addition to ROMPLUS, the richest information in terms of significant MGBL earthquakes was incorporated by the PDE (USGS-NEIC) data-base. Consequently, our further analysis took into account an additional, supporting criterion, according to which the most important earthquakes having occurred within the MGBL domain were expected to be those that the ROMPLUS and PDE catalogs simultaneously documented.

4. DISCUSSION

In Fig. 3 is illustrated the seismic strain release regime in the *sub-crustal* domain of Vrancea area, as compared to the contemporary strain release recorded in the MGBL *crustal* sub-zone. There can be noticed that several months/tens of months after each major *sub-crustal* event (of 1977, 1986 and 1990 respectively), an intensified seismic activity was recorded in the MGBL *crustal* domain. Alternatively, over the long time-spans which separate those episodes of increased seismicity, the two Benioff curves display gentle slopes which are, moreover, essentially similar.

Previously, by comparing an analogous pair of Benioff curves, Mantovani *et al.* (1987) had conjectured that the large earthquakes located on the western margin of the Adriatic plate were triggered by the major events that had occurred, a few years earlier, on the opposite (eastern) boundary of the same tectonic plate. Similarly, the overall setting recorded in Vrancea area suggests that each of the three destructive *intermediate-depth* earthquakes having occurred between 1976–1995, has triggered a significant seismic activity at shallow (*crustal*) depths in the MGBL domain.

When considering, on the other hand, the MGBL domain earthquakes occurred during the 1976–1995 time-interval and which both the ROMPLUS and the PDE catalogs documented (in accordance with discussion in § 3, above), there can be readily noticed (Figs. 3, 4) that *almost all* those *assumedly main* events belonged to the three previously indicated episodes of intensified seismic activity – *i.e.* they were generated only in the aftermath of a destructive, intermediate-depth Vrancea earthquake. Alternatively, virtually none of the MGBL events having occurred during the seismic quiescence periods outlined in Fig. 3 was also documented by the PDE catalog.

Besides the three previously indicated destructive earthquakes of 1977, 1986 and 1990, another important event has occurred in the Vrancea intermediate-depth seismicity domain on 10th November 1940 (Figs. 4, 5); in fact, this earthquake has been even stronger (M_w = 7.7) than each of the subsequent ones. It would be therefore of interest to analyze if this important Vrancea earthquake has also been followed by a significant crustal event in the MGBL region.

Unfortunately, the seismic recording equipment operating by that time in Romania was generally unable to document rather weak shocks, like those which normally occurred in the crustal seismic region of Vrancea. Accordingly, it was only in early 1950-ies that the currently available catalogs started to mention instrumentally-documented *crustal* earthquakes in Vrancea area.

However. much earlier, on April 28, 1943, a quite unusual seismic event had been recorded, which at the time of its occurrence had not passed unnoticed (Petrescu, 1943, 1944a).

Specifically, the epicenter of that earthquake was positioned more than 40 km to the E with respect to the narrow, well-defined epicentral region of the intermediate-depth Vrancea earthquakes (Fig. 5). In addition, the P and S waves arrivals recorded by various seismic stations were quite atypical (Petrescu, 1943) as compared to those of the "habitual" (*i.e.* intermediate-depth) Vrancea earthquakes. Relying on all these facts, as well as on the distribution of the macroseismic intensities, Petrescu (1944a) estimated that the focal depth of the 28th April 1943 earthquake must have been "abnormally" shallow (specifically, 45–50 km). If his assessment was correct, and considering the fact that the epicenter location he computed fell inside the MGBL domain (Fig. 5), then the 28th April 1943 earthquake could plausibly be included in the distinct category of the MGBL crustal earthquakes triggered in response to a major intermediate-depth Vrancea event – which in this specific case should be the one of 10th November 1940 (Fig. 4).

Further evidence that the 28th April 1943 earthquake has occurred at a shallow (crustal) depth can be derived from its macroseismic intensities distribution. According to the data provided by Petrescu (1944b), the corresponding isoseismal line of intensity 5 extended prevalently along a NW–SE direction; it is well known, in contrast, that the isoseismals of the intermediate-depth Vrancea earthquakes display a predominant NE–SW orientation (Mândrescu and Radulian, 1999; Böse *et al.*, 2009). Even more significant, hazard maps in terms of macroseismic intensities, which Moldovan *et al.* (2008) constructed by taking into account only the *crustal* seismic sources (10–20 km depth) of the concerned region, are very similar (Fig. 6) to the macroseismic intensities distribution indicated for the 28th April 1943 earthquake by Petrescu (1944b).

It is anyway surprising that – at odds with all the above-discussed issues – the hypocentral depth stipulated by the ROMPLUS catalog for the 28th April 1943 Vrancea earthquake is 100 km. Similarly questionable appears to be the magnitude value (M_w = 5.9) ascribed to that seismic event by the indicated catalog. The earliest available assessment (apparently in terms of Gutenberg – Richter magnitude) indicates a more plausible value of 5.0 (Petrescu and Radu, 1961). The latter value seems to be, in addition, consistent with the maximum recorded macroseismic intensities of 5–6 that had been indicated by Petrescu (1943).

5. SUGGESTED KINEMATIC INTERPRETATION

The previously discussed results imply that the strongest events ($M_w \geq 3.4$) of the MGBL domain systematically occurred within a relatively short time-interval (1–2 months to 2–4 years) after a destructive ($M_w \geq 6.9$) intermediate-depth Vrancea earthquake. This setting suggests that seismic activity increase along the MGBL could represent the effect of post-seismic relaxation triggered by the strong earthquakes occurred in the intermediate-depth Vrancea region. A further step in checking this hypothesis was to directly compare the corresponding fault plane solutions for the two indicated categories of earthquakes.

In Fig. 7, overall information concerning the MGBL fault plane solutions for the 1976–1995 time-interval has been corroborated, by taking into account the most comprehensive focal-mechanism catalogs which addressed the considered region (Mostrioukov and Petrov, 1994; Radulian *et al*., 2002; Sandu and Zaicenco, 2008). The illustrated plots were obtained by using WinTENSOR, a software developed by Damien Delvaux of the Royal Museum for Central Africa, Tervuren, Belgium (Delvaux and Sperner, 2003).

The general impression derived from the analysis of Fig. 7 is that the focal mechanisms of the MGBL events are not particularly well-constrained: in many cases, different authors provided strikingly dissimilar solutions for one and the same earthquake (that of 8th July 1985, for instance).

In an attempt to get an overall "clarified" picture, periods of intensified MGBL seismic activity (with fault plane solutions available for earthquakes in the magnitude range $3.3 \le M_w \le 4.4$), have been distinctly considered from periods of "seismic quiescence" (when fault plane solutions were only available for earthquakes in the magnitude range $2.5 \le M_w \le 3.3$).

There became consequently discernible (Fig. 7) that the significant MGBL shocks (those having occurred during the intensified seismic activity periods) exhibited two notable characteristics: an overall NE–SW strike of most nodal planes, and a significant percentage of normal-fault solutions (illustrative in this respect appear to be the rather well constrained events of 19th July 1990, of 11th November 1990, and especially that of 19th July 1987). In contrast, it resulted that most reverse-fault solutions, and a significant percentage of the NW–SE striking focal planes, were characteristic to the weaker events – those which had occurred during the "seismic quiescence" periods.

The observation concerning the frequent occurrence of NE–SW oriented nodal planes in the case of the MGBL *shallow* (and mostly of *normal fault* type) earthquakes, brings forth a series of additional issues:

1. Also the corresponding destructive, *intermediate-depth* earthquakes possess nodal planes which systematically strike NE–SW, being yet always involved in *thrust* deformations (Fig. 7). It is therefore suggested that – at least under a first-order approach – the mechanics associated to both the *sub-crustal* and the *crustal* displacements could be appropriately described simply by considering in-plane deformation (specifically, one which essentially operates within a single, vertical, NW–SE striking plane, Fig. 8).

2. The high percentage of NE–SW oriented slip-planes identified at shallow levels is somehow surprising, when one considers (Fig. 1) the basically NW–SE strike exhibited by the major Peceneaga-Camena fracture zone (it was this latter fault that Răileanu *et al.*, 2007, assumed to account for the MGBL seismic activity). Moreover, the focal mechanisms of the main MGBL seismic events (Fig. 2) appear to be at odds also with the role inferred to have been played by a set of Quaternary *normal* faults, which extend *parallel* the Peceneaga-Camena fracture, within a wide, nearby zone: those faults have been conjectured (Cloetingh *et al.*, 2005; Leever *et al.*, 2006; Mațenco *et al.*, 2007) to accommodate the contrasting behavior recorded between the relatively stable East European/Scythian domain on the one hand, and the crustal/lithospheric buckling recently undergone by the Moesian Plate, on the other (Fig. 1).

3. In fact, it rather seems that precisely this Moesian domain buckling is the one that the MGBL earthquakes accommodate: the corresponding fault plane solutions (Figs. 2, 8), generally imply a tilting (by means of stepwise normal faulting) down toward the southeast – in accordance with the overall displacement experienced nowadays by Moesia.

It results that in attempting to identify an appropriate kinematic pattern for the considered area, three main constraints have to be reconciled: (i) horizontal compression generating brittle failure in the intermediate-depth domain (70–180 km, *i.e.* in the lithospheric mantle); (ii) buckling/tilting-induced horizontal tension, causing normal faulting at shallow depths (<55 km), i.e. in the crust; (iii) both above-mentioned stress fields operating in the same vertical plane (basically, in an in-plane deformation regime).

There appears that a specific group of numerical models actually exist (Toussaint *et al.*, 2004; Yamato *et al.*, 2008; Burov and Yamato, 2008; Faccenda *et al.*, 2008), which indeed accommodate the above-indicated set of constraints. Those models address, in particular, a tectonic regime which Faccenda *et al.* (2008) designated as "two-sided collision": a mantle lithosphere wedge is detaching from the *overriding plate*, to be dragged downward by the sinking *lower plate* and to join in the vertical descent (Fig. 8).

While detailed presentation of specific assumptions and parameters adopted in the above-indicated models is beyond the scope of the present paper, it is nonetheless important to highlight the main relevant features incorporated in the modeling results:

• The overriding plate lithosphere undergoes the indentation of the subducting plate (see Fig. 8, for a schematic illustration of the involved processes), so that the retro-continental lithosphere yields and is crosscut by the indenting slab. It then seems perfectly plausible to assume that the resulting backthrusting, due to the compressive forces applied by the subducting plate, might be accommodated by reverse faulting mechanisms like those systematically recorded in the case of the strong, intermediate-depth Vrancea earthquakes. Similar dislocations may also concern brittle portions belonging to lower-plate crust or even to sediments, which the subducting slab dragged downward in the intermediate-depth domain.

• Large-scale buckling/tilting occurs within both plates, as a consequence of the stronger rheology of the lower crust which ensures its mechanical coupling with the lithospheric mantle. In the case of the subducting plate, such differential vertical motions are expected to be accommodated by horizontal, along-plate extension: this setting seems to be in accordance with most of the fault plane solutions (Fig. 8) computed for the MGBL events that occurred in the aftermath of the destructive, intermediate-depth Vrancea earthquakes. In addition, the crustal tilting down toward the southeast could explain also the intriguing dip exhibited by the Moho surface within the subducting plate: slightly to the east (Panea *et al.*, 2005; Mucuţa *et al.*, 2006; Enciu *et al.*, 2009), *i.e.* away from the Vrancea seismic zone.

• As emphasized by Burov and Yamato (2008), the rheologically "strong" mantle considered in the invoked numerical models serves as a "guide" for tectonic stress. This behavior concerns not only the generally downward-directed subduction/collision processes: it also involves – al least episodically – the upward transfer of the stresses induced by the intermediate-depth backthrusting and associated strong earthquakes: as the lithospheric mantle relaxes, the stress diffuses upwards, to finally result, at shallow depths, in crustal tilting and triggering of normal-fault earthquakes. Such episodes definitely illustrate the fact that the gravitational stretching of the Vrancea intermediate-depth slab might actually exert just a rather insignificant control on the regional stress pattern: instead, stress-distribution in that area seems to be mainly controlled by some kind of "retro-tilting", undergone by the entire L-shaped section of the subducting plate (Fig. 8).

For Vrancea area, a regime somehow similar to the above-mentioned "two-sided collision" has already been suggested by Cloetingh *et al.* (2004). The thermo-mechanical model of the latter authors predicts that two mantle-lithosphere "roots" – one belonging to the subducting plate and the other one to the overriding plate – undergo simultaneous downwelling: the major Vrancea earthquakes are inferred to occur at the contact between those two sub-vertical bodies of the mantle lithosphere – yet the actual failure mechanism is predicted to be *gravity stretching*. In addition, besides explaining the intermediate-depth Vrancea seismicity by gravitational elongation of the slab and its sinking into the asthenosphere, the invoked model also predicts that the mantle lithosphere deformation (associated with the intermediate-depth earthquakes zone) is *decoupled* from that of the lower-plate crust. Moreover, the decoupling between the crust and the mantle lithosphere is also held responsible for the observed crustal-scale buckling occurred in the concerned region during the Pliocene-Quaternary. A somehow analogous numerical model (Toussaint *et al.*, 2004; Burov and Yamato, 2008), which predicts at its turn that the dense part of the Vrancea lithosperic mantle stretches and thins "in a chewing gum manner", even stipulates – in contrast to the model of Cloetingh *et al.* (2004) – that for the considered modeling parameters, *lithospheric buckling is not possible*.

However, when simply considering a stiffer rheology for the lower crust, the numerical model of Toussaint *et al.* (2004) and Burov and Yamato (2008) provide results which are significantly more compliant with the Vrancea zone kinematic constraints: specifically, substantial coupling is predicted to occur between deep mantle-lithosphere deformation on the one hand, and crustal buckling/tilting on the other – in accordance with the previously discussed relationships noticed to exist between the sub-crustal and the crustal seismicity regimes of Vrancea zone. It just appears that Vrancea zone had been improperly ascribed, in each of the above-indicated papers, to inadequate modeling-parameters settings (such a circumstance is, anyway, perfectly understandable, when one bears in mind that in performing their analysis of the Vrancea area kinematics, neither Cloetingh *et al.*, 2004, nor Toussaint *et al.*, 2004, or Burov and Yamato, 2008, were aware of specific interactions possibly existing between sub-crustal and crustal seismicity regimes).

Despite the fact that the previously discussed numerical modeling results exhibit a general compliance with the broad seismo-tectonic behavior of Vrancea area, more specific ("post-seismic stress transfer") modeling approaches are still required (analogous, for instance, to those of Rydelek and Sacks, 1990; Freed and Lin, 2001, or Viti *et al.*, 2003). It is necessary, in particular, to explain the severe contrast in terms of seismic energy release-rate recorded between the Vrancea *sub-crustal* earthquakes domain on the one hand, and the *crustal* MGBL domain on the other. In addition, such modeling should attempt to elucidate the apparently systematic relationships noticed to exist between the intermediate-depth destructive earthquakes magnitude, and the period of time elapsed till the ensuing shallow MGBL event occurs (specifically, the stronger the intermediate-depth shock, the longer the time-lag till the subsequent shallow MGBL event).

6. CONCLUSIONS

Over the time-interval 1976–1995, during which the three most recent destructive earthquakes ($6.9 \leq M_w \leq 7.4$) had occurred in the *intermediate-depth* (sub-crustal) seismogenic body of Vrancea, a distinct time-pattern became discernible also in the *shallow* seismic activity that was developing in a neighboring region. Specifically, it appeared that a few months/tens of months after the generation of a major intermediate-depth Vrancea earthquake, significant earthquakes (maximum M_w in the 3.4-4.4 range) were also generated at shallow (crustal) depths, within the so-called "Mărăşeşti–Galaţi–Brăila Lineament" (MGBL). Alternatively, over the long time-spans which separated those increased earthquake-activity episodes, a weak seismic background was recorded in both considered domains. The indicated overall pattern is clearly illustrated by the fact that the autonormalized Benioff strain-release diagram constructed for the MGBL *crustal* seismicity domain, closely "mimics" the analogous diagram devised for the *intermediate-depth* Vrancea seismic region.

There have been, in addition, reinterpreted certain historic records which provided evidence that also in the aftermath of another, even stronger, Vrancea earthquake – that of 10th November 1940 – a significant seismic event had been generated in the *crustal* seismicity MGBL domain.

There was thus suggested that each of the *intermediate-depth* destructive earthquakes ($6.9 \leq M_w \leq 7.7$) which had occurred in the Vrancea region over the last 70 years have systematically triggered in the MGBL *crustal* domain one or several seismic shocks of rather significant strength (the corresponding maximum M_w values ranged between 3.4 and about 5.0).

The inferred earthquake-triggering process appears to accommodate a "two-sided collision" geodynamic setting, associated, in particular, with a "stiff" lower-crust. Specifically, as the *subducting* plate crosscuts a mantle lithosphere wedge detached from the *overriding* plate, strong earthquakes of reverse fault type are expected to be induced at intermediate-depths. The resulting stresses are transferred upwards – via both the mantle lithosphere and the "stiff" lower crust – to finally result, at shallow depths, in crustal buckling/tilting and associated triggering of normal-fault earthquakes. The post-seismic redistribution of the stress and strain seems to be mainly controlled by the viscoelastic interaction which operates between the "stiff" lower crust (that subduction dragged down to large, lithosperic depths), and the lower viscosity zones of the surrounding mantle lithosphere.

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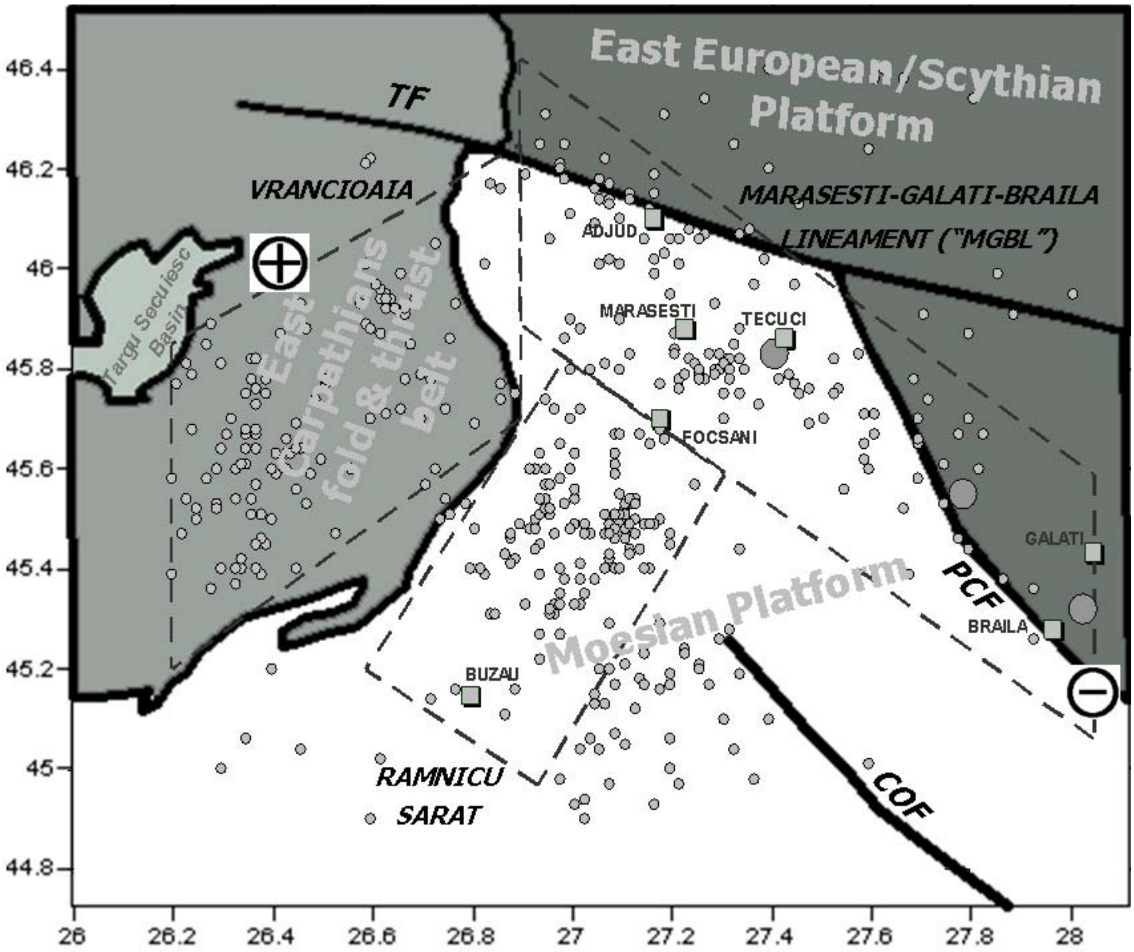


Fig. 1 – General geotectonic setting of the considered area (geology after Dumitrescu and Săndulescu, 1970): TF – Trotuş Fault; PCF – Peceneaga–Camena Fault; COF – Capidava–Ovidiu Fault. Significant present-day uplift and subsidence (as delineated by GPS observations of Schmitt *et al.*, 2007) are indicated by the + and − signs, respectively. Vrancea *crustal* earthquakes (h < 55 km) recorded by the ROMPLUS catalog over the time-interval 1976–1995 are indicated by dots: larger dots indicate the moderate-magnitude events ($4.0 < M_w \leq 4.4$), while weaker events ($2.5 \leq M_w < 4.0$) are indicated by small dots. The dashed polygons outline the crustal seismicity sub-zones *RÂMNICU SĂRAT*, *VRÂNCIOAIA* and the *MĂRĂŞEŞTI–GALAŢI–BRĂILA LINEAMENT* (*MGBL*), as defined in the present study.

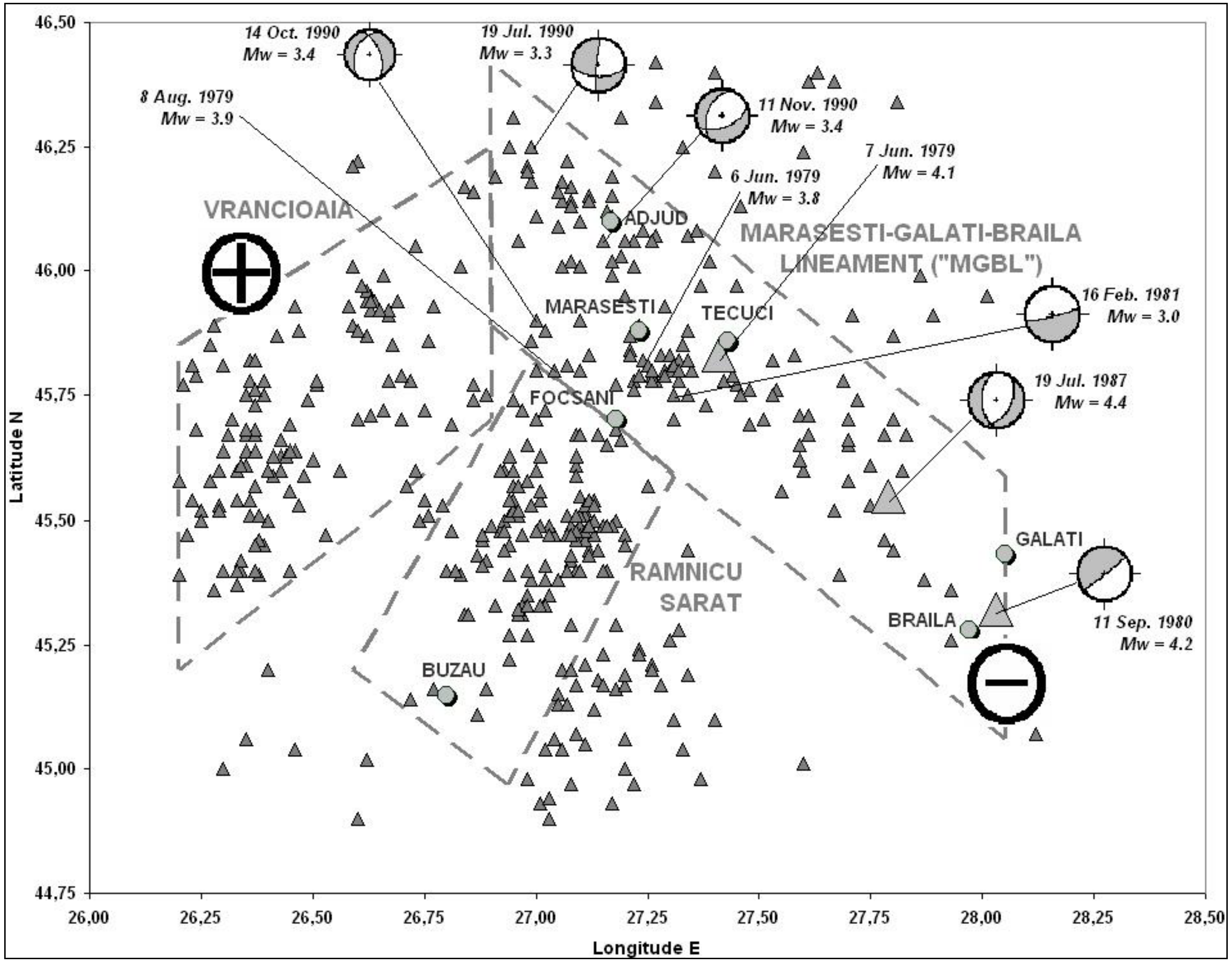


Fig. 2 – Epicenter map of the Vrancea *crustal* earthquakes (h < 55 km) recorded by the ROMPLUS catalog over the time-interval 1976–1995. Large triangles indicate moderate-magnitude earthquakes ($4.0 < M_w \leq 4.4$), while small triangles indicate the weaker events ($2.5 \leq M_w < 4.0$). The dashed polygons outline the crustal seismicity sub-zones *RÂMNICU SĂRAT*, *VRÂNCIOAIA* and the *MĂRĂŞEŞTI–GALAŢI–BRĂILA LINEAMENT* (*MGBL*), as defined in the present study. Labels specifying the date of occurrence, the moment magnitude, and – when available – the focal mechanism (the latter retrieved from Radulian *et al.*, 2002), are provided exclusively in the case of the MGBL *crustal* domain, and only if the concerned earthquakes were documented also by the PDE (USGS-NEIC) catalog. Significant present-day uplift and subsidence (as delineated by GPS observations of Schmitt *et al.*, 2007) are indicated by the + and − signs, respectively.

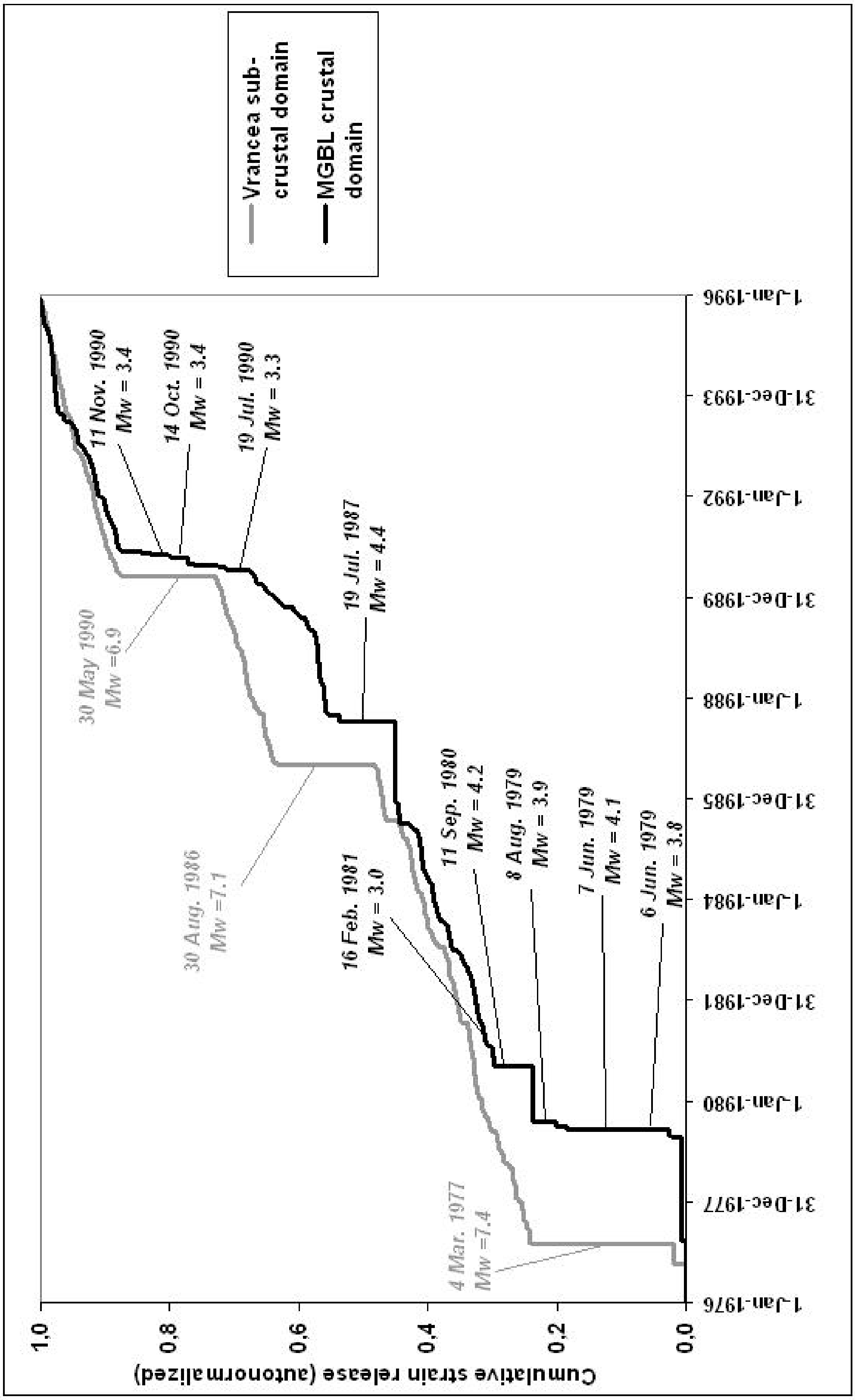


Fig. 3 – Benioff strain release diagrams (autonormalized as indicated in the text) constructed for the Vrancea *intermediate-depth* seismic domain (grey), and for the MGBL *crustal* domain (black). The three destructive, intermediate-depth Vrancea earthquakes of the 1976–1995 period are designated by grey labels indicating the date of occurrence and the moment magnitude. In the case of the MGBL *crustal* domain, analogous black labels specifying the date of occurrence and the moment magnitude are provided only for the earthquakes which are documented both by the ROMPLUS, and by the PDE (USGS-NEIC) catalogs.

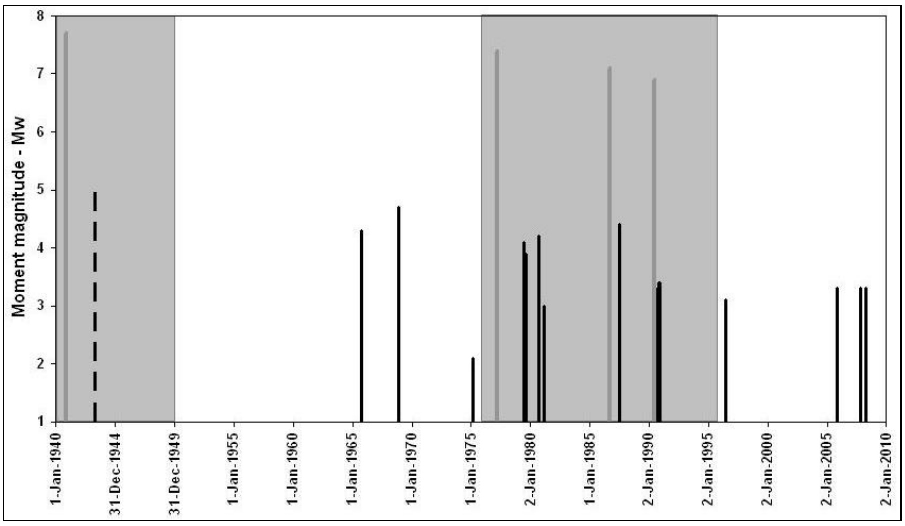


Fig. 4 – Vrancea earthquakes time-series (1940–2010): the *intermediate-depth destructive* earthquakes ($6.9 \leq M_w \leq 7.7$) are indicated by grey solid bars; the MGBL *main* crustal events (those which both the ROMPLUS catalog and the USGS earthquake data-base documented) are indicated by black solid bars; the dashed black bar indicates the only instrumentally-recorded Vrancea earthquake of the pre-1950 period (see text) which was inferred (Petrescu, 1944a) to have occurred at *shallow depth* (45–50 km) and as such, appeared to have had its hypocenter located within the MGBL *crustal* domain. Shaded regions designate the time-periods when significant seismic events in the MGBL crustal domain were recorded only in the aftermath of a destructive, intermediate-depth Vrancea earthquake. Alternatively, within the un-shaded sections of the diagram, no destructive intermediate-depth Vrancea earthquakes occurred; therefore the MGBL crustal seismicity intensifications during such periods must have been controlled by processes other than remote earthquake-triggering.

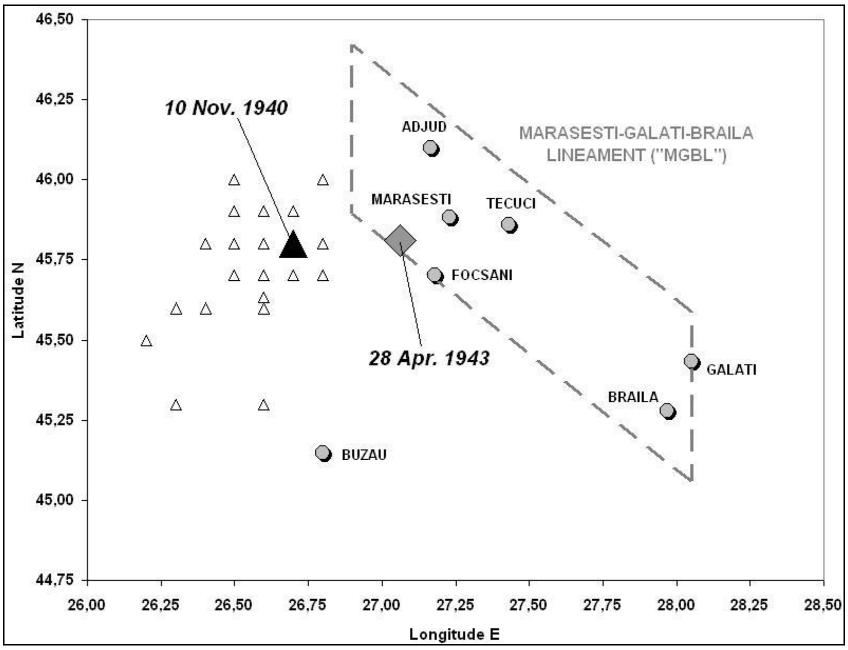


Fig. 5 – Epicenter map of the Vrancea earthquakes recorded over the time interval 1935–1949. Small open triangles indicate the events which undoubtedly occurred in the *intermediate-depth* domain (in fact, instrumentally-documented *crustal* earthquakes in Vrancea area started being mentioned by the currently available catalogs only in the early 1950-ies). The large black triangle indicates the destructive earthquake of 10th November 1940 (M_w = 7.7), which also has occurred at *intermediate-depth* (150 km). The grey diamond indicates the *only* instrumentally-recorded Vrancea earthquake of that period that was inferred (Petrescu, 1944a) to have occurred at *shallow depth* (45–50 km). The dashed polygon outlines the *crustal* seismicity sub-zone of the *MĂRĂŞEŞTI–GALAŢI–BRĂILA LINEAMENT* (*MGBL*), as defined in the present study.

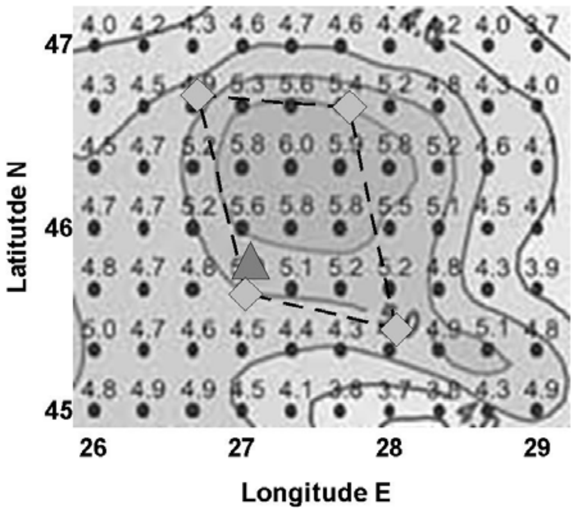
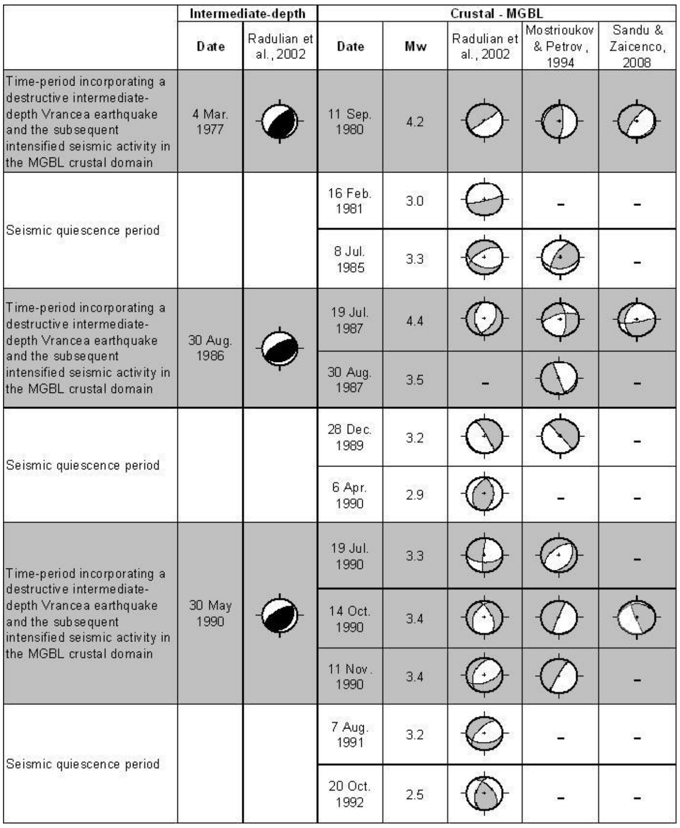


Fig. 6 – The background hazard assessment map has been devised by Moldovan *et al.* (2008) in terms of macroseismic intensities: the intensities are simulated for a return period of 150 years, and only for the *crustal* seismic sources (10–20 km depth) of the concerned region. By superimposing the epicenter of the 28th April 1943 earthquake (the dark-grey triangle), together with the extreme SE, NE, NW and SW localities (light grey diamonds) in which a macroseismic intensity of 5 has been estimated for that earthquake (Petrescu, 1944b), a close similarity becomes apparent in terms of intensity distribution patterns.



	Intermediate-depth		Crustal - MGBL				
	Date	Radulian et al., 2002	Date	Mw	Radulian et al., 2002	Mostrioukov & Petrov, 1994	Sandu & Zaicenco, 2008
Time-period incorporating a destructive intermediate-depth Vrancea earthquake and the subsequent intensified seismic activity in the MGBL crustal domain	4 Mar. 1977		11 Sep. 1980	4.2			
Seismic quiescence period			16 Feb. 1981	3.0		-	-
			8 Jul. 1985	3.3			-
Time-period incorporating a destructive intermediate-depth Vrancea earthquake and the subsequent intensified seismic activity in the MGBL crustal domain	30 Aug. 1986		19 Jul. 1987	4.4			
			30 Aug. 1987	3.5	-		-
Seismic quiescence period			28 Dec. 1989	3.2			-
			6 Apr. 1990	2.9		-	-
Time-period incorporating a destructive intermediate-depth Vrancea earthquake and the subsequent intensified seismic activity in the MGBL crustal domain	30 May 1990		19 Jul. 1990	3.3			-
			14 Oct. 1990	3.4			
			11 Nov. 1990	3.4			-
Seismic quiescence period			7 Aug. 1991	3.2		-	-
			20 Oct. 1992	2.5		-	-

Fig. 7 – Fault-plane solutions of the intermediate-depth destructive events occurred in Vrancea between 1976–1995 (black beach-balls), and of crustal earthquakes occurred within the MGBL domain during the same period (grey beach-balls). Lower hemisphere projections, with white quadrants indicating compression. References specify the catalogs which provided the illustrated focal mechanisms. The moment magnitudes (M_w) are derived from the ROMPLUS catalog.

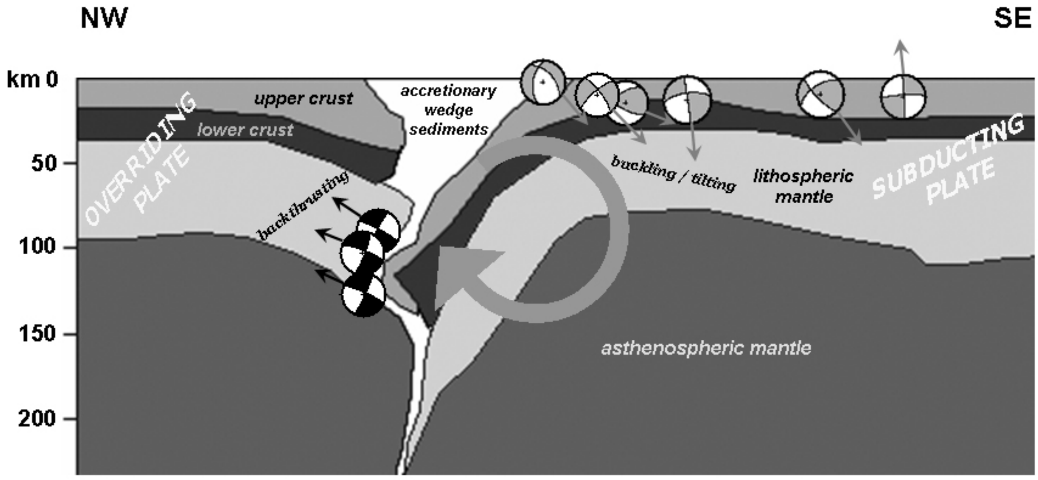


Fig. 8 – "Two-sided collision" setting (cartoon compiled from various numerical models – Toussaint *et al.*, 2004; Yamato *et al.*, 2008; Burov and Yamato, 2008; Faccenda *et al.*, 2008; Warren *et al.*, 2008), which suggests a general analogy with the main seismo-tectonic features of Vrancea zone. In particular, model predictions (backthrusting in the overriding plate, as a result of the compressive forces applied by the subducting plate) are consistent with the focal mechanisms of the major (1977, 1986, 1990) intermediate-depth Vrancea earthquakes (black beach-balls, transposed here in a vertical view, with arrows indicating hanging-wall displacements). On the other hand, the crustal/lithospheric buckling predicted to occur within the subducting plate seems to be accommodated by deformation associated with shallow MGBL events (indicated by grey beach-balls, with arrows showing hanging-wall displacements: notice that exactly the same fault-plane solutions are also displayed in Fig. 2, yet here the beach-balls are transposed in a vertical view). The thick curved arrow suggests subducting plate episodic displacements, inferred to be responsible for triggering the shallow events in the aftermath of the destructive, intermediate-depth earthquakes.

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