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HOMMAGE À DOREL ZUGRĂVESCU, MEMBRE CORRESPONDANT DE L'ACADÉMIE ROUMAINE, À L'OCCASION DE SON 80e ANNIVERSAIRE / HOMAGE TO DOREL ZUGRĂVESCU, CORRESPONDENT MEMBER OF THE ROMANIAN ACADEMY, AT HIS 80th ANNIVERSARY

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DOREL ZUGRĂVESCU AT HIS 80th ANNIVERSARY

In 2010, the geophysical community celebrated the 80th anniversary of Dorel Zugrăvescu, member of the Romanian Academy, distinguished successor of a gallery of great scientific personalities of the Romanian Geophysics, reputed researcher in the field, promoter and organizer of research in Geodynamics. As a follow up, the present volume of the Revue Roumaine de Géophysique (Romanian Geophysical Journal), edited by the Romanian Academy with significant and sometimes decisive efforts of Dorel Zugrăvescu, is dedicated to the celebration of his personality. A presentation of Dorel Zugrăvescu's activity, following these introductory words, and several scientific papers written on purpose as a homage to his personality and leadership, have been chosen for this celebration.

* * *

Born on the 25th of November, 1930, Dorel Zugrăvescu is the first of the three sons of a family of intellectuals: father, a well-known lawyer, and mother, from whom he inherited the sensitivity, published poetry and prose and established the literary magazine "Slovar". The youngest brother is a well-known jurist and the middle one, deceased, was a reputed chemist.

Dorel Zugrăvescu graduated with Highest Honours the high school "Alexandru Lahovary" in Râmnicu Vâlcea, in 1948, and with "Merit Diploma" the Geophysical Department of the Mining Institute in Bucharest, in 1954. Also, from his childhood his love for nature formed, strengthened during adolescence, in the frame offered by the Olt Valley and Vâlcea surroundings. He began the research

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activity while a student, under the supervision of Acad. Prof. George Atanasiu, participating at monitoring the space-time variation of the geomagnetic field in Romania. In 1955, following a contest, he got the position of scientific researcher at the Institute of Physics and in 1965 the position of senior scientific researcher at The Center of Geophysical Research of the Romanian Academy, where he created the Laboratory of Geodynamics. Since 1977 Dorel Zugrăvescu has also taught the course of Geodynamics at the Geophysics Department of the Geology and Geophysics Faculty, Bucharest University. Since 1990 he has been a supervisor for PhD studies. In 1991 Dorel Zugrăvescu was elected corresponding member of the Romanian Academy.

The scientific domain that has brought to him the recognition as a top researcher in the Romanian and international Geophysics, has been the Geodynamics.

The initiation in Romania of research in instrumental geodynamics – the construction of research facilities and training of the first specialists – began in 1961, on the occasion of the total solar eclipse, by setting up, with own construction equipment, of the first observatory of geodynamics in Eastern Europe, at Căldăruşani. The recordings were taken with the approval and support of the then abbot of the Căldăruşani Monastery, today his Excellency Gherasim Cristea, Bishop of Râmnic, in a building of the Căldăruşani Monastery, with thermo-insulating thick walls and stabilized foundations in about 100 years of existence. That beginning established the basis of the first collaboration of an orthodox church – The Romanian Orthodox Church – and science – The Romanian Academy, the Laboratory and later the Institute of Geodynamics. In the over 50 years that passed from the first recordings of the earth tides, Dorel Zugrăvescu has established a network of polygons and observatories of geodynamics, equipped with own construction horizontal pendulums, water-tube tiltmeters, extensometers, and other specific devices that allowed high quality measurements, comparable with those made in the best observatories of the kind in economically and technically developed countries.

As a result of an ample scientific and managerial activity of Dorel Zugrăvescu, after transforming in 1990 the Laboratory of Geodynamics into a research institute, the Institute of Geodynamics, the material and human basis of the experimental geodynamics consolidated through:

– structuring the Institute as a strong research group, helped by skilled technicians and workers;

– constructing new sensors and recording systems, such as tiltmeters with vertical pendulum, mono- and tri-axial quartz extensometers, and mobile laboratories destined to study the deep structure of the crust and deformation and displacement of tectonic compartments;

– structuring three astro-geodynamical polygons, of which the Căldăruşani-Tulnici one, allowing the monitoring of space-time evolution of some parameters causally linked to accumulation/ triggering of seismic energy in the Vrancea geodynamically active area, presents an undisputed major scientific, social, and economic interest;

– participation, with own construction equipment included, to research activities in other world geodynamically active areas, such as the geodynamic polygon Piton de la Fournaise, the Reunion Island in the Indian Ocean, or areas in Europe (Black Forest Mountains – Germany, Southern Belgium, Arette and Chamonix – France, Tonale – northern Italy);

– setting in 2001 the International Virtual Laboratory of Geodynamics, in cooperation with the All-Union "O. Yu. Schmidt" Institute of Earth Physics of the Russian Academy of Sciences, coordinated according to Statutes by the two founding members – Dorel Zugrăvescu, corresponding member of the Romanian Academy, and, respectively, Acad. V. N. Strachov. Later on, experienced researchers from France, Belgium, Germany, Luxemburg, United Kingdom, Italy, Austria, Hungary, Republic of Moldova, Ukraine have been admitted too;

– by organizing, in bi- and multi-lateral partnerships, of common research themes with Romanian and foreign researchers;

– establishing, in 2004, of the Geodynamics Chair – UNESCO Bucharest.

The scientific results published by Dorel Zugrăvescu as unique author or in collaboration, in more than 100 papers, refer both to instrumental geodynamics and, due to the original approach and data analysis, to some aspects regarding crustal movements, tectonic stress distribution, water contribution to tectonic processes, monitoring space-time evolution of the natural fields and of certain parameters causally linked to accumulation/ triggering of tensions responsible for earthquake occurrence. His views on the displacements of tectonic compartments as limited plasticity and elasticity entities changed the image of recent crustal movements maps. A notable opportunity to internationally affirm these conceptions and the results obtained, under Dorel Zugrăvescu's leadership, by researchers of the Institute of Geodynamics was the European Mission of Geodynamics, an unprecedented action that took place in the summer of 2000.

Toward the end of this presentation, I would like to underline what I think very well characterizes the personality of Dorel Zugrăvescu, namely the full implication in solving important problems of the Romanian scientific research, in general, and of the geophysical one, in particular, especially in difficult times for the research. Some examples would illustrate that:

In the 70s and 80s of the last century, extremely difficult decades experienced by the Romanian Academy, in his capacity of

– Scientific Secretary of the Editorial Boards of the geophysical journals published by the Romanian Academy, Dorel Zugrăvescu essentially contributed to maintaining the continuity of academic publications and of the international book exchange;

– Secretary General of the Romanian National Committee for Geodesy and Geophysics, had a decisive part in organizing, every other year, the Earth Physics and Applied Geophysics symposia, and in maintaining the affiliation of Romania to the international organizations in the field;

– Honorary Scientific Secretary of the Geological, Geophysical, and Geographical Sciences Department of the Romanian Academy, he significantly contributed to the continuity of academic activities.

Closer to our time, I would like to mention only the successful efforts to ensure the free of charge services for the journal exchange of the Romanian Academy, and, not in the least, his essential contribution to obtaining more decent salaries for the researchers of the Academy system of institutes.

Dorel Zugrăvescu is the founding and Honorary Director of the *Sabba S. Ştefănescu* Institute of Geodynamics of the Romanian Academy, the President of the Romanian National Committee for Geodesy and Geophysics of the Romanian Academy, President of the Remote Sensing Commission of the Romanian Academy, member of the National Romanian Committee for the International Program Geosphere-Biosphere, Editor in Chief of the journals *Revue Roumaine de Géophysique* and *Studii şi cercetări de geofizică*, member in the corresponding sub-commission of the National Council for Assessing Diplomas and University Certificates, member in the College of Directors of the Romanian Space Agency, founding and full member of the Romanian Technical Sciences Academy (AŞTR), President of the Oil Engineering, Mining and Geonomy – AŞTR, member of the Romanian Geophysical Society, member of the Romanian Physical Society and president of the Earth Physics Department, Honorary Member of the General Association of Engineers in Romania, Honorary Member of the Civil Engineers Society in Romania.

Dorel Zugrăvescu has been distinguished with the National Order *Pentru merit*, *în grad de Ofiţer*, and with several Excellency Diplomas (Romanian Academy, ANSTI, MEC), is *Doctor Honoris Causa* of Petroşani University, and *Doctor Honoris Causa* of The Society for Alternative Medicine (USA).

The scientific activity has been doubled also by a remarkable managerial activity that allowed the scientific research in the Institute of Geodynamics to develop in its 20 years of existence. Not in the least, we underline also the humanistic culture of Dorel Zugrăvescu, his artistic sensitivity, and his devotion capacity. Everybody, professors, colleagues, collaborators and friends, know how dedicated Dorel Zugrăvescu is when offering his help in case of health problems.

I cannot conclude without mentioning the presence of his spouse, the distinguished Mrs. Olga Zugrăvescu, with her discrete but strong support, in the life and actions of Dorel Zugrăvescu, the scientist we celebrate at his 80th anniversary.

CRIŞAN DEMETRESCU

IDENTIFICATION OF CHANGE IN SPATIO-TEMPORAL PATTERNS: TWO MULTISCALE APPROACHES TO VOLCANIC SEISMICITY

Dedicated to Professor Dorel Zugrăvescu, on his 80th anniversary

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L'identification des changements dans les modèles spatio-temporels: deux approches multi-échelle pour la séismicité volcanique. La séismicité liée à l'activité volcanique est à la fois importante pour l'étude des volcans et difficile à caractériser de façon utile. Les événements séismiques impliquent des processus irréversibles (ruptures, glissements, dissipation de chaleur, reconfigurations du stress). Par conséquent, la succession des tremblements de terre à travers une certaine période de temps et les influences réciproques des événements ne devraient pas être ignorées. Pour la caractérisation de ce type d'ensembles spatio-temporels, l'article présente deux approches multi-échelle complémentaires: l'analyse des fils d'événements et l'analyse des réseaux. L'analyse des fils d'événements reflète les relations inter-événement des tremblements de terre successifs dans l'espace tridimensionnel. L'analyse du réseau décrit la connectivité dans les séries de séismes qui se produisent à travers de différents intervalles de temps. Les deux approches peuvent être facilement incluses dans des programmes de surveillance séismique. Les méthodes sont illustrées avec des exemples d'application pour la Grande Ile d'Hawaii.

Key words: seismicity patterns, volcanoes, Hawaii, events thread analysis, network analysis.

1. INTRODUCTION. PREMISES AND GOALS

Change has become a defining keyword for today's world. Rigorous identification of change in complex patterns represents an important goal in many disciplines in the natural sciences, the social sciences, economics, etc. Paradoxically, while the available methodology dedicated to this goal has become increasingly powerful, rich, and diversified, so have the challenges it must face. Our approaches shed more light on some aspects of the studied systems, but by doing so they also uncover deeper layers, previously unknown or considered simply negligible.

Perhaps the best paradigm in this regard has been offered by complexity science. Not only has it opened the lid to what was previously often considered a "black box", but it has proven that looking into the box does not provide us with the "complete" view we expected. In one way or another, "boxes" typically possess intricate depths and elaborate interconnections, which transcend walls and ignore box delimitations. New approaches have continued to emerge, based on novel ways of crossing disciplinary boundaries and innovative attitudes towards scale, predictability, and strongly irregular dynamics.

One of the significant lessons drawn from these endeavours speaks to the fact that no particular method is able to exhaustively describe complex natural patterns. Each approach and each method can only provide a certain perspective regarding the studied systems, with some methods being more valuable to specific tasks than others. Therefore, to get a comprehensive picture of a given complex systems it is worth considering more than just one method of analysis.

The aim of this paper is to illustrate a dual approach to patterns in geosystems, with the goal of characterizing them and identifying their change.

Seismicity related to volcanic activity is both relevant to the study of the dynamics of volcanoes, and challenging to characterize in a comprehensive and useful way (Chouet, 2003).

Numerous approaches to the evaluation of seismicity patterns exist. Most studies consider sets of earthquakes seen side-by-side, and aim at geometrically describing the patterns of points. However, since seismic events typically involve irreversible processes such as rupture, slip on rough surfaces implying heat dissipation and stress reconfiguration, the succession of earthquakes in time and mutual influences among events are important to consider. Different paths can be addressed for the evaluation of event-event interaction. The paper presents recent results we obtained in this direction in a multiscale perspective. It will show that quantitatively evaluating patterns on a range of scales can significantly support the search for relevant information regarding their temporal change.

On one hand, by choosing to study seismicity patterns, one faces relatively high complexity due to strongly variable patterns, which can be characterized from the point of view of time, space, and event size. On the other hand, the analysis tasks ultimately refer to sets of points, which offer a greatly simplified access to the evaluation process, compared to other spatial features.

One should bear in mind, however, that the point-like nature of pattern components is an approximation. Neither the temporal nor the spatial characteristics of seismicity are, in reality, point-like. The temporal approximation is based on the discrepancy between the time scales corresponding to individual earthquakes and those involved in stress accumulation, magma movement, etc. The spatial approximation takes into account the fact that the areas involved in earthquake processes are small compared to the distances among the various events.

Although seeing earthquakes as points in space and in time has become a widespread approach, we think that it is worth remembering that such an approach represents a model that relies on an approximation process. Moreover, depending on the specifics involved in the studied volcanic and tectonic processes and the spatio-temporal scales of interest, the above-mentioned scale contrasts underlying the model may not always be strong enough to grant this simplification.

Therefore, even if the spatial and temporal context considered in this paper is expected to offer proper conditions for the application of space-time points approximation, it is important to remember that the results of the study are obtained based on point-model premises.

2. APPLICATION AREA

The presented methods are expected to be particularly effective in situations that fulfill several requirements:

– the area should be subject to intense volcanic and seismic activity (which leads to rich datasets reflecting temporal changes in the studied patterns);

– long-term reliable information concerning seismicity and volcanic processes should be available;

– events should be confined to an area that can be objectively isolated from the surroundings (to avoid arbitrary cuts in datasets).

The Big Island of Hawaii fulfills these criteria. It is characterized by active volcanism (Kilauea is one of the most active volcanoes on Earth – Decker and Decker, 1998) and is subject to intensive monitoring (Ryan, 1988; GVP, 2007). The study area lies between 18.50º and 20.51º northern latitude, and between 154.50º and 156.51º western longitude. Earthquakes data from the Advanced National Seismic System (ANSS) catalog were used for this study. To preserve catalog homogeneity, we have delimited the time interval to the period from 1989 to 2005. The number of earthquakes that are available in this space-time window is 41,260. Each event is specified in terms of spatial position, time of occurrence, and magnitude.

Volcanism in Hawaii is related to hot spot activity. The Island of Hawaii includes five volcanoes: Hualalai, Mauna Kea, Kohala, Kilauea and Mauna Loa, Kilauea being the most active among them. Eruptions do not occur only at the volcano summit: two major rift zones are present on the island (Fig. 1), representing areas of eruption and increased seismic activity. These areas are characterized by strong space-time variability in terms of earthquake patterns. The generation of fractures and the injection of magma into rift zones lead to earthquake swarms, mainly at shallow depths. The largest events in such swarms usually have magnitudes up to M = 3, although larger events (M > 5) have also occurred (McNutt, 1996). Earthquake etiology includes slip on faults, stress changes due to magma movement, volcano loading and lithospheric flexure, as well as thermal cooling (Wolfe *et al.*, 2004).

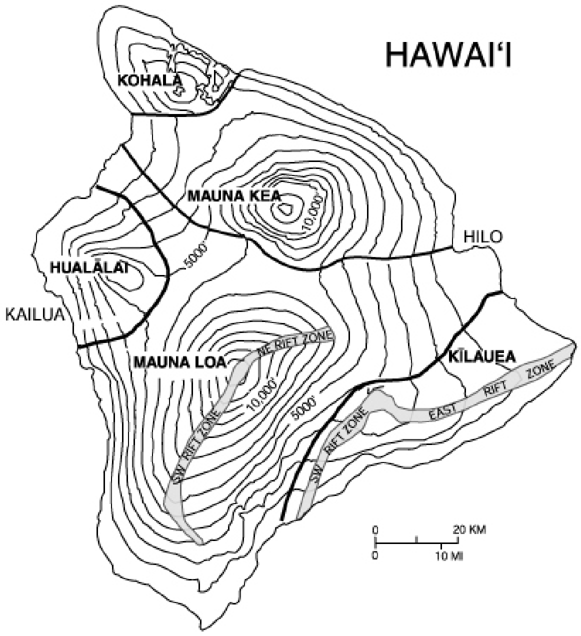

Fig. 1 – The Big Island of Hawaii and its rift zones (http://www.uhh.hawaii.edu/~nat_haz/volcanoes/contour_rift_zones.jpg)

Although earthquake patterns are among the most useful sources of information regarding volcanic processes, the space-time variability of patterns and the changes of earthquake positions from episode to episode (McNutt, 1996) make it difficult to effectively interpret seismicity patterns. The next two sections of this paper present two approaches to the quantitative assessment of the space-time features of these patterns.

3. SCALING AND SPATIAL ORIENTATION

To capture interrelationships among seismic events occurring at successive moments in time, a method called Events Thread Analysis (ETA) was introduced in 1998 (Șuțeanu, 1998) and further developed on different levels (see Șuțeanu *et al.*, 2001 for an application in an n-dimensional phase space, and Șuțeanu and Ioana, 2007, for analyses using smoothing dimension exponents). The main reason for the introduction of the concept of “events thread” was the necessity to overcome limitations of methods that focused on sets of points (either epicentres or hypocenters) as if they were independent from each other. However, the temporal sequence of earthquakes is important, especially because each event includes processes typically characterized by irreversibility.

In this paper, the ETA method is upgraded with the inclusion of a more effective multiscale time series analysis method and a differential approach to the evaluation of results, meant to better characterize pattern change.

The method described in this section is applied to the dataset described above with the aim of characterizing scaling properties of patterns related to temporal succession and spatial orientation. It is thereby expected to shed light on relations between seismicity and volcanic processes. The method consists of three distinct phases.

1) In the first phase of the ETA method, the studied set of events is considered in its temporal succession: all the points corresponding to earthquakes are connected in this order, which leads to an “events thread”. This operation can be performed in multidimensional phase space, as well as in physical space, based on the information regarding hypocenters. It is this latter approach that we apply in this paper.

2) In the second phase, the generated events thread is projected on a straight line D passing through the origin of an orthogonal system and successively taking “all” possible spatial orientations. The position of the line D can be defined with the help of two angles: γ, the angle between D and the vertical axis (Z), and α, the angle between the projection of D on the horizontal plane, and the horizontal east-west axis (X). In practice, one selects the values for γ from 0° to 90° with a certain step size. For each value of γ, with γ unchanged, one rotates the line D on a cone stepwise, so that α will vary from 0° to 180°, with the same step size. In this study, we used a step size of 3°.

For each position of D, the projection of the events thread is subject to multiscale time series analysis, as shown below, and a scaling exponent is identified. The resulting matrix of 30×60

elements comprises all the selected orientations of the mobile line D.

The time series resulting from events thread projections corresponding to different spatial orientations are subject to multiscale analysis. Here we use a robust and effective method: detrended fluctuations analysis, or DFA (Peng *et al.*, 1994). DFA is capable of characterizing scaling aspects in time series even in the presence of trends, and even if the origin and shape of trends are unknown (Bunde *et al.*, 2000; Kantelhardt *et al.*, 2001). The method was successfully applied to a large variety of data, such as atmospheric temperature (Rybski *et al.*, 2008), sea surface temperature (Monetti *et al.*, 2003; Gan *et al.*, 2007), height fluctuations in the global tropopause (Varotsos *et al.*, 2009), or river discharge patterns (Kantelhardt *et al.*, 2003; Fraedrich and Zhu, 2009).

If the analyzed time series is self-affine, a scaling exponent K can be found for a certain scale range. The exponent K characterizes the persistence in the time series: a persistent signal ($K > 0.5$) has a pronounced tendency to continue the current – increasing or decreasing – trend, more so than a random signal ($K = 0.5$); the larger the value of K, the stronger the persistence. An antipersistent signal changes its increasing/ decreasing tendencies more frequently and more abruptly than a random signal; the lower the value of K, the stronger the antipersistence.

3) In phase three, the matrix consisting of scaling exponents K calculated for all possible spatial orientations of the line D is graphically represented and analyzed.

All the three phases outlined above can be usefully applied to successive segments of the dataset, so that each orientation / scaling exponents matrix can be associated to a certain time interval.

4) Beyond the three phases outlined above, a fourth phase is added in this study. In order to support the identification and assessment of pattern change, we show that a difference matrix can be produced from each pair of temporally successive matrices. The 3-dimensional graphical representation of difference matrices supports a fast and effective evaluation of pattern change.

Figs. 2 to 4 show the results obtained for the specified temporal intervals.

In Fig. 2 (pattern A), there is a low persistence (K = 0.53) for small values of γ (γ = 0º corresponds to the vertical direction). A stronger persistence (K = 0.65) is present closer to the horizontal plane (especially for a horizontal direction α = 25º), suggesting intense activity along superficial fissures, along which the magma actively advances; this aspect of seismicity patterns is in agreement with surface observations that highlight superficial swarms and eruptions along the East Rift Zone (GVP, 2007). In contrast, Fig. 3 (pattern B) highlights a shift in horizontal orientation towards maxima along α angles of 0 and 160..170º. Subsequently (Fig. 4, pattern C), the persistence in vertical direction decreases even more, reaching values typical of a random pattern, while the persistence in horizontal direction increases from 0.6 to 0.7; at the same time, the direction of highest persistence moves to α = 90º. Interestingly, during all this time, surface observations highlight variable activity along the East Rift Zone, including earthquake swarms and numerous eruptions (GVP, 2007).

To highlight pattern change, we propose that one can generate difference K-matrices, which highlight the occurring changes in a suggestive and precise manner. By subtracting the values corresponding to the matrices that characterize different stages of the studied system, the amount of change in persistence as well as the shift in spatial directions become clearly visible. Examples are shown in Figs. 5 and 6.

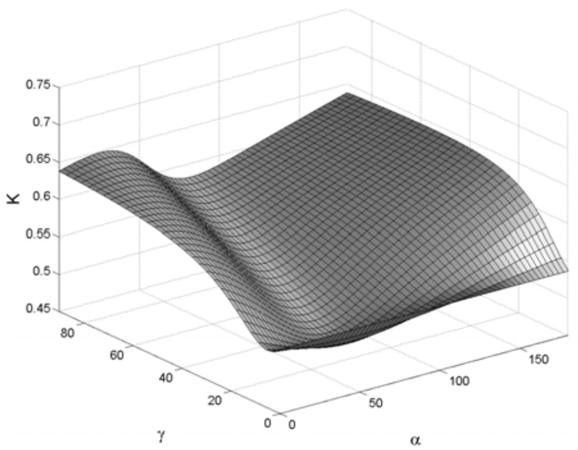

Fig. 2 – Pattern A. February–May 1990.

Fig. 5 illustrates the change from pattern A to pattern B. One can assess the change much better than by comparing the surfaces in Figs. 2 and 3. In fact, there is only a slight positive change, mainly in the horizontal and close-to-horizontal plane, but a more significant drop in persistence in the horizontal direction around $\alpha = 60^\circ$. On the other hand, there is practically no change in the vertical direction (for $\gamma = 0^\circ$).

There is a stronger anisotropic contrast in the change from pattern B to pattern C (Fig. 6). A strong increase of persistence in the horizontal plane (of around 0.17 in *K*) dominates the pattern, while vertical persistence drops even more.

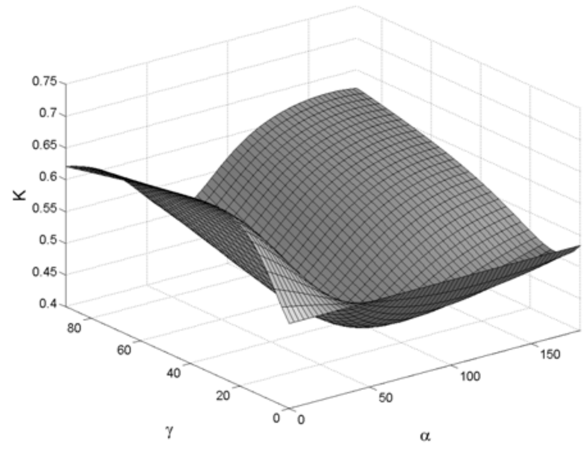

Fig. 3 – Pattern B. June–October 1990.

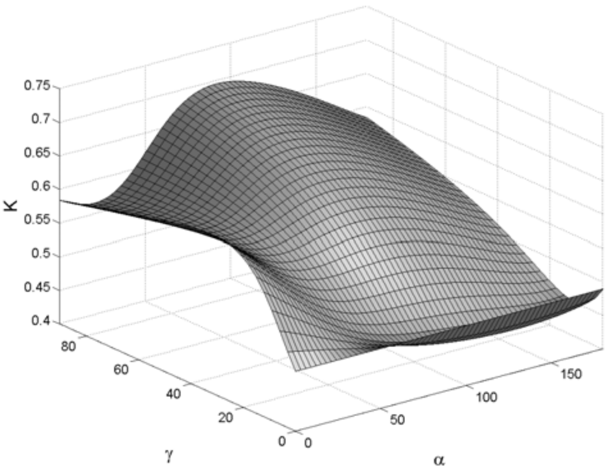

Fig. 4 – Pattern C. October 1990 – January 1991.

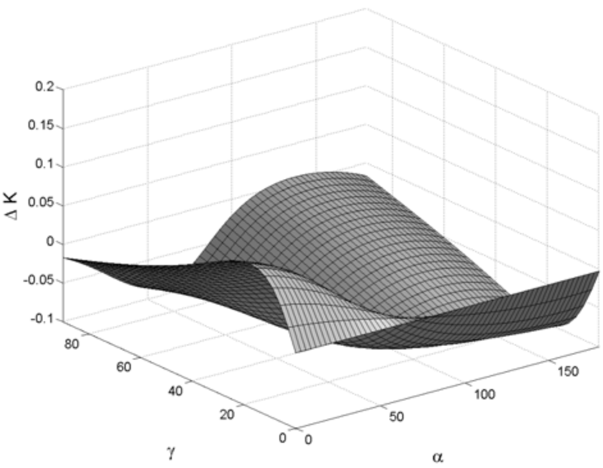

Fig. 5 – Change from pattern A to pattern B.

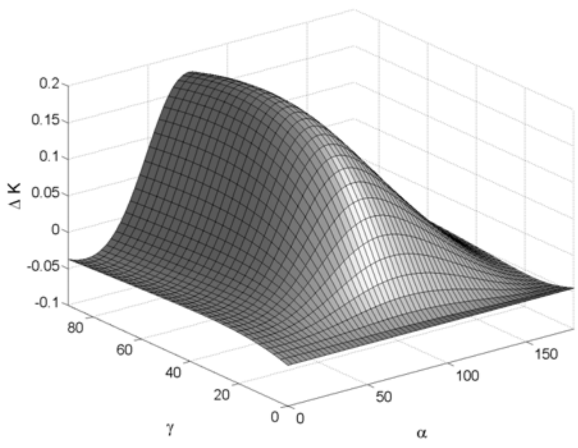

Fig. 6 – Change from pattern B to pattern C.

Overall, these changes document an intensified volcanic activity in horizontal and close-to-horizontal fractures, and decreased events persistence in the vertical conduits of the volcano. The surface observations confirm these conclusions (GVP, 2007). However, the performed analysis provides geometric details as well as a quantitative measure of the relations among the seismic events, which are not obtained from other information sources regarding the volcano.

The results of the methodology described above can be corroborated with those from other approaches to volcano monitoring (McNutt, 1996; Van der Laat, 1996; Martini, 1996). By setting up a system capable of continuously generating *K*-matrices, which show the relations between scaling exponents and spatial orientation, and permanently representing the actual *K*-surfaces as well as the difference surfaces, one obtains comprehensive and easy to interpret information regarding the patterns and their changes in time, which are expected to represent a step forward in geosystem monitoring.

4. SCALING AND NETWORKS

Studies based on network analysis principles (Albert and Barabasi, 2002) have produced relevant results; implementations of this idea in earthquake research can address a variety of objectives. For instance, Davidsen *et al.* (2008) focus on the causal dynamics involved in space-time point processes, by considering recurrent events (a recurrence of an event is defined as the situation in which a later event is closer to it in space than all the intervening events). In this study, we wish to describe the relationships among earthquake events from the point of view of time, space, and event size. To this end, we turn earthquake patterns into networks analyzed in a geographical information system (GIS) framework.

The set of earthquakes occurring in a certain time interval becomes thus a directed network: its nodes correspond to event locations, and the directed edges characterize relationships among nodes, reflecting temporal irreversibility and the magnitude-, distance- and time-dependence of such relationships. In order to quantitatively assess earthquake interdependency, network weights are described as a function of magnitude, distance and time. Moreover, the dynamics of the earthquake network is evaluated by following the attributes of successive network windows in time.

A key step in the generation of earthquake networks consists of the selection of weight functions for network edges. Numerous studies on earthquake distributions in space, time and event size have shown the ubiquity of power laws governing these distributions as well as the relations among events (Bodri, 1994; Wang and Ou, 1998; Lei and Kusunose, 1999; Nanjo and Nagahama, 2000; Lapenna *et al.*, 2000; Carbone *et al.*, 2005). A power law was used in this study to evaluate the influence events exert on later events in a space-time-size perspective. The following weights were applied:

– for magnitude: $V_M = M / M_{max}$, where M_{max} is the maximum magnitude of the set;

– for time: $V_t = t^{\tau}$, where t is the time interval in hours, V_t is one hour for all
$t < 1$h, and $\tau = -1$;

– for distance: $V_d = d^{\xi}$, where d is the distance in km, $V_d = 1$ km for all $d < 1$ km, and
$\xi = -1$.

We consider that an earthquake can exert an influence upon future earthquakes only if the combination of its variables V_M, V_t, V_d is strong enough. For each earthquake, a measure of the influence V that it exerts upon a future earthquake is the product of its weights: $V = V_M * V_t * V_d$.

Subsequently, we keep only earthquake pairs with the resulting weight V larger than a certain threshold (*e.g.* 0.01). Finally, each earthquake pair must be connected by a directed (time oriented) link.

Based on these rules, we construct the earthquake networks for successive temporal windows (Cohen and Havlin, 2010). Since seismic events are distributed irregularly in time, rather than focusing on equal temporal intervals and having heterogeneous datasets in terms of data length, we chose to apply the analysis methodology to comparable sets of data, and therefore windows are defined for equal-length successions of earthquakes (*e.g.* 1,000 events per window).

Following the network generation (Fig. 7), we analyze the result by focusing on its degree distribution. The connectivity (degree) of a node is equal to the number of edges corresponding to that node (Boccaletti *et al.*, 2006). Our results show that the distribution of node connectivity in the earthquake network is a power law (Fig. 8). In a weighted network, the node weight is equal to the sum of all weights in that node (Bocalletti *et al.*, 2006). Our results show that the weight distribution in the earthquake network is a power law as well.

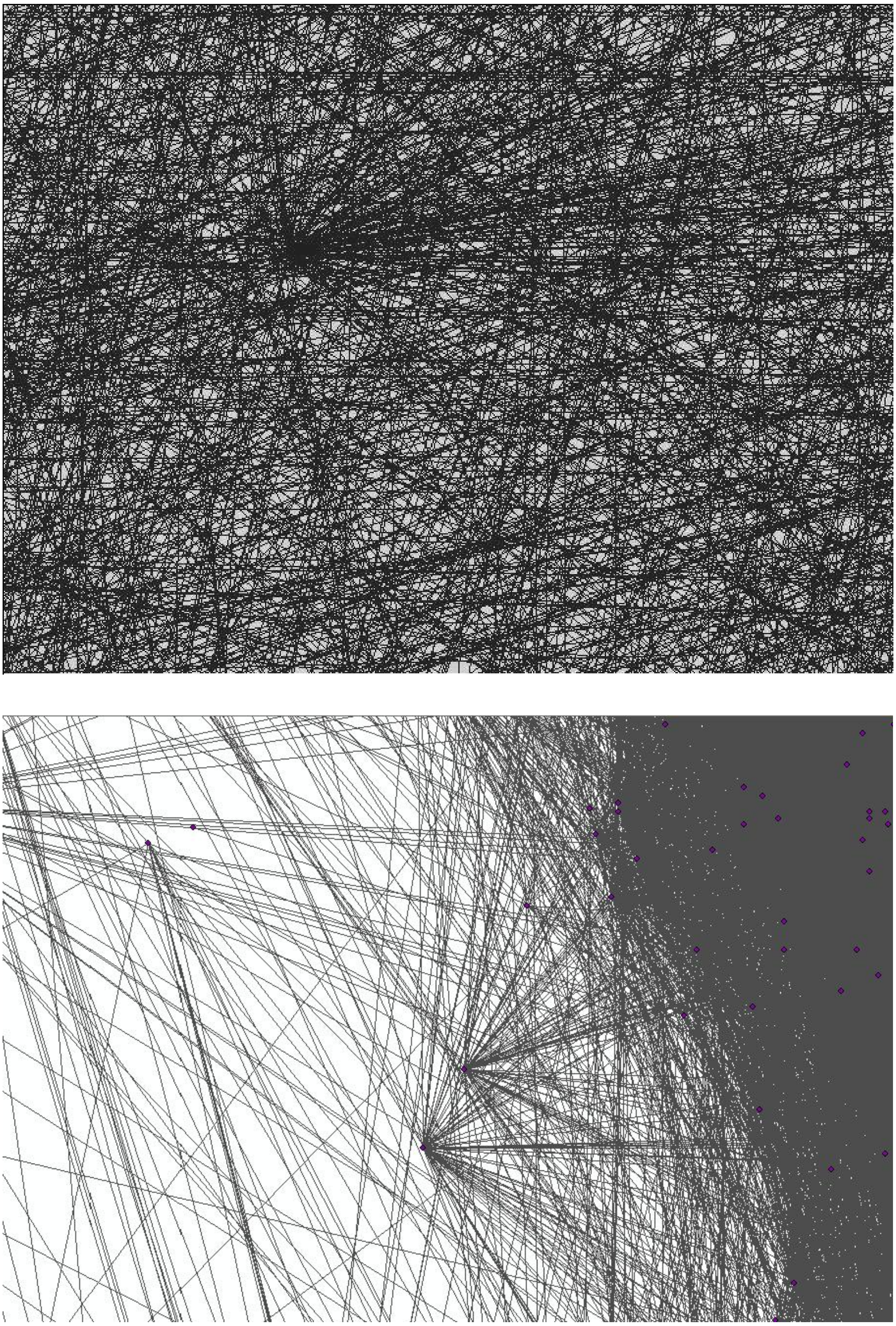

Fig. 7 – Two examples of network fragments. Nodes are seismic events, edges are relations between earthquakes.

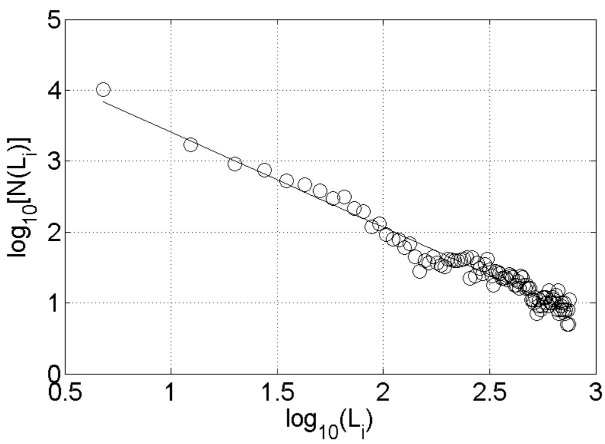

Fig. 8 – Example of a node degree distribution.

Fig. 9a shows the variation of gamma, the exponent of the distribution of nodes as a function of their weights, over different time windows. Gamma reaches a minimum in January/February 1997, at the onset of the largest earthquake swarm (letter A). In spite of the end of the seismic and eruptive episodes, gamma keeps increasing until 2004, when it decreases until the next largest swarm occurs. This suggests that the network has kept evolving consistently between the two large swarms.

To investigate the role played by the selected exponents of weight functions, we change the distance weight (initially taken according to a power law with $\xi = -1$) to ξ -1.37, following the suggestion of work by Felzer and Brodsky (2006) and Lemarchand and Grasso (2007). The resulting temporal evolution can be seen in Fig. 9b. One can notice that in spite of the differences in details, the overall system evolution as expressed in terms of earthquake interaction is similar in the two cases.

The graphs in Fig. 9 reveal a surprising aspect, one which is not identified by other methods, including the events thread analysis presented above. They show that the earthquake sets undergo transformations affecting their interrelationships: the connectivity strength gradually changes from a state of high gamma, *i.e.* dominated by low connectivity values, to one of low gamma, in which high connectivity values play a more important role. This change occurs over intervals of years. Perhaps the most interesting and important aspect of this part of the study is the fact that, while the points where the graphs in Fig. 9 reach low values can be easily identified in surface observation- and earthquake temporal density records (due to remarkably violent volcanic processes), the gradual year-long oscillation of event interconnectivity could not be identified otherwise. This slow variability suggests that the identified connectivity corresponds to property changes in this complex geosystem, which provides an expectedly fruitful angle with respect to volcano-related seismicity.

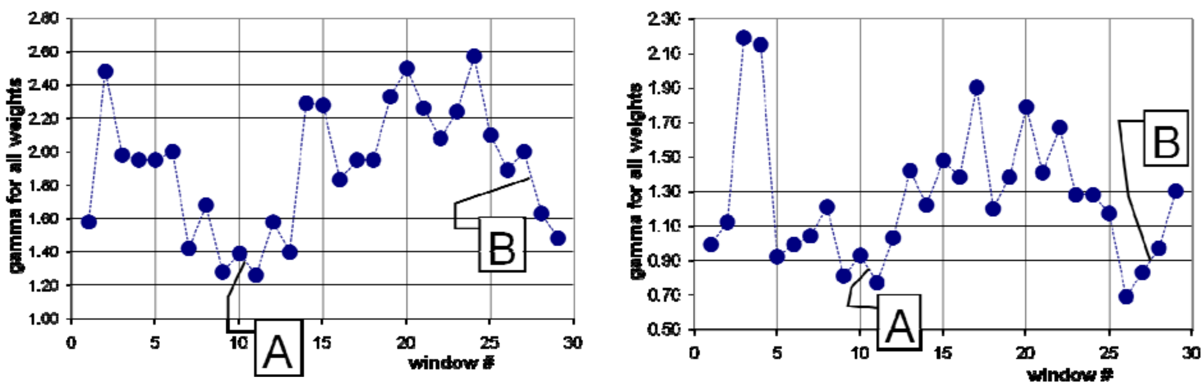

Fig. 9 – Earthquake network change over time,
for networks constructed with different distance weight exponents: a) $\xi = -1$, b) ξ -1.37.
A and B mark violent volcanic processes.

5. CONCLUSIONS

The two approaches presented in this paper provide complementary views on a complex geosystem. Both methodologies focus on relationships among events, and use the assessment of pattern scaling properties. However, they operate in distinct ways. Events thread analysis captures information regarding the inter-event relations from the point of view of their 3-dimensional orientation, which provides insights into geometrical properties of patterns and their transformation over time. While network analysis does not offer such a geometrically detailed perspective, its scope is wider in terms of the number of the considered inter-event links: events thread analysis detects successions of points in time (the "thread"), while network analysis includes many possible links connecting each event to subsequent events. Network analysis is also capable of assessing a more general state of connectivity of the set of earthquakes occurring in a given time interval. Both approaches can be easily included in programs of monitoring seismically active areas, and are expected to significantly enhance the effectiveness of monitoring operations.

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VRANCEA EARTHQUAKE OF 25TH APRIL 2009: SOURCE PARAMETERS AND DIRECTIVITY

Homage to Professor Dorel Zugrăvescu

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The moderate-size earthquake recently generated in the Vrancea subcrustal domain, on April 25, 2009 (17:18, 45.68^{0}N, 26.62^{0}E, h = 110 km, M_w = 5.2), was the largest shock recorded since the event of October 27, 2004 (M_w = 6.0). The main shock was followed by a well-recorded aftershock on April 26, with similar location and focal mechanism (23:19, 45.69^{0}N, 26.64^{0}E, h = 104 km, M_w = 3.8). The difference of 1.4 magnitude units between the two shocks is lower than the typical value (~ 2) for the aftershock activity in the Vrancea subcrustal domain, showing a stress redistribution comparable with the crustal events of similar size. The purpose of the present paper is to determine the seismic source parameters of the event of April 25, 2009 using the Empirical Green's function deconvolution technique and spectral ratios. At the same time, the large number of high-quality waveforms recorded for the mainshock-aftershock pair provides a valuable data set to investigate the possibility to detect source directivity properties. The source directivity effects are caused by the rupture propagation along a fault plane and manifest in different *P* pulse amplitude and width depending on the station position relative to the rupture fault plane. Our results show that possible directivity effects are too small for the study event to be consistently detected.

Key words: subcrustal earthquakes, Vrancea, source directivity, empirical Green's function deconvolution.

1. INTRODUCTION

The Vrancea seismic region, located at the triple junction of the East-European plate, Intra-Alpine and Moesian subplates (Constantinescu *et al.*, 1976) generates earthquakes clustered in a well-defined seismogenic volume at the bend toward west of the South-Eastern Carpathians. The seismic energy is mostly radiated in the upper mantle (60–170 km depth) within a narrow focal volume descending nearly vertically. The yearly rate of seismic moment release per unit volume is the highest in Europe (~ 1.2 x 10^{19} Nm/year in a volume of about 80 km x 30 km x 110 km). In the last 100 years three major shocks with M_w > 7 were produced in the Vrancea region: 10 November 1940 (M_w = 7.7, h = 150 km), 4 March 1977 (M_w = 7.4, h = 90 km) and 30 August 1986 (M_w = 7.1, h = 132 km). The most recent significant event occurred on October 27, 2004 (M_w = 6.0).

The earthquake generated on 25 April 2009 at 17:18 is the largest event generated after the 2004 event with the greatest number of recording stations on the Romanian territory (52 stations). The shock of moderate magnitude (M_w = 5.2) was followed by three detectable aftershocks on 26 April at 01:27 (M_w = 2.7), 16:33 (M_w = 2.8) and 23:19 (M_w = 3.8). The last aftershock was the largest and relatively well recorded by 30 stations. Taking into consideration the proximity of the foci for the main event and its aftershock, the difference in size and similarity of the focal mechanisms, this is a favorable case to apply relative deconvolution techniques, such as spectral ratios and empirical Green's functions.

The goal of the present paper is the evaluation of the source parameters of the Vrancea earthquake of 25 April 2009 and its directivity effects using relative deconvolution techniques. Source directivity effects are caused by rupture propagation along a particular plane in a particular direction and manifest themselves by variation in amplitude and width of the radiated pulses for different site locations. The large number of recordings of good quality available for the mainshock–aftershock pair for different locations provides a suitable data set to investigate the source directivity effects.

2. THE APRIL 25, 2009 EVENT IN THE FRAMEWORK OF VRANCEA SEISMICITY

The earthquake of April 25, 2009 is a moderate-size event which belongs to the so-called background seismicity of the Vrancea intermediate-depth source. Typically for the Vrancea source, the background seismicity is persistent and rather constant as rate in time. In Fig. 1 the evolution of the seismicity is plotted for 15-year time interval preceding the study event. The monthly rate of earthquake generation is evaluated on the basis of a catalogue of 2676 intermediate-depth earthquakes ($h \geq 60$ km) recorded by the Romanian seismic network (including the stations in the Republic of Moldavia, as well) and located between January 1995 and September 2009.

Apart from the purely statistical fluctuations (of the order of square of N), other fluctuations can be noticed that can be explained by modifications from time to time in the earthquake survey system (for example, the sudden increase of earthquake number per month starting with the end of 2004 is due to the increase of the detection capacity of the seismic network once a new system of acquisition and processing (Antelope) started to work at the data centre in Bucharest (Neagoe *et al.*, 2009)) and by enhancements associated with the larger earthquakes triggering in the investigated time interval: April 28, 1999 ($M_w = 5.3$), October 27, 2004 ($M_w = 6.0$) and April 25, 2009 ($M_w = 5.2$).

The increase in the seismic activity associated with these events affects a time window of about one year around the main shock. However, it is difficult to be detected from the noise in the background seismic activity and consequently it is hazardous to declare such fluctuations as anomalies. We suppose that a decrease of the detection level to lower Vrancea intermediate-depth events would lead to improved detections and inferences for both pre-shock and after-shock activities.

The location of the epicenter of the April 25, 2009 event together with the available recording stations are plotted in Fig. 2.

The distribution of epicenters for the earthquakes in the January 1995 – September 2009 time interval shows a clear NE–SW alignment (Fig. 3). A careful inspection of the geometrical configuration of hypocenters suggests that the event of April 25, 2009 is located in a less fractured area, taking into consideration the lower density of hypocenters around its focus.

According to previous studies (*e.g.*, Oncescu, 1986; Trifu and Radulian, 1994; Enescu and Enescu, 1998; Popescu *et al.*, 2001; Hurukawa *et al.*, 2008), the mantle seismic activity beneath Vrancea region is unevenly distributed into two or even more characteristic segments. The seismicity tendency to occur in clusters is related to a hierarchical structure of inhomogeneities, with specific nuclei of resistance (asperities) at different scales. The largest earthquakes are generated by failure of major asperities, and apparently these events occur alternatively in the upper ($60 \leq h \leq 110$ km) and lower ($h > 110$ km) lithospheric slab.

We shall adopt in the following the hypothesis of a fragmentation into two segments: A ($60 \leq h \leq 110$ km) and B ($h > 110$ km), characterized by specific major asperities and background seismicities (Radulian *et al.*, 2008). The two active segments are separated by a sort of transition zone, around 100 km depth, where the seismicity is more diffuse in space (Cărbunar and Radulian, 2010), the energy release is less important and the focal mechanisms significantly deviate from the typical reverse faulting mechanism which prevails in the other two zones (Oncescu and Trifu, 1987).

The distribution of number of earthquakes on depth (Fig. 4) is consistent with the segmentation in two zones, especially if we look to the larger events, for which the locations are more reliable ($M_L > 2.8$). Hypocenters distribution on vertical cross sections (Fig. 5) shows specific geometrical patterns for the upper and lower active zones. According to this hypothesis of fragmentation, the earthquake of 25 April 2009 was generated at the upper edge of the zone B.

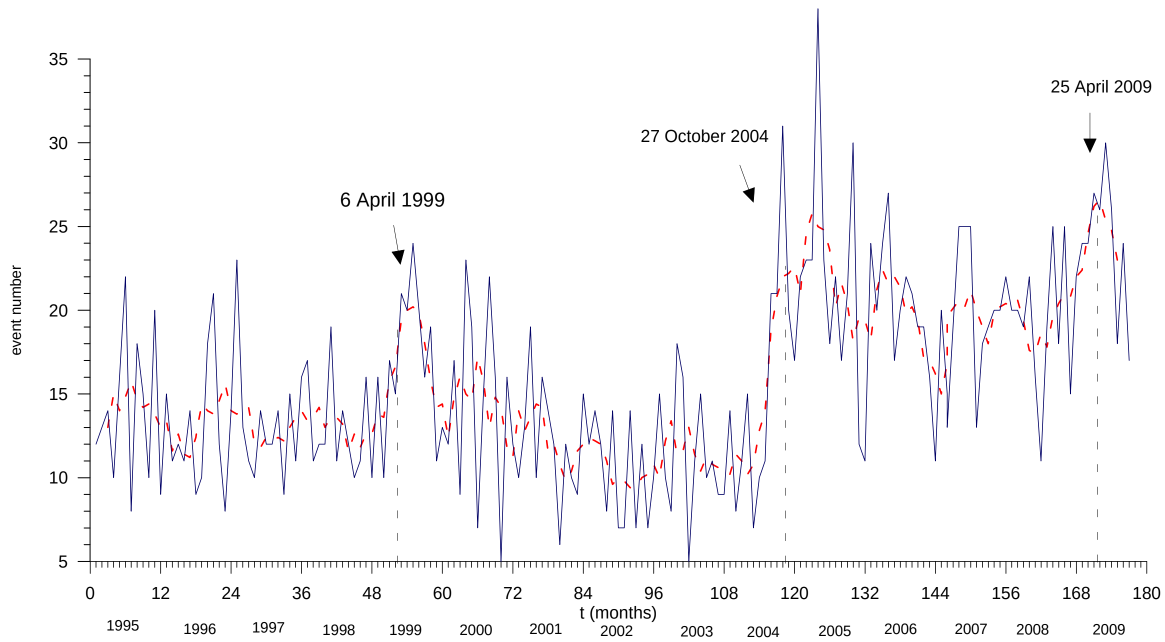


Fig. 1 – Monthly seismic activity in the Vrancea subcrustal zone between January 1995 and September 2009. The dashed line is the average using a running moving window of five points with a step of one point.

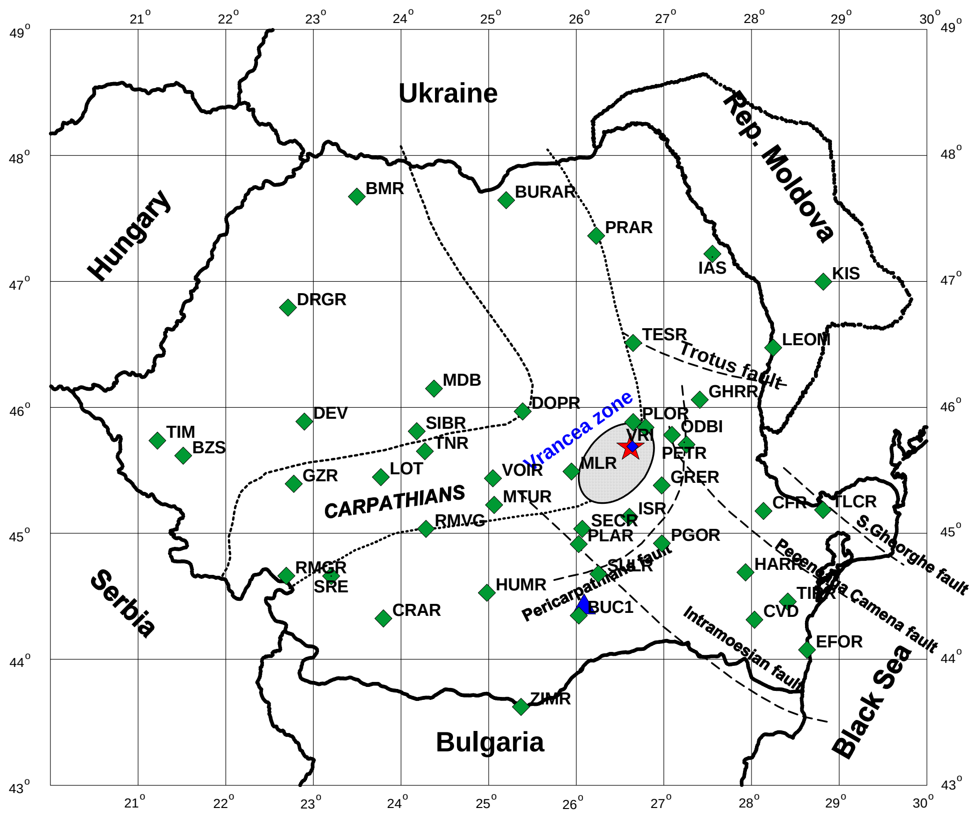


Fig. 2 – Epicentral locations of the April 25, 2009 main shock (star). The seismic stations are represented by diamonds.

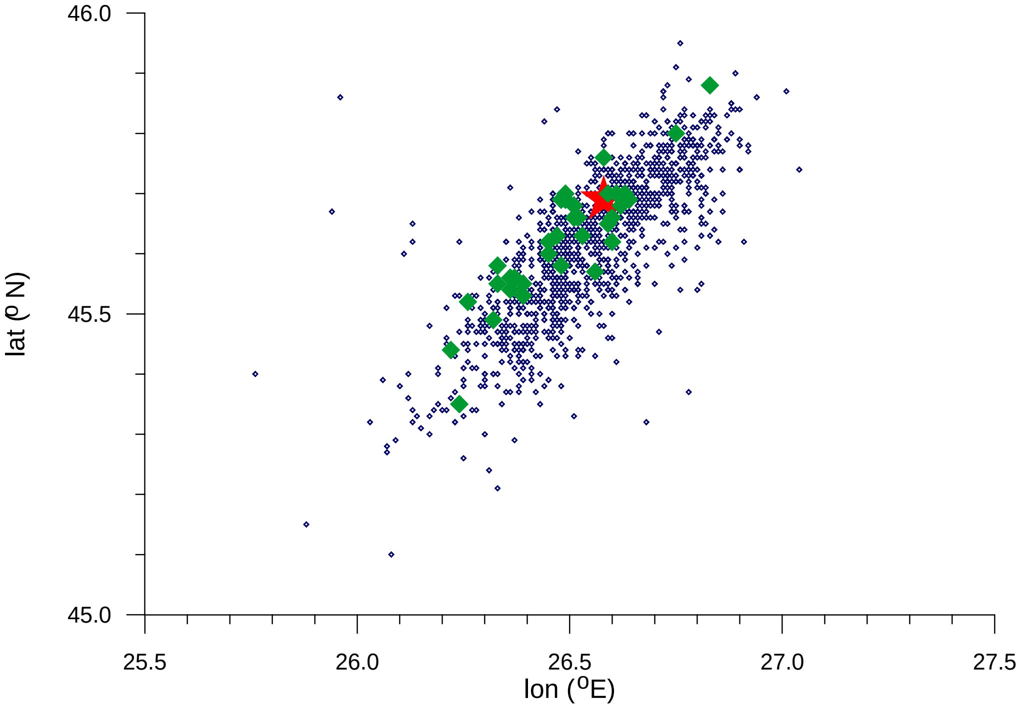


Fig. 3 – Distribution of epicenters of the earthquakes in the Vrancea zone. Smaller symbols are for the earthquakes of magnitude M ≥ 3; solid diamonds are for the earthquakes of magnitude M ≥ 4; star is for the event of April 25, 2009.

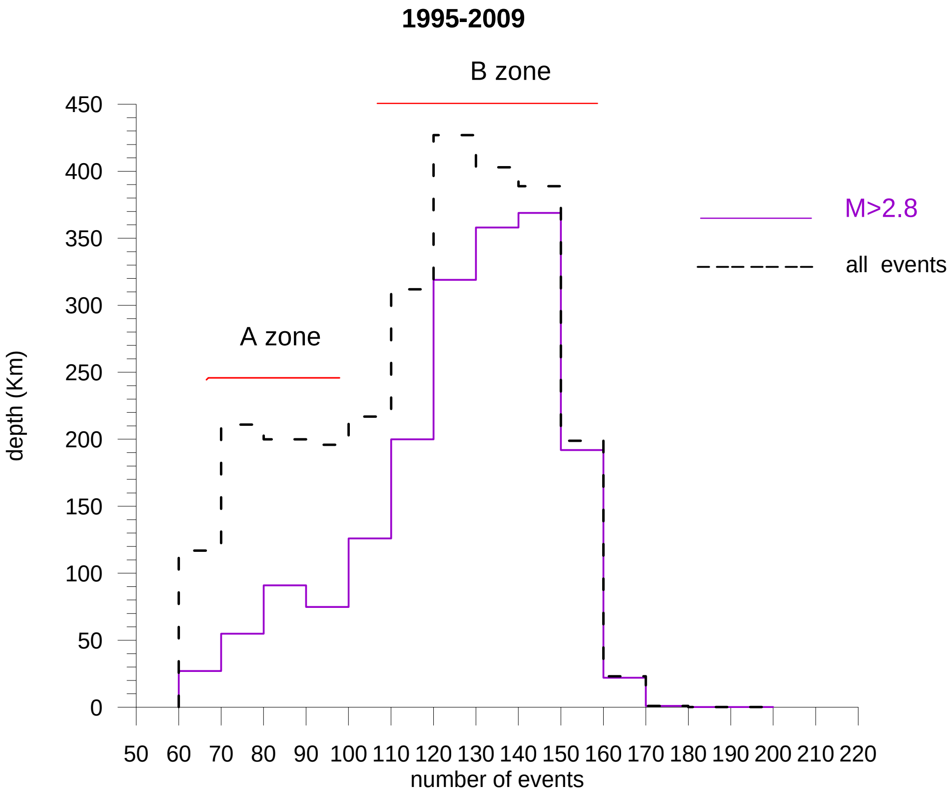


Fig. 4 – Distribution on depth of the Vrancea subcrustal earthquakes (January 1995 – September 2009).

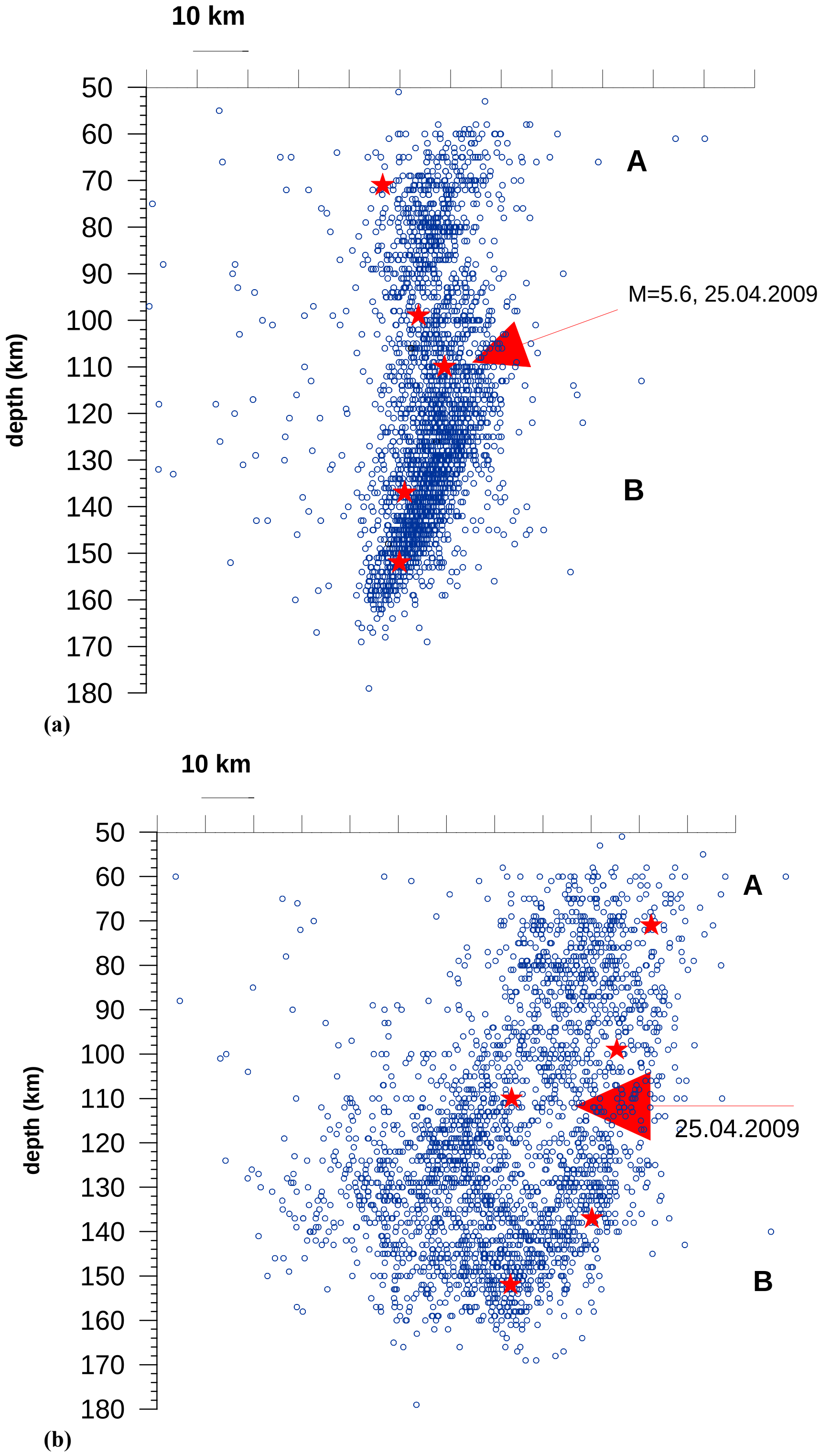


Fig. 5 – Hypocenter distribution of the Vrancea subcrustal earthquakes (January 1995 – September 2009): a) on a vertical projection N130°E oriented; b) on a vertical projection N40°E oriented. The stars represent the foci of the largest events (27 October 2004 in zone A; 28 April 1999, 6 April 2000 and 25 April 2009, in zone B).

3. APPLICATION OF RELATIVE METHODS TO ESTIMATE SOURCE PARAMETERS

To apply relative deconvolution techniques to retrieve source characteristics, at least one pair main event – empirical Green's function event is required. For the study earthquake of April 25, 2009, we can use its largest aftershock of April 26, 2009, since all the necessary conditions are fulfilled:

– the two events are located in the vicinity (45.68^0N, 26.62^0E, h = 110 km and 45.69^0N, 26.64^0E, h = 104 km);

– the difference in size is sufficient to approximate the second event as a Dirac function ($M_w = 5.2$ vs. $M_w = 3.8$);

– a sufficient number of common stations recorded both events;

– the fault plane solutions for the events are similar (Fig. 6).

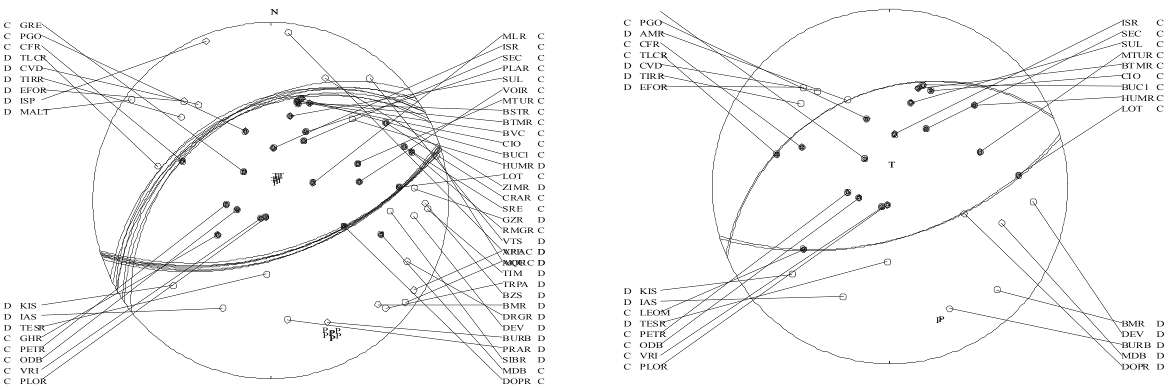
The fault plane solutions for the two events are determined inverting the polarities of the P-wave first motions using SEISAN algorithm (Havskov and Ottemöller, 2001). This algorithm allows the evaluation of the degree of constraint for the parameters of the nodal planes and principal axes of the seismic moment tensor. The fault plane solution for the main shock (Fig. 6a), obtained from 52 polarities and for the 26 April aftershock (Fig. 6b), obtained from 30 polarities, are close each other, showing a reverse faulting mechanism, typical for all the Vrancea subcrustal earthquakes.

When the conditions required are fulfilled, the relative deconvolution techniques are very efficient in eliminating the path, site and instrument effects, which distort to a large extent the ground motion, observed at the surface. The smaller event (empirical Green's function – EGF) approximates a Dirac's function in the frequency band of interest (1–10 Hz) and therefore its recorded seismogram is close to the response function for the medium between the focus and recording site (Mueller, 1985; Frankel *et al.*, 1986; Mori and Frankel, 1990; Hough *et al.*, 1989). The source time function or source spectrum for the main event is obtained by deconvolving the EGF waveform from the main event waveform. In the case of spectral ratios method, if common broadband recording instruments are available, we can simultaneously retrieve the source parameters for both main event and empirical Green's function event (Lindley, 1994). Obviously, the success in retrieving source parameters depends on the level of signal-to-noise ratio for the EGF event.

For a source model with uniform rupture velocity and high-frequency $\omega^{-\gamma}$ spectral fall-off, the spectral ratio can be approximated by:

$$R(f) = \frac{\Omega_0{}^{P}\left[1+\left(f/f_c{}^{G}\right)^{2\gamma}\right]^{1/2}}{\Omega_0{}^{G}\left[1+\left(f/f_c{}^{P}\right)^{2\gamma}\right]^{1/2}} \qquad (1)$$

where $\Omega_0{}^P$, $\Omega_0{}^G$ are the low-frequency asymptotes of the displacement amplitude spectra for the principal event and EGF event, γ is the spectral decay at the high frequencies, while $f_c{}^P$, $f_c{}^G$ are the corresponding corner frequencies.



a b

Fig. 6 – Fault plane solutions: a – main shock (25 April 17:18), b – largest aftershock (26 April 23:19) obtained by inverting the first P-wave polarities.

The free parameters, ratio of the seismic moments – proportional to the ratio of the low-frequency asymptotes and corner frequencies (we fixed the parameter γ to 2) are estimated through a nonlinear regression procedure <the best fitting of the observed spectral ratios by a function of type (1)>. The corner frequency is a measure of the source dimension (Brune, 1970):

$$r = 0.28\ \beta/f_c \qquad (2)$$

where r is the equivalent radius of the source and β is the shear wave velocity at the focus depth.

We applied the spectral ratios method and EGF technique to the pair of the main event and its largest aftershock (Table 1). The waveforms recorded at MLR and VRI stations for the main event – EGF event pair are represented in Fig. 7.

The corner frequency (source radius, respectively) is estimated for each main event – EGF pair and for each component (Z – vertical component, N, E – horizontal components). The estimates are given in Table 2. Finally, the parameter values are computed as averages of all available estimates. The approximation of spectral ratios by the best fitting theoretical ratio (1) provides estimates for the ratio of low-frequency asymptotes (***a***) and the corner frequencies of the main event and the EGF event (f_c^P, f_c^G). Then, using (2), the source radius r_{rs} is computed. In parallel, the source parameters are estimated using EGF deconvolution (Tables 2 and 3).

For the same pair of events we applied in parallel the EGF deconvolution to retrieve the source time function (STF) of the main event. The source duration is estimated as the total width of the STF (τ), while the rise time as the duration of the ascending part of the STF ($\tau_{1/2}$). The source radius is computed using (Boatwright, 1980):

$$r = (\tau_{1/2} v)/(1 - v/\alpha \sin\theta) \qquad (3)$$

where the rise time $\tau_{1/2}$ is practically half of the STF pulse, v is the rupture velocity (fixed at $v = 0.9\beta$, with β – shear wave velocity in the focus), α is longitudinal wave velocity in the source and θ is the angle between the normal to the fault and P-wave emergent angle in the focus (we adopted an average value of $\theta = 45^o$). An average value of the rise time is considered using all available $\tau_{1/2}$ estimations per stations. The resulted values are given in Table 3.

As seen in Table 2, the corner frequency is higher on vertical components than horizontal components, both for main event and EGF event. The average radius of the main event source, estimated by (2), is $\boldsymbol{r}$ = 782 ± 76 m, and of the aftershock of 26th April is $\boldsymbol{r}$ = 270 ± 38 m. The average values per component are:

r_Z^P = 697 m (16 values), r_E^P = 804 m (9 values), r_N^P = 845 m (7 values)

r_Z^G = 226 m (16 values), r_E^G = 294 m (9 values), r_N^G = 291 m (7 values)

The average source radius estimated with (3) is $\boldsymbol{r}$ = 985 ± 96 m, and on each component is:

r_{MZ} = 905 ± 272 m (19 values), r_{ME} = 1091 ± 181 m (9 values), r_{MN} = 958 ± 132 m (8 values).

The analysis of the results shows a smaller source duration for Z components as compared with horizontal components, matching the result obtained using spectral ratios. Generally, the STF resulted at different stations shows an apparent uni-pulse shape, implying a homogeneous rupture process in the source.

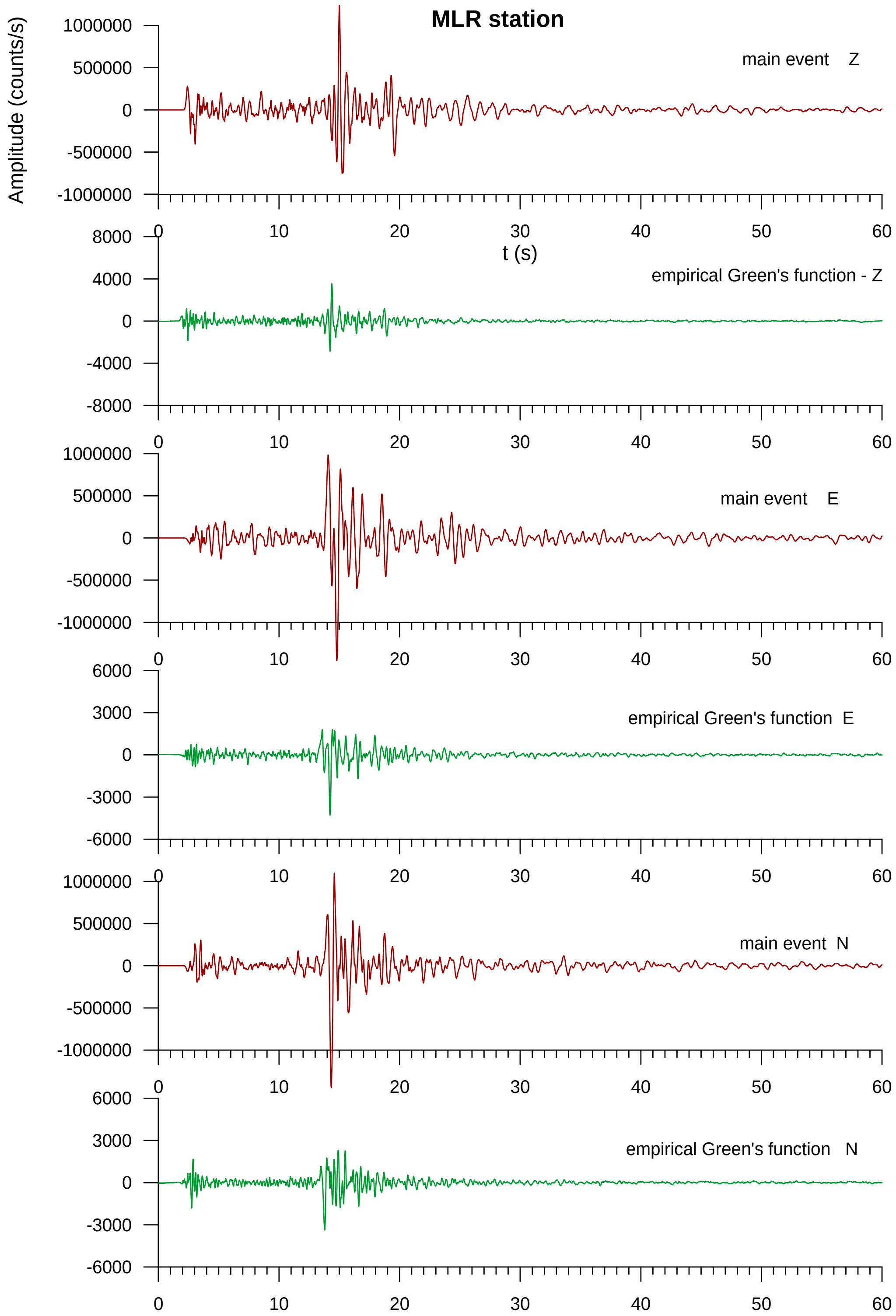
Examples of spectral ratios and source time functions are presented in Fig. 8.

If we adopt the value of the source radius of 782 m for the main event and 270 m for the EGF event, and a ratio of 2.76 between the low-frequency levels of the two events, we obtain the seismic moment values and the stress-drop values for the two events:

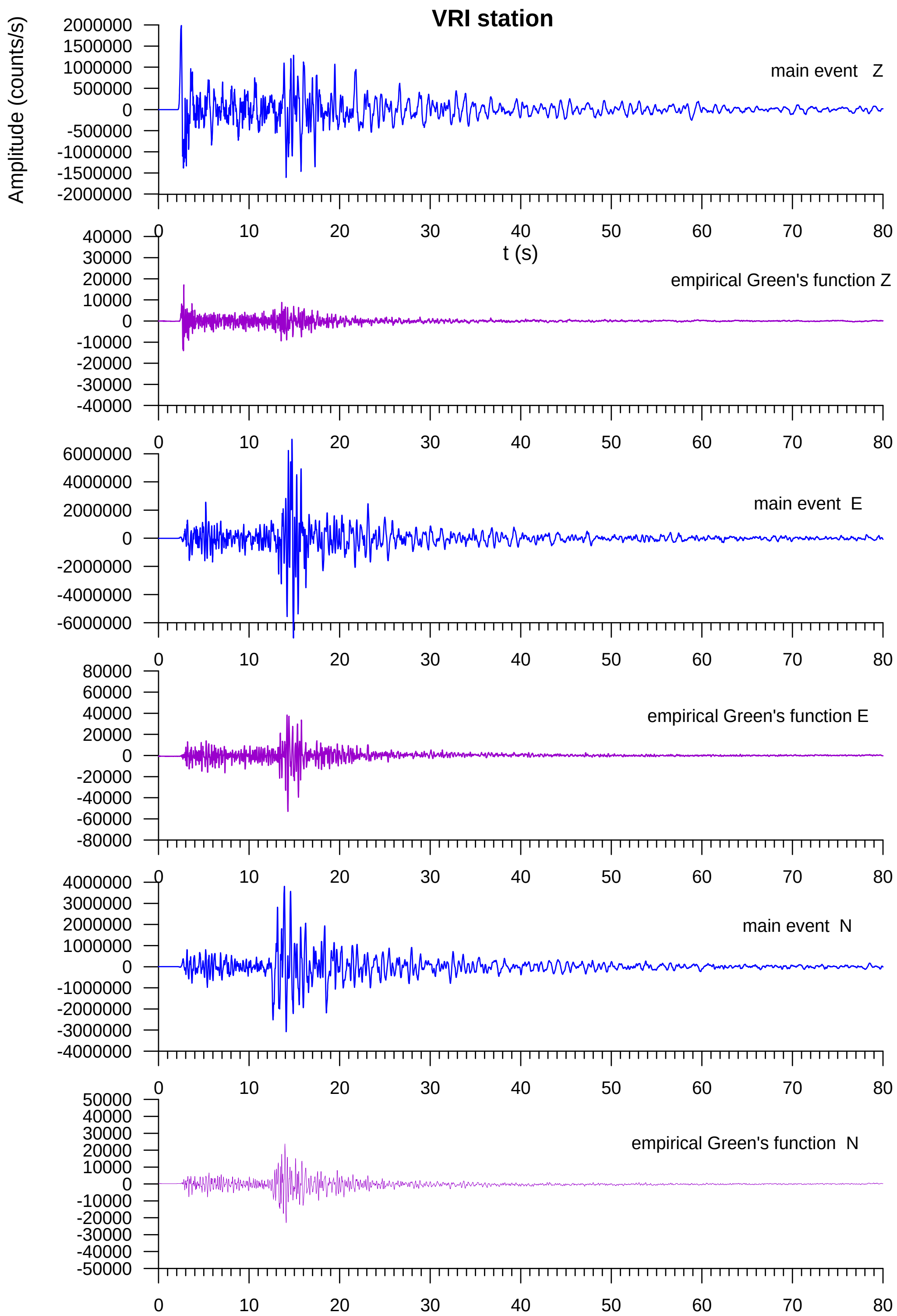
$M_0 = 7.7 \times 10^{16}$ Nm, $\Delta\sigma$ = 70 MPa for the main-shock event;

$M_0 = 1.6 \times 10^{14}$ Nm, $\Delta\sigma$ = 4 MPa for the aftershock event.

The relative techniques of deconvolution do not allow the estimation of the seismic moment simultaneously for both main and EGF events, but only of their ratio. For this reason, we adopt the seismic moment value for the event of 25 April 2009 from USGS solution ($M_0 = 7.7 \times 10^{16}$ Nm).


MLR station
Amplitude (counts/s)
main event Z
t (s)
empirical Green's function - Z
main event E
empirical Green's function E
main event N
empirical Green's function N
1000000
500000
0
-500000
-1000000
8000
4000
-4000
-8000
6000
3000
-3000
-6000
0
10
20
30
40
50
60

(a)



(b)

Fig. 7 – The waveforms (velocity) for the main event – empirical Green's function pair recorded at: a) MLR station; b) VRI station. The plots are scaled to the maximum amplitude (in counts/s).

Table 1

The pair of main and EGF events used in deconvolution

	Date	hh:mm	lat (^{0}N)	lon (^{0}E)	h (km)	M_w
Main	2009/04/25	17:18	45.68	26.62	110	5.6
EGF	2009/04/26	23:19	45.69	26.64	104	3.7

Table 2

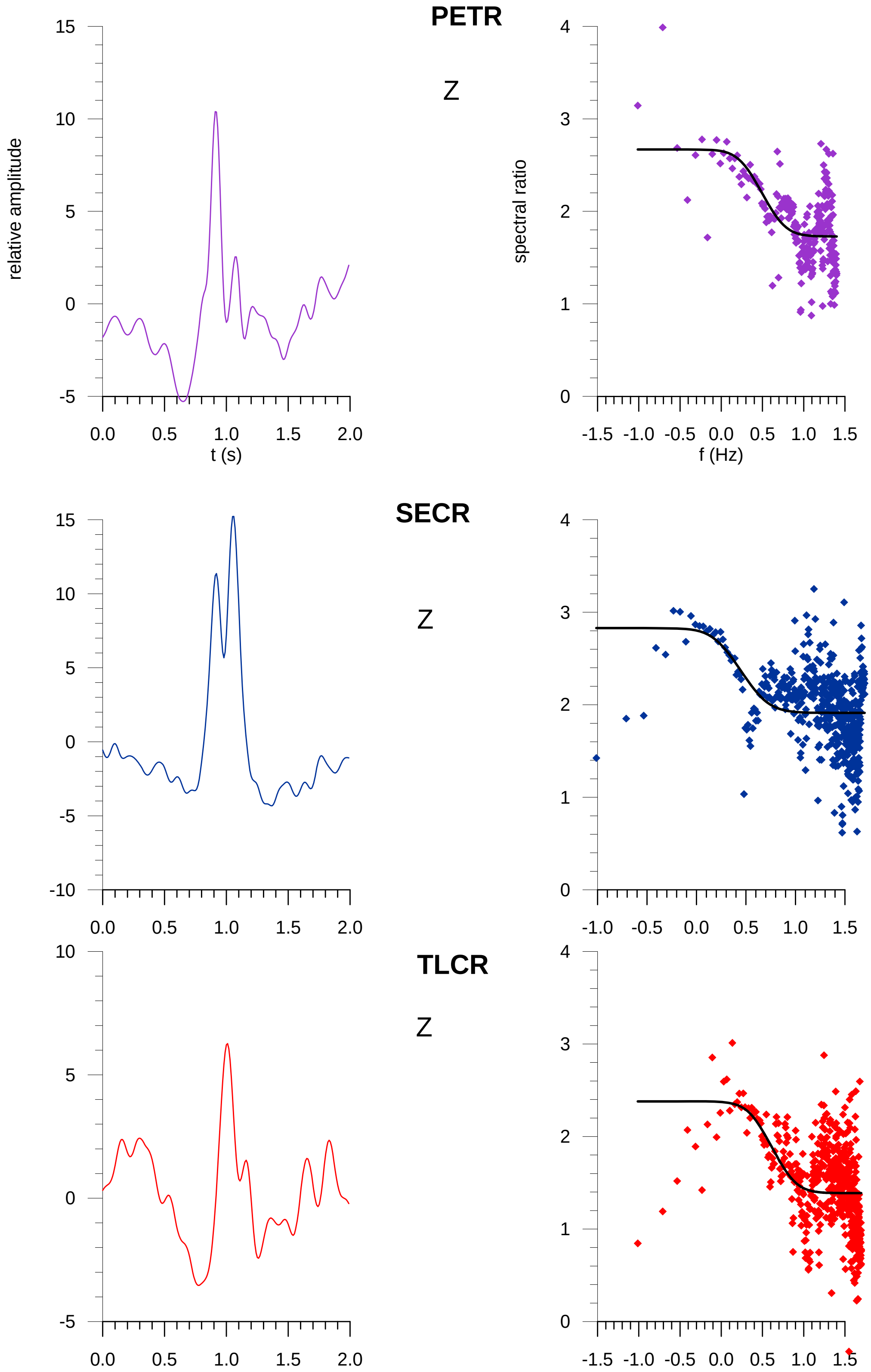
Parameters a, f_c^P, f_c^G, obtained for the considered pair of events from spectral ratios at 16 stations and for each component

No.	Station	*a* (spectral ratios low-frequency level)			f_c^P (Hz)			f_c^G (Hz)		
		Z	E	N	Z	E	N	Z	E	N
1.	CFR	2.54	2.52	2.45	2.24	2.08	2.26	5.38	5.05	5.05
2.	GHRR	2.52	–	–	2.68	–	–	7.55	–	–
3.	GRER	2.86	–	–	1.41	–	–	6.99	–	–
4.	HUMR	2.64	2.90	–	2.47	2.31	–	4.94	4.25	–
5.	IAS	2.69	–	–	2.58	–	–	7.11	–	–
6.	ISR	2.68	–	–	1.66	–	–	4.48	–	–
7.	MLR	2.87	2.94	2.82	1.50	1.21	1.56	4.57	2.74	3.55
8.	PETR	2.66	–	–	1.82	–	–	5.38	–	–
9.	PGOR	2.82	2.85	2.92	1.55	1.30	1.36	5.08	4.32	5.08
10.	PLOR	2.84	2.85	2.91	1.56	1.24	1.20	5.26	3.18	3.18
11.	PRAR	2.75	–	–	1.81	–	–	6.18	–	–
12.	SECR	2.82	2.85	–	1.65	1.60	–	4.75	3.08	–
13.	TESR	2.71	2.65	2.82	2.04	1.93	1.70	7.1	5.95	5.87
14.	TIRR	2.52	2.71	2.75	1.99	1.56	1.45	5.14	4.70	4.50
15.	TLCR	2.38	–	–	2.33	–	–	7.31	–	–
16.	VRI	2.83	2.86	2.84	1.60	1.44	1.35	5.54	5.07	4.34
Average		2.70 ± 0.15	2.79 ± 0.14	2.79 ± 0.16	1.93 ± 0.41	1.63 ± 0.39	1.55 ± 0.35	5.80 ± 1.07	4.45 ± 0.97	4.51 ± 0.93

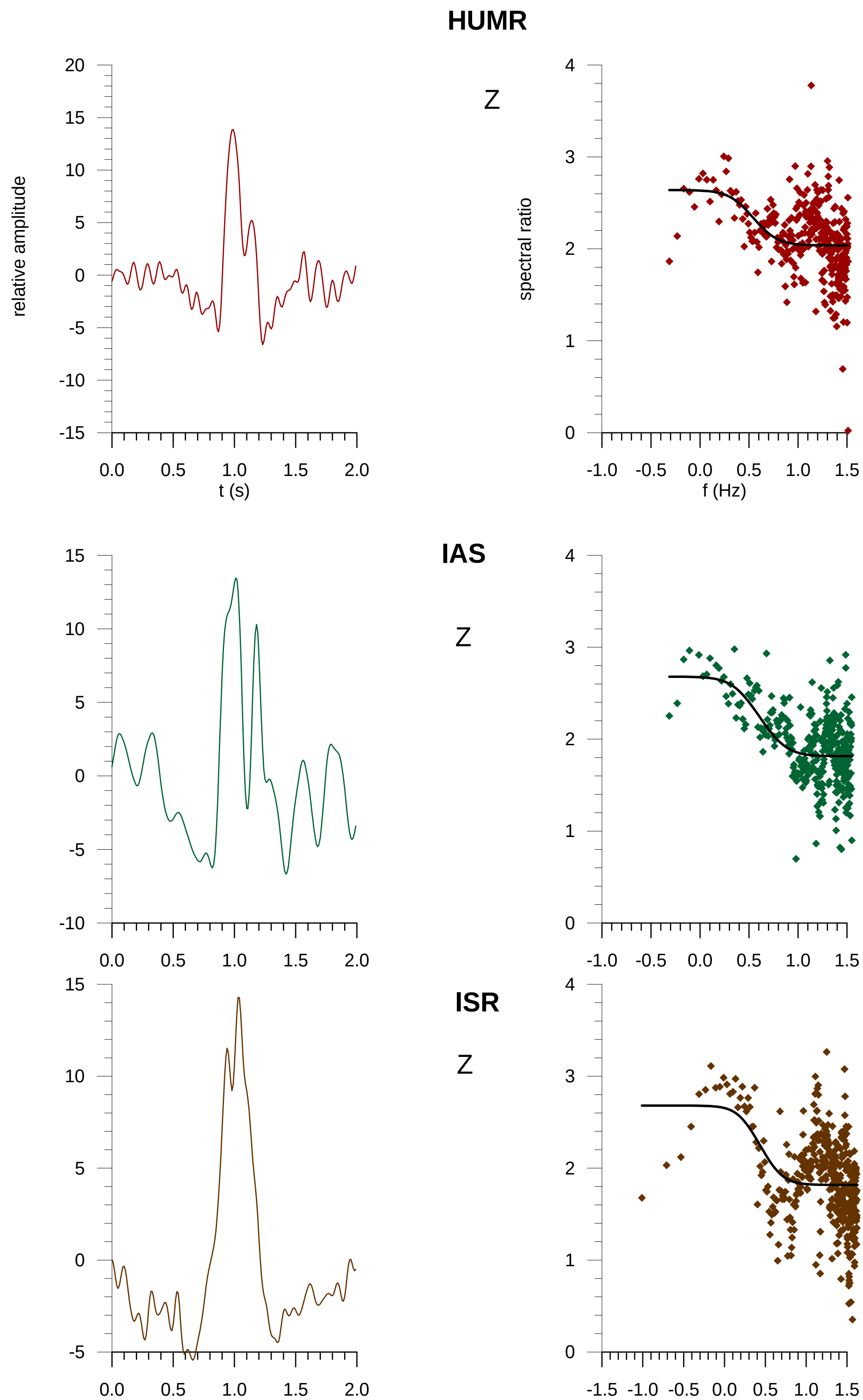
Table 3

Rise time (**$\tau_{1/2}$**) obtained for the main event at 19 stations by EGF deconvolution

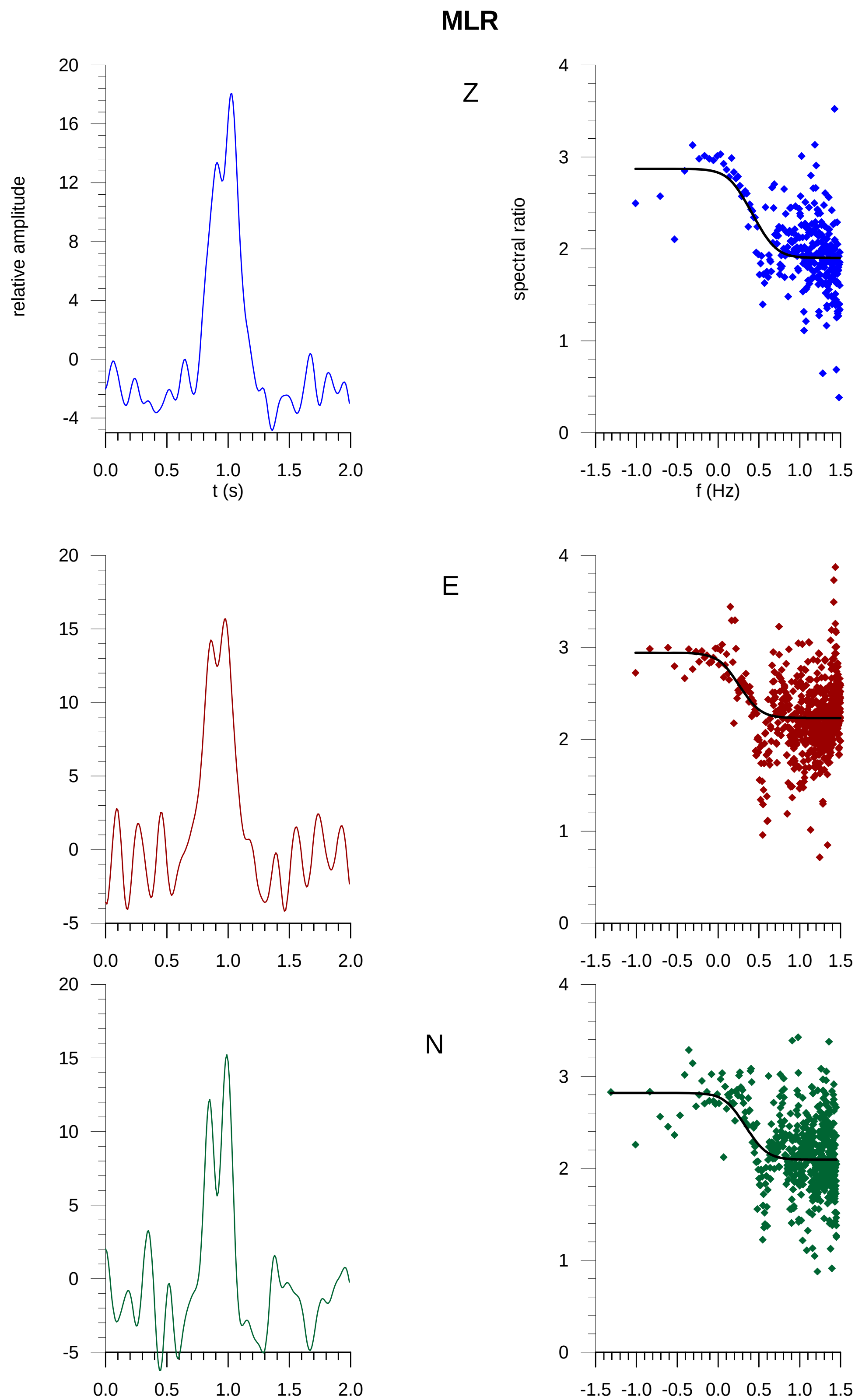
No.	Station	$\tau_{1/2}$ (s)		
		Z	**E**	**N**
1	CVD	0.135	–	–
2	CIOR	0.199	–	–
3	BMR	0.138	–	–
4	BURB	0.153	–	–
5	CFR	0.161	0.140	0.118
6	GHRR	0.111	–	–
7	GRER	0.205	–	–
8	HUMR	0.124	0.189	0.172
9	IAS	0.145	–	–
10	ISR	0.190	–	–
11	MLR	0.199	0.200	0.151
12	PGOR	0.157	0.165	0.150
13	PLOR	0.175	0.210	0.180
14	PRAR	0.142	–	–
15	SEC	0.172	0.170	–
16	TESR	0.180	0.150	0.170
17	TIRR	0.160	0.210	0.185
18	TLCR	0.128	–	–
19	VRI	0.193	0.220	0.180
Average		0.154 ± 0.046	0.186 ± 0.031	0.163 ± 0.023


PETR
Z
relative amplitude
t (s)
spectral ratio
f (Hz)
SECR
Z
TLCR
Z

(a)



(b)



(c)

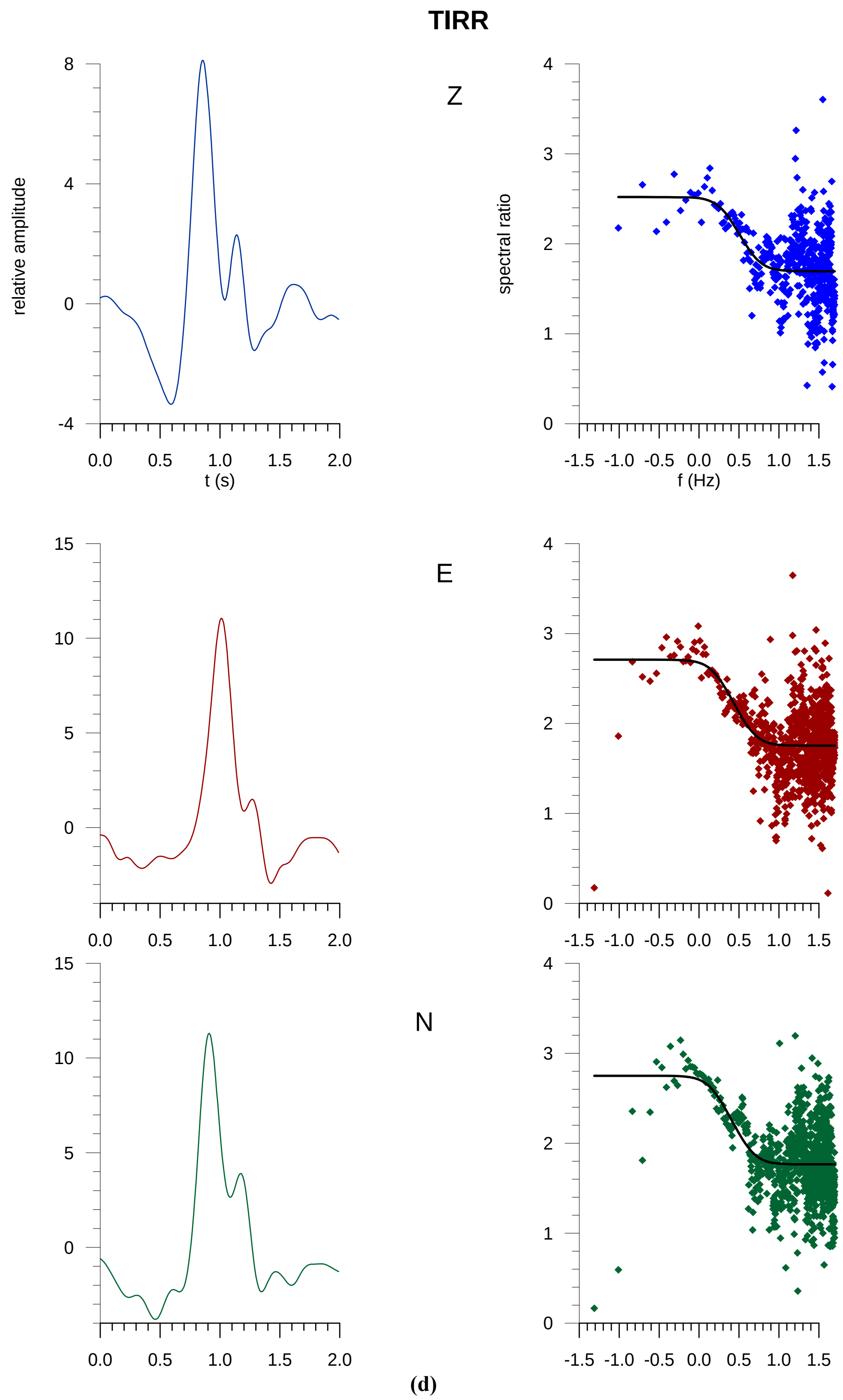


Fig. 8 – Examples of spectral ratios and source time functions: a) vertical component for PETR, SECR, TLCR stations; b) vertical component for HUMR, ISR, IAS stations; c) vertical and horizontal components for MLR station; d) vertical and horizontal components for TIRR station.

After the estimation of seismic moment and source radius we calculate the Brune's stress drop (1970) using:

$$\Delta\sigma_B = \frac{7M_0}{16r^3} \tag{4}$$

Source directivity effects occur as a consequence of the rupture propagation along a particular fault plane and in a particular direction. As a result of source directivity the amplitude and width of the pulses resulted by deconvolution at different locations can depend on the site location relative to the rupture plane. For example, the source signal radiated in the same direction with the rupture propagation has larger amplitude and narrower pulse width as compared with the signal radiated in the opposite direction. The inspection of the pulse amplitude distribution indicates the nodal plane dipping to SE as rupture plane. If we compare the pulse widths at different stations no clear directivity effects can be identified (Fig. 9).

We ascribe this result to the fact that the rupture process was most likely uniform in all directions on the fault plane on one hand, and to the fact that the source dimension of this moderate size earthquake is too small relative to the hypocentral distance, on the other hand.

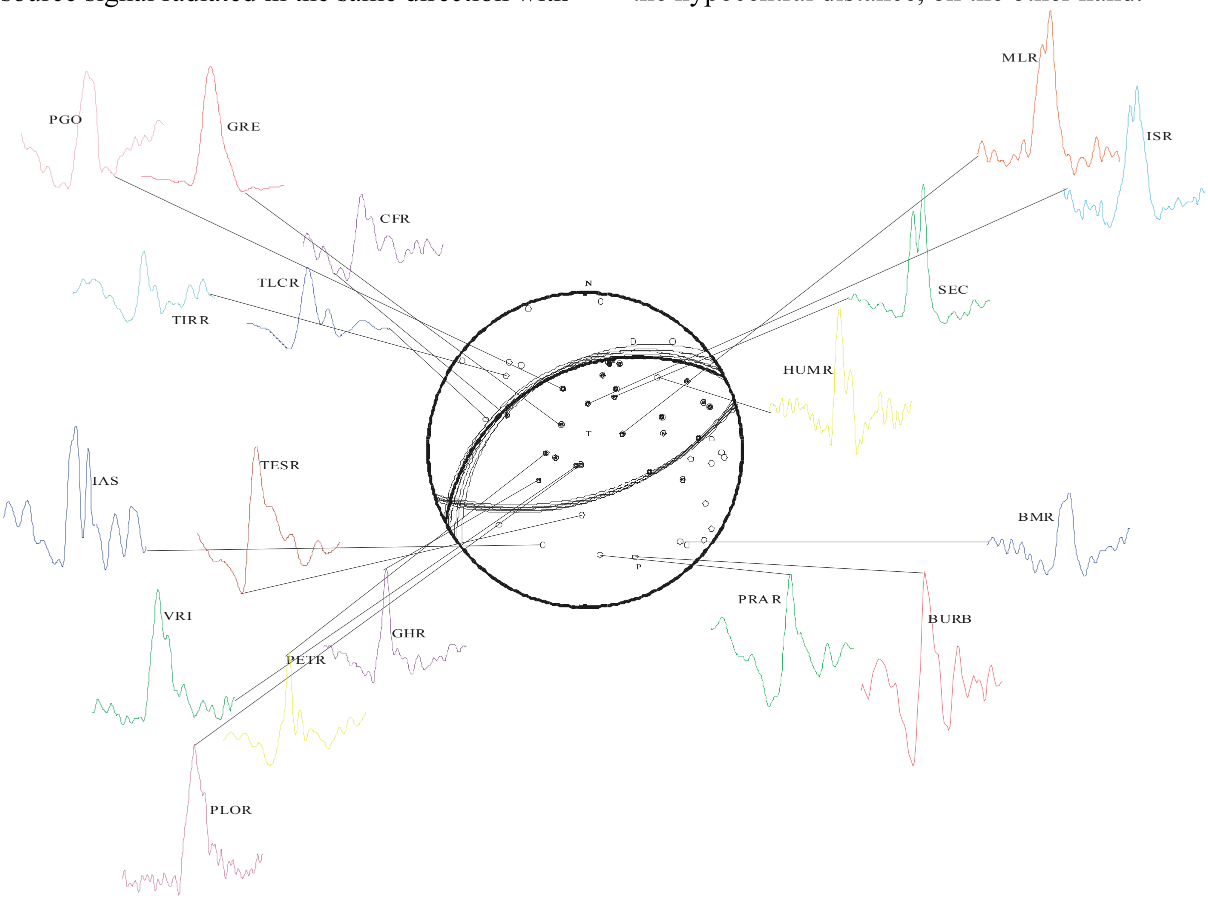


Fig. 9 – Analysis of directivity effects for the source of April 25, 2009 event.

CONCLUSIONS

The main goal of the present study is to investigate the source parameters of the Vrancea intermediate-depth earthquake occurred on April 25, 2009 (h = 110 km, M_w = 5.2). The availability of a large set of high-quality waveforms recorded for this event and for its aftershock on April 26, 2009 (h = 104 km, M_w = 3.8) allows a refined analysis of this pair of earthquakes using spectral ratios techniques and EGF deconvolution. The application of these relative methods proves to be efficient in retrieving source parameters taking into consideration the study events are closely located and their focal mechanisms are similar (Fig. 6).

The source corner frequency is retrieved by fitting the computed spectral ratio to the observed one, while the source duration is estimated by deconvolving the seismogram of April 26 event (considered as empirical Green's function for the main event) from the seismogram of the April 25 event. The source radii obtained from corner frequency and from source time function width are close each other within 20% relative errors. The tendency of the corner frequency to be higher when estimated from vertical components than when estimated from horizontal components is in agreement with the results from other seismic areas.

The application of the spectral ratios and empirical Green's deconvolution techniques for the waveform data available in the case of the two study earthquakes let to the following source parameters:

source radius = 782 ± 76 m
seismic moment = 7.7×10^{16} Nm
stress-drop = 70 MPa

for the event of 25 April, and

source radius = 270 ± 38 m
seismic moment $M_0 = 1.6 \times 10^{14}$ Nm
stress-drop = 4 MPa

for the event of 26 April.

The analysis of the source time function obtained by EGF deconvolution for different seismic stations shows a general uni-pulse like pattern. This form indicates a homogeneous rupture process in the focus. Moreover, since the apparent source time functions at different sites look similar in width and amplitude, we conclude that possible directivity source effects related to a particular geometry of the seismic radiation in the source are too small to be detected by our analysis.

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A MAJOR REASON TO FUNDAMENTALLY REVISE THE TRADITIONAL CONCEPT OF MACROSEISMIC INTENSITY: TO AVOID POSSIBLE ZONATION MISTAKES. AN ILLUSTRATIVE CASE

Homage to Professor Dorel Zugrăvescu

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The paper is intended to advocate a radical modernization of the concept of seismic intensity and the ways of its post-earthquake assessment. After referring to the developments proposed for characterizing and quantifying seismic intensity on the basis of instrumental data, a case study illustrating the erroneous results for seismic zonation, due to the use of traditional intensity scales in post-earthquake surveys, is presented. Conclusions on the needs of modernization and on the ways to proceed are finally presented.

Key words: intensity quantification, seismic zonation, spectral contents of ground motion, strong motion records.

1. INTRODUCTION

A case study concerning the possible erroneous influence of traditional macroseismic survey techniques, mentioned already in Sandi & Floricel (1998), namely the case of zonation around Bucharest, is dealt with subsequently.

The territory of Romania was subjected during the twentieth century to two destructive earthquakes, on 1940.11.10 (M_{GR} = 7.4) and on 1977.03.04 (M_{GR} = 7.2), respectively. While in 1940 a community of engineers involved in earthquake protection did not exist at all and little was learnt from the earthquake experience (a notable exception: the remarkable study Beleş (1941), the situation was totally different in 1977, when a strong and fairly well educated professional community existed and was able to learn a lot from this experience. Quite numerous publications were drafted subsequently to the earthquake (the most important among them: the monograph Bălan *et al.*, 1982). One important point raised in the frame of studies devoted to the earthquake experience was represented by the analysis of the spectral features of ground motion, given the need to forecast these features for future severe events. Two main sources were at hand for this purpose:

a) the accelerographic information obtained during the earthquake;

b) the survey of earthquake induced damage on the basis of techniques aimed at identifying the damage distribution as a function of various different spectral bands.

The occurrence of the 1977 earthquake provided the first strong motion accelerographic records of Romania. The recording network available at that time was little developed: one single complete accelerogram at ground level was obtained in Bucharest, at INCERC, by means of a Japanese SMAC-B strong motion accelerograph. That record, even if single, was remarkable and most important, since it put to evidence the unusual spectral content of ground motion (nevertheless, its relevance for the ground motion features in a quite wide area is advocated in Section 5 of the paper). The situation was very much different during the subsequent strong earthquakes of 1986.08.30 (M_{GR} = 7.0), 1990.05.30 (M_{GR} = 6.7) and 1990.05.31 (M_{GR} = 6.1).

Thanks to the generous aid provided by the Agency of International Development of the US Department of State, the accelerographic network was considerably extended after 1977 and provided in 1986 and 1990 some 150 valuable records, at ground level or at the upper floors of some buildings. The outcome of the examination of the INCERC record of 1977 was subsequently completed by the outcome of examination of the much richer data obtained during the events of 1986 and 1990.

The older zonation map of Romania, expressed in terms of MSK intensities, in force up to 1991, (IRS, 1977), relied mainly on the isoseismal maps developed subsequently to the 1940 and 1977 destructive earthquakes. The new zonation map (editions of 1991 and of 1993), (IRS, 1993), brought modifications mainly on the basis of instrumental data at hand after 1990. This topic is dealt with in more detail, in Section 5, where some related methodological aspects are tackled too.

The experience of the 1977 earthquake also showed that the microzonation standards in force at that time that had been developed for several towns, among which the City of Bucharest, were not confirmed by the geographic damage distribution. The standards referred to were put out of force and a special survey was organized in Bucharest, with the primary intention to lie at the basis of a more appropriate microzonation. The survey referred to paid attention to the geographic damage distribution, estimated this time in spectral terms, and provided some data that represented *an incentive for the development of a different approach to the concept of seismic intensity*, as presented in the paper.

After discussing some details and shortcomings of the zonation maps developed on the basis of assessment of macroseismic intensities in agreement with the concepts of traditional intensity scales MCS and MSK respectively, some important corrections brought on the basis of interpretation of instrumental data obtained during recent strong earthquakes are presented. The causes of erroneous zonation having relied on traditional macroseismic concepts (primarily, the disregard of the problem of spectral contents of ground motion) are identified.

The case study presented brings strong arguments in favour of the need to revise the definition and the ways of assessing the intensity of earthquake ground motion.

2. METHODOLOGICAL ASPECTS

2.1. General

The shortcomings of the currently widely used intensity scales of traditional type, of which the mostly used are MSK (Medvedev, 1977) and EMS-98 (Grünthal, 1998), were pointed up in various publications. A critical look, even from the traditional position of seismologists, as *e.g.* in Aptikaev *et al.* (2008), emphasized needs of improvement in this field.

The developments of the paper are based on an attempt of radical modernization of the concept of seismic intensity and of the ways of assessing seismic intensity during post-earthquake studies. The analytical developments referred to in the paper originate in the experience of the destructive earthquake having occurred in Romania on 1977.03.04. This experience puts to evidence significant conceptual shortcomings of macroseismic intensity scales of traditional type. The main shortcoming to be recalled at this place is represented by the total lack of concern for the spectral contents of ground motion (one could mention, additionally, a lack of concern for the ground motion directionality).

Visual observation data, as well as the outcome of the in depth engineering survey of damage inflicted to a sample of more than 18,000 buildings of Bucharest, made it possible to develop statistical damage spectra (Bălan *et al.*, 1982). These were convergent in putting to evidence the relevance and need of consideration of the spectral features of ground motion. Some details on this subject are given in Section 4, where some of the rich instrumental information now at hand is presented. Further on, it is also emphasized in Section 5 how the lack of concern for the spectral features of ground motion led to erroneous interpretation of macroseismic survey data after the destructive earthquakes of 1940.11.10 and 1977.03.04 and, as a consequence, to erroneous zonation of some parts of the territory of Romania. The features of zonation could be corrected after the interpretation of the rich instrumental information obtained during the strong earthquakes of 1986.08.30, 1990.05.30 and 1990.05.31.

A solution envisaged to surpass the shortcomings put to evidence by this experience relies on the consideration and extensive use of accelerographic instrumental data on ground motion. This solution consists of developing a system of alternative (yet, convergent), analytical definitions concerning seismic intensity, together with the specification of rules on how to deal with them. The developments presented start from some basic requirements, desired to be fulfilled by a more thorough approach to intensity assessment:

– the recognition of relevance of severity measures based on processing of instrumental data, and consideration of corresponding methodological implications;

– the recognition of the possible differences of the destructive potential of ground motion for various spectral bands (eventually for different directions too);

– the interest for a flexible approach to the degree of detailing of intensity estimates (relating *e.g.* such estimates, when suitable, even to various different spectral bands, in a way to lead to the determination of *intensity spectra*);

– the recognition of the possibility, and even desirability, of relevant reevaluations of macroseismic information on past earthquakes, reprocessed on the basis of modern concepts concerning especially the spectral content of ground motion;

– the compatibility between the approaches adopted by seismologists and engineers, in the sense that the use of definitions intended to be equivalent to macroseismic intensity lead to approximately the same results when applied to acquired data of macroseismic and of instrumental nature respectively;

– the recognition of the complex nature of seismic vulnerability (keeping in view the influence of the spectral content of ground motion, the evolutionary nature of vulnerability due to the cumulative nature of earthquake effects, etc.).

The authors believe thus that a consistent way of modernizing the approach to the concept of seismic intensity, consisting of the definition and characterization / quantification of seismic intensity on the basis of instrumental data is not in contradiction with the further use of macroseismic criteria. These latter ones, they think, should nevertheless be updated, such as to better fulfill the requirements of improved accuracy and certainty, as required by the engineering profession. More specifically, to be sensitive to the spectral features of ground motion.

Some analytical developments by Sandi, aimed at presenting solutions in this sense, led initially to two directions of characterizing and quantifying seismic intensity on the basis of instrumental data:

(i) *destructiveness spectra* and, consequently, *intensity spectra* (Sandi, 1979, 1980), and

(ii) *spectrum based intensities* and, consequently, *intensity spectra* relying on a different approach (Sandi, 1986).

Note here that destructiveness spectra represent, among other, a generalization of Arias' approach (Arias, 1970) oriented towards the definition of a global intensity, based on an integral of the square of ground motion acceleration. While Arias' concept is blind towards the spectral composition of ground motion, the concept of destructiveness spectrum offers the possibility of its significant spectral characterization, and this fact may strongly enhance the ability of in depth investigation of ground motion features.

Experience of use of these concepts was gradually cumulating. Both ideas appeared to be useful. The results obtained in these two ways appeared to be convergent and there was no reason to eliminate either of them, unless extensive experience will offer strong arguments in this sense. On the contrary, more practical experience based on case studies was felt to be necessary.

The two directions of work mentioned were merged into a more complex system (Sandi, Floricel, 1998), which made it possible to define global intensities, intensities related to a frequency of motion and intensities averaged upon a frequency band (all of them relying, alternatively, on different basic ways of processing ground motion data). A third approach to a basic definition was additionally introduced on that occasion: the integrals corresponded now to the frequency domain, while the integrands corresponded to Fourier transforms of acceleration time histories. The outcome of application of this idea was quite similar to that of the use of destructiveness spectra, with the difference that curves based on the latter idea were less smooth (Sandi, Floricel, 1998). The statistical tests performed put to evidence the strong correlation existing between the alternative definitions developed. To be mentioned also the close results obtained when comparing macroseismic intensity estimates with the global spectrum based intensities (Sandi, 1986). A summary view on the system is presented in Subsection 2.2. Some results in the latter connections are presented subsequently too, in Section 4.

The positive results referred to led to the idea of determining discrete intensity spectra (averaged upon successive spectral bands, corresponding to <averaged upon> *e.g.* 6 dB frequency intervals) for various records. The outcome was encouraging when comparing the results with the outcome on the statistical damage spectra developed in 1977 on the basis of field survey (Bălan *et al.*, 1982). By the way, a look at the intensity spectra for the strong motion record of 1977 explains why a careful macroseismic estimate of traditional type of the field survey data led to erroneous zonation, as mentioned before (see Sections 4 and 5). Results on intensity spectra referred to are presented for some records obtained during the recent strong earthquakes referred to.

Some conclusions and recommendations on the use of intensity spectra (eventually revising even available information about historical earthquakes) are presented in last section.

2.2. Structure of the system of alternative intensity measures

As mentioned before, the system developed for the quantification of seismic intensity on instrumental basis consists of several alternative measures. The variants developed differ from two viewpoints:

– basic functions of recorded accelerograms on which the intensity measures rely;

– frequency or frequency band to which they refer.

A summary view of the system of quantification of seismic intensity (on the basis of post-earthquake instrumental, accelerographic data) is given in Table 1. The table makes it obvious that:

– there are three different approaches, or kinds of basic functions, to which the rows correspond;

– there are three levels at which intensities are alternatively quantified: global, related to an oscillation frequency, and related to (*i.e.* averaged upon) a spectral band respectively.

Table 1

System of instrumental criteria for intensity assessment

Name	Symbols used for intensities: * global ** related to a frequency *** averaged upon a frequency interval			Source of definition / comments
	*	**	***	
Spectrum based intensities	I_S	$i_s(\varphi)$	$i_s^{\sim}(\varphi', \varphi'')$	Linear response spectra for absolute accelerations and velocities / use of *EPA*, *EPV*, redefined as *EPAS*, *EPVS* respectively (see relations (10)); averaging rules specified
Intensities based on Arias' type integral	I_A	$i_d(\varphi)$	$i_d^{\sim}(\varphi', \varphi'')$	Quadratic integrals of acceleration of ground (for I_A), or of pendulum of natural frequency φ (for $i_d(\varphi)$) / extensible to tensorial definition; averaging rules specified
Intensities based on quadratic integrals of Fourier images	I_F ($\equiv I_A$)	$i_f(\varphi)$	$i_f^{\sim}(\varphi', \varphi'')$	Quadratic integrals of Fourier image of acceleration (for I_F), or quadratic functions of Fourier images (for $i_d(\varphi)$) / extensible to tensorial definition; averaging rules specified.

The main ideas on which the system relies are as follows:

– spectrum based intensities (Sandi, 1986) originate in the idea of using convex polygonal envelope boundaries, inspired by the shape of design spectra as used *e.g.* in the design of nuclear facilities, where logarithmic scales (which are the same for abscissas representing frequency or period) are adopted; these can be related to a response spectrum as a whole or to a definite oscillation frequency (or period); in case averaging upon a definite spectral band is wanted, averaging procedures specified subsequently should be used; the ideas of *EPA* and *EPV* (effective peak acceleration and velocity respectively <ATC, 1986>) were adapted for these developments;

– intensities based on Arias' type integral are relying at their origin on integrals of ground motion accelerations (Arias, 1970), in order to characterize the motion as a whole; in case one wants to consider frequency related intensities, the integrand (depending upon the time variable) is related no longer to ground motion, but to the motion of a pendulum connected to the ground, having the (undamped) natural frequency equal to the frequency of interest (Sandi, 1979); in case the frequency referred to is very high, the pendulum motion tends to be the same as the ground motion, which means that the corresponding definition tends to Arias' definition; averaging for a spectral band is to proceed in the same way as for spectrum based intensities;

– intensities based on integrals homologous to those referred to previously, but relying on the use of Fourier images of motion accelerograms are treated in a similar way (Sandi & Floricel, 1998); note that, due to analytical reasons, the global intensities determined on the basis of integrals in the time domain and of integrals in the frequency domain respectively, are identical.

Detailed analytical definitions and relations on this system are given in Sandi & Floricel (1998).

It is of interest to reproduce at this place, in Table 2, as a quite well-known reference for further discussion, the calibration of kinematic ground motion parameters adopted in relation to the MSK intensity scale (Medvedev, 1962, 1977). Note here that while *PGA* (peak ground acceleration and *PGV* (peak ground velocity) are directly related to ground motion, *PSD* (peak seismoscope displacement) is related to the motion of the standard Medvedev seismoscope, having a natural period of 0.25 s and a logarithmic decrement of 0.5.

It may be mentioned here that the attempt to assess the intensity of ground motion at the Bucharest – INCERC site, where the single full accelerographic record for the 1977.03.04 event was obtained, led to perplexing results. If the most severe (N–S) component is considered, it turns out that, according to data of Table 2:

– to a *PGA* value of about 200 cm/s^2, an intensity of VIII corresponds;

– to a *PGV* value of more than 60 cm/s, an (extrapolated) intensity of X corresponds;

– to a *PSD* value slightly higher than 4 mm, an intensity VII corresponds.

These contradictory results are due to the fact that a firm velocity/acceleration corner period of 0.5 s, derived from the analysis of several Californian records (Medvedev, 1962), was implicitly accepted/postulated in Table 2, while in case of the Bucharest – INCERC record the same corner period exceeded 1.5 s. This case analysis confirmed the stringent need to revise the definition and ways of assessing seismic intensity.

Table 2

Instrumental criteria according to the MSK-76 scale (average values)

Intensity	*PGA*, cm/s^2	*PGV*, cm/s	*PSD*, mm
VI	50	4	2
VII	100	8	4
VIII	200	16	8
IX	400	32	16

3. A BRIEF HISTORY OF RECENT SEISMIC ZONATION MAPS OF ROMANIA

Returning to the destructive earthquakes having occurred in Romania on 1940.11.10 and 1977.03.04, the isoseismal maps derived on the basis of post earthquake surveys, using the MCS and MSK techniques and criteria respectively, are reproduced in Figs. 1 and 2 (Radu *et al.*, 1990). It may be remarked that, in both cases, the City of Bucharest is covered by an island of an intensity that is higher than the intensity assessed for the surroundings. Indeed, damage to buildings was in both cases more severe inside the City than in its surroundings, in spite of the fact that an examination of the sequences of geological layers, up to depths exceeding 1 km, at several different sites, did not provide an immediate justification for this fact. Note, on the other hand, that the building stock was strongly different inside Bucharest than in the surroundings, and this is an important point, dealt with in Section 5.

The zonation map endorsed in 1977 (IRS, 1977), derived mainly on the basis of isoseismal maps shown in Figs. 1 and 2 (and implicitly accepted at that time to represent a map of maximum observed intensities), is reproduced in Fig. 3. According to this latter map, an island of intensity VIII covers Bucharest, while the intensity for the surroundings is VII.

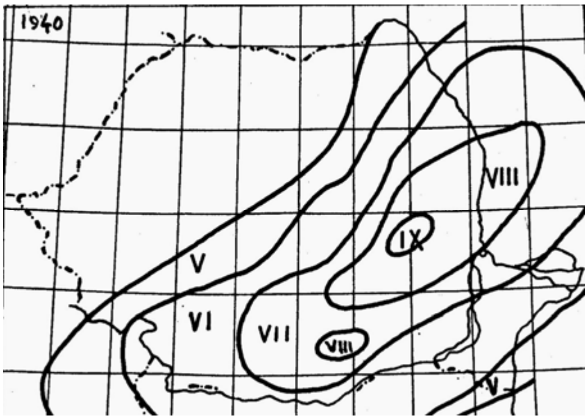


Fig. 1 – Smoothed isolines for the Vrancea earthquake of 1940.11.10 (Radu *et al.*, 1990).

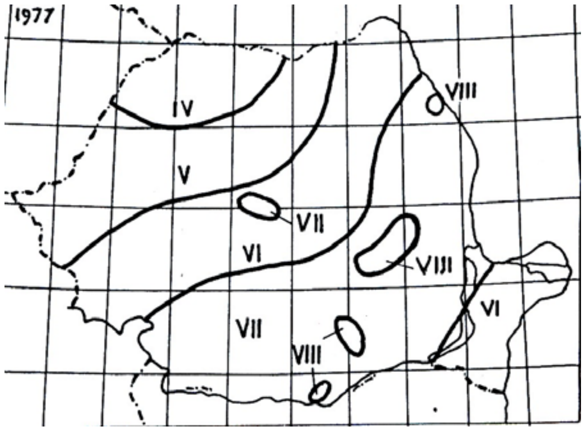


Fig. 2 – Smoothed isolines for the Vrancea earthquake of 1977.03.04 (Radu *et al.*, 1990).

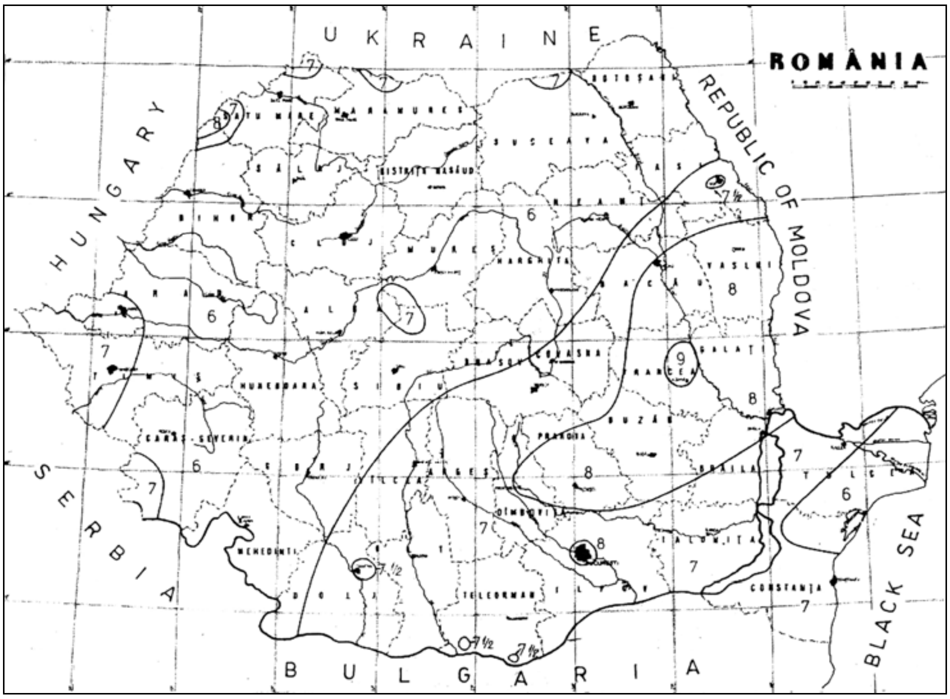


Fig. 3 – Zonation map of Romania, endorsed in 1977 (IRS, 1977).

The strong earthquakes of 1986.08.30, 1990.05.30 and 1990.05.31 (see Table 3) occurred at a time when, as mentioned, the strong motion network was much better developed. The analysis of the records obtained during the latter three strong earthquakes represented the main reason to modify the zonation map as in Fig. 4 (IRS, 1993). A careful look at the ensemble of records obtained showed that, according to instrumental information, there is no reason to differentiate, in the zonation map, the City of Bucharest with respect to its surroundings. Bucharest pertains this time to a quite large zone of intensity VIII. A discussion on this subject is due, of course, and this is presented in Section 5, after presenting in Section 4 some data on the instrumental information at hand and on the results of its processing and interpretation.

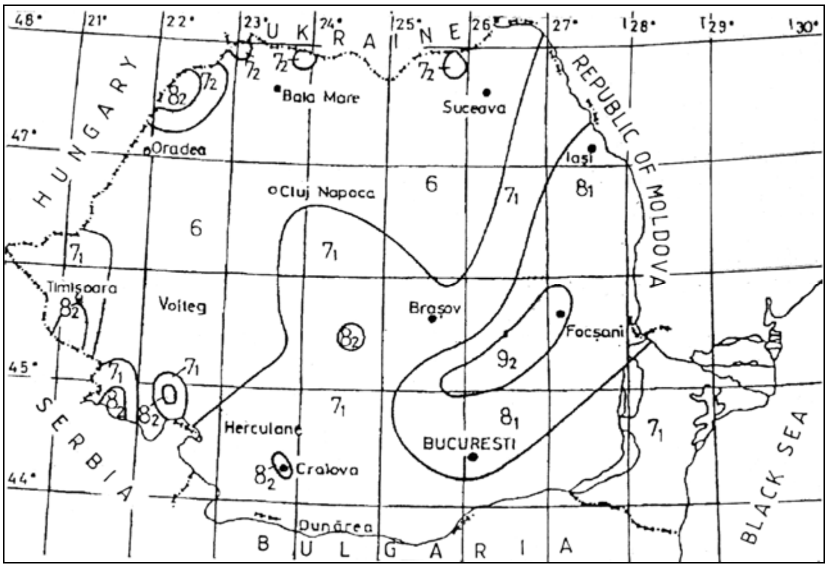


Fig. 4 – Zonation map of Romania, endorsed in 1993 (IRS, 1993). Zone of intensity IX according to MSK scale. The indices 1 and 2 mean a return period of at least 100 years respectively.

4. INSTRUMENTAL DATA AT HAND AND SOME MAIN CONCLUSIONS DERIVED FROM THEM

Some general data on the five strong Vrancea earthquakes referred to in connection with the discussion on the influence of macroseismic intensity assessing techniques and their effect on zonation, are given in Table 3.

As mentioned in Section 2, rich and particularly valuable instrumental information on the features of ground motion became available subsequently to these events. The network in operation at the time of the last three events referred to in Table 3 is presented, at country level (for the part of the territory affected primarily by Vrancea earthquakes), in Fig. 5, and, for a smaller area, inside Bucharest as well as in the surroundings of the City, in Fig. 6 respectively.

Some systems of response spectra of absolute accelerations and of intensities respectively, which are relevant for the discussion of Section 5, are presented according to Table 4.

The names of recording stations of Fig. 6 are given further on in Tables 5 and 6, in connection with the presentation of some of the instrumental information obtained there.

Some of the relevant instrumental information obtained on the basis of processing of accelerographic data, which is discussed subsequently, is presented in following figures:

– in Fig. 7, response spectra for absolute accelerations, for the sequence of records obtained at Bucharest – INCERC (INC), the single station where a valuable record at ground level was obtained during the destructive earthquake of 1977.03.04;

– in Fig. 8, response spectra for absolute accelerations, for the sequence of records obtained at Cernavodă – Town Hall (CVD).

Table 3

General data on the strong Vrancea earthquakes of 1940, 1977, 1986 and 1990

No.	Date of occurrence	Code of earthquake	Instrumental epicentre		Depth, h (km)	M_{GR}	M_w
			Lat. N	Long. E			
1	1940.11.10	401	45.80	26.70	150	7.4	7.7
2	1977.03.04	771	45.34	26.30	109	7.2	7.5
3	1986.08.30	861	45.53	26.47	133	7.0	7.3
4	1990.05.30	901	45.82	26.90	91	6.7	7.0
5	1990.05.31	902	45.83	26.89	79	6.1	6.4

Table 4

Arrangement of response spectra and of intensity spectra for recording stations located inside and around Bucharest

Location of stations	Type of spectra	Event	Figure
Inside Bucharest, arranged as in Table 5	Response spectra	1986.08.30	9 13
Inside Bucharest, arranged as in Table 5	Response spectra	1990.05.30	10 14
Along alignments crossing Bucharest, arranged as in Table 6	Response spectra	1986.08.30	11 15
Along alignments crossing Bucharest, arranged as in Table 6	Response spectra	1990.05.30	12 16

Table 5

Arrangement of response spectra and of intensity spectra for recording stations located inside Bucharest

TIT – Titulescu	EXP – ROMEXPO	INC – INCERC
MLT – Militari	CRL – Carlton	BLA – Balta Albă
PND – Panduri	MET – Metalurgiei	MTR – Metro Berceni

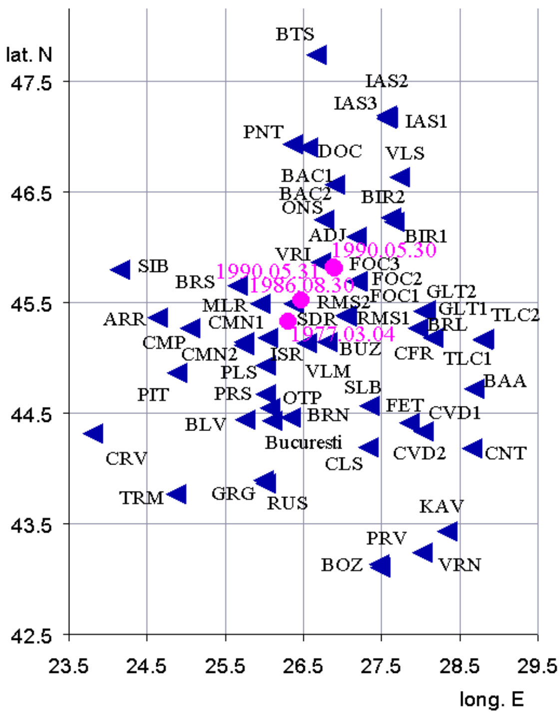


Fig. 5 – Analogical accelerographic network of the parts of Romania and Bulgaria affected primarily by Vrancea earthquakes.

Table 6

Arrangement of response spectra and of intensity spectra for recording stations located inside and around Bucharest

	PRS – Periş (N of city)	
BLV – Bolintin Vale (W of city)	CRL – Carlton (inside)	BRN – Brăneşti (E of city)
	MAG – Măgurele (S city)	

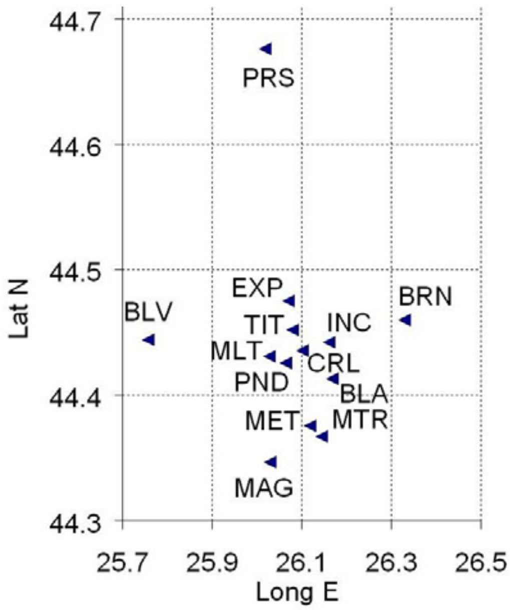
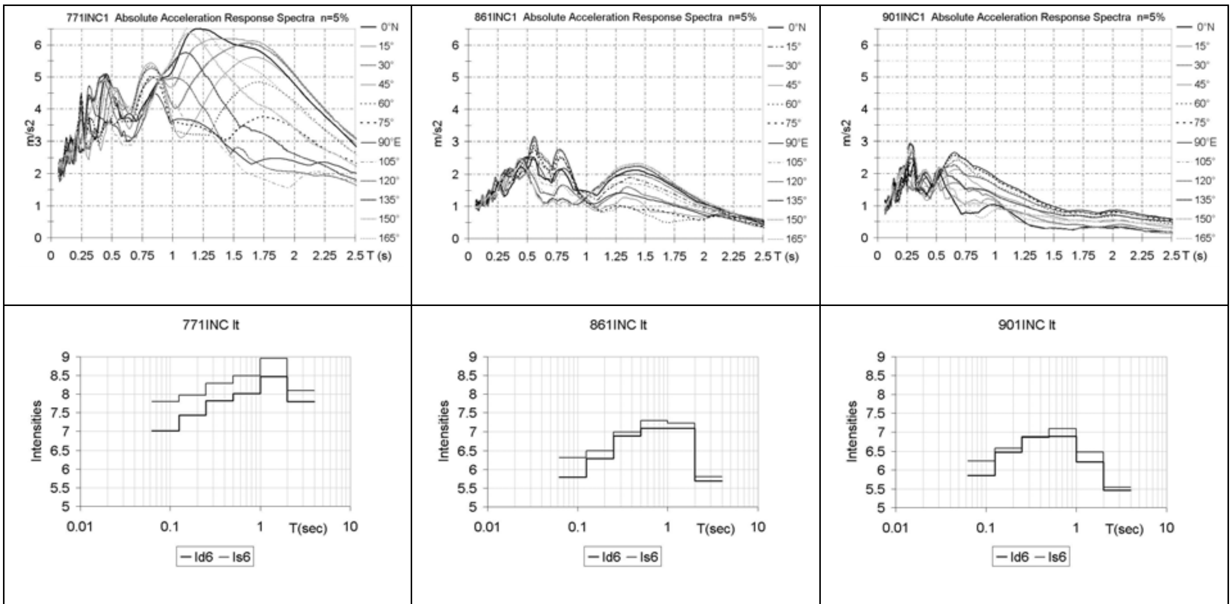
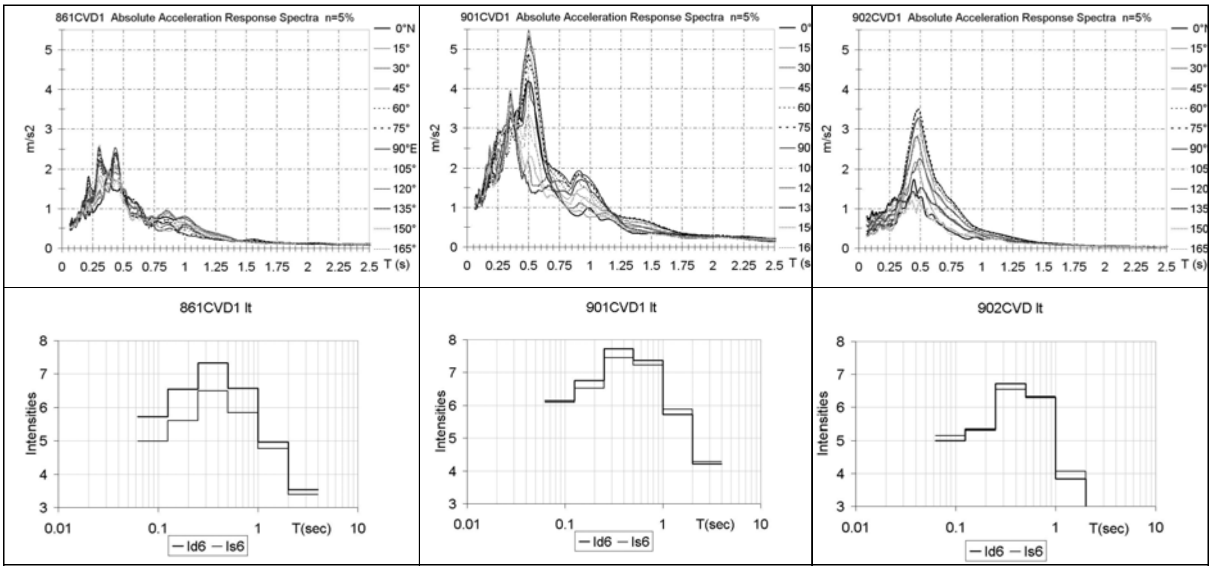


Fig. 6 – Analogical accelerographic network of Bucharest and surroundings.



1977.03.04 (M_{GR} = 7.2)	1986.08.30 (M_{GR} = 7.0)	1990.05.30 (M_{GR} = 6.7)

Fig. 7 – Response spectra and averaged intensity spectra $\tilde{is}(\varphi', \varphi'')$ (Is6) and $\tilde{id}(\varphi', \varphi'')$ (Id6), for 6 dB intervals, for the sequence of records obtained at Bucharest – INCERC on 1977.03.04, 1986.08.30 and 1990.05.30.



1986.08.30 (M_{GR} = 7.0)	1990.05.30 (M_{GR} = 6.7)	1990.05.31 (M_{GR} = 6.1)

Fig. 8 – Response spectra and averaged intensity spectra $\tilde{is}(\varphi', \varphi'')$ (Is6) and $\tilde{id}(\varphi', \varphi'')$ (Id6), for 6 dB intervals, for the sequence of records obtained at Cernavodă – City Hall on 1986.08.30, 1990.05.30 and 1990.05.31.

Note here that:

– response spectra were determined for 12 azimuthally equidistant horizontal directions, in agreement with the developments of Stancu & Borcia (1999);

– the intensity spectra, developed according to techniques referred to in Section 2, are averaged for 6 dB spectral bands.

These two stations were selected as prototype stations, due to the features of the corresponding sequences of spectral characteristics of ground motion: while the results for Bucharest – INCERC illustrate a quite strong variability of spectral contents, the results for Cernavodă – Town Hall illustrate a strong trend to spectral stability. These facts were discussed in depth in Sandi *et al.* (2004), emphasizing the role of local sequences of geological layers, up to depths in the range of thousands of meters.

The examination of the figures presented makes it possible to derive following remarks:

– the response spectrum of the Bucharest – INCERC record of 1977.03.04, given in Fig. 7, is characterized by a long period (of about 1.5 s) of the main spectral peak, which is in agreement with the fact that the most severe effects were undergone by relatively tall, flexible, buildings;

– the response spectrum of the Bucharest – INCERC record of 1986.08.30, given in Fig. 7 too, has a shorter period main spectral peak, while instead of the long period main peak of 1977.03.04, a secondary peak appeared;

– the response spectrum of the Bucharest – INCERC record of 1990.05.30, given in Fig. 7 too, has an even shorter period main spectral peak, while no long period secondary peak can be remarked any more;

– looking at Figs. 9 and 11, it turns out that long period secondary peak exists as such, at comparable peak ordinates, for all recording stations located inside or around Bucharest;

– looking at Figs. 10 and 12, it turns out that a long period secondary peak is absent everywhere;

– assuming the acceptance of the analytical developments of Section 2, in order to provide additional information, some specific data on the features of intensity spectra for the cases dealt with are given in Figs. 7, 8, 13–16.

Given these hard facts, the authors believe that, for Bucharest – INCERC, the long period spectral peak is due essentially to the source mechanism, which was different from one event to the other, while the local geological conditions did not play a significant role in this view. Consequently, they also believe that the long period main spectral peak characterizing the Bucharest – INCERC record of 1977.03.04 must have been of about the same importance for all locations for which results were given in Figs. 9 to 12. In other words, the response spectrum of Bucharest – INCERC of 1977.03.04 should have been characteristic in case of that event for a wide area, including Bucharest and surroundings. A more in depth look, based on RFS analysis of microtremors and on determination of transfer functions for the sequences of geological layers at the reference sites of Bucharest and Cernavodă was presented in Sandi *et al.* (2004). This made it possible to explain the causes of the trend to spectral variability, observed for Bucharest (Fig. 7), and the trend to spectral stability (Fig. 8), observed for Cernavodă.

The main point for this paper, in this connection, is represented by the conclusions derived from the examination of instrumental information (Sandi *et al.*, 2004; Borcia & Sandi, 2009), according to which:

– the determining influence on the relevant spectral contents of ground motion inside and around Bucharest was played by the source mechanism and not by the local geological conditions, and

– the amplitude of the response spectra in the range of relatively long periods (of about 1.0 to 2.0 seconds), which had the main contribution to the destructive potential of ground motion, varied quite simultaneously, for a wide area including Bucharest and surroundings, from one event to the other.

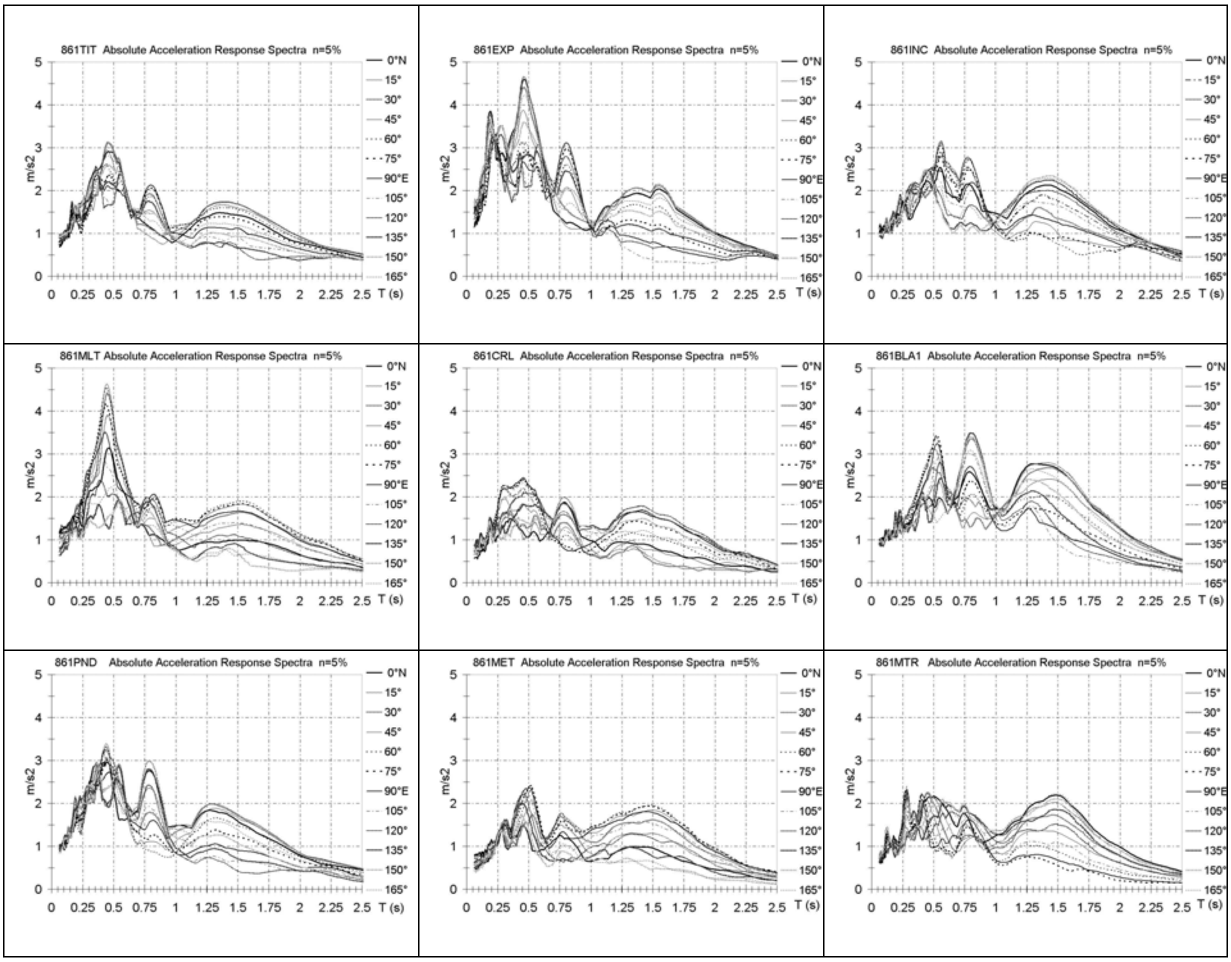


Fig. 9 – Response spectra for 12 azimuthally equidistant directions,
for stations arranged as in Table 5, for the event of 1986.08.30.

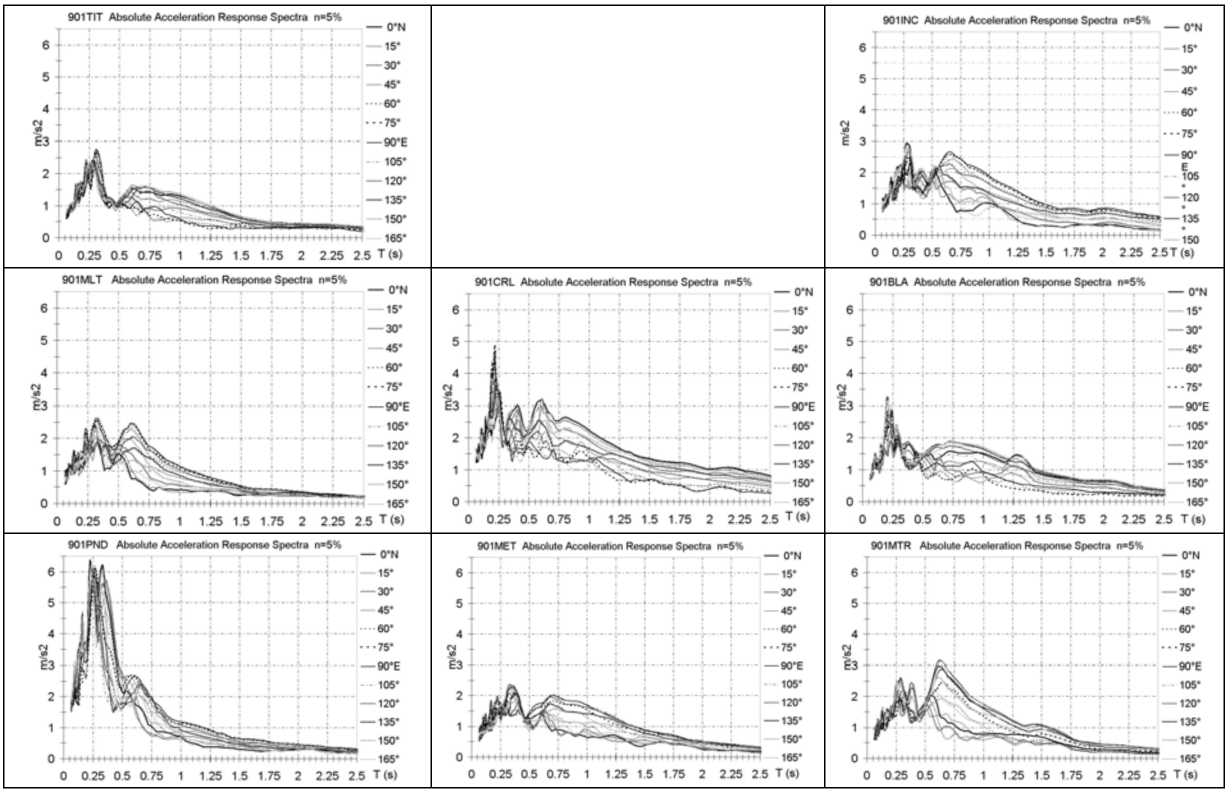


Fig. 10 – Response spectra for 12 azimuthally equidistant directions, for stations arranged as in Table 5, for the event of 1990.05.30.

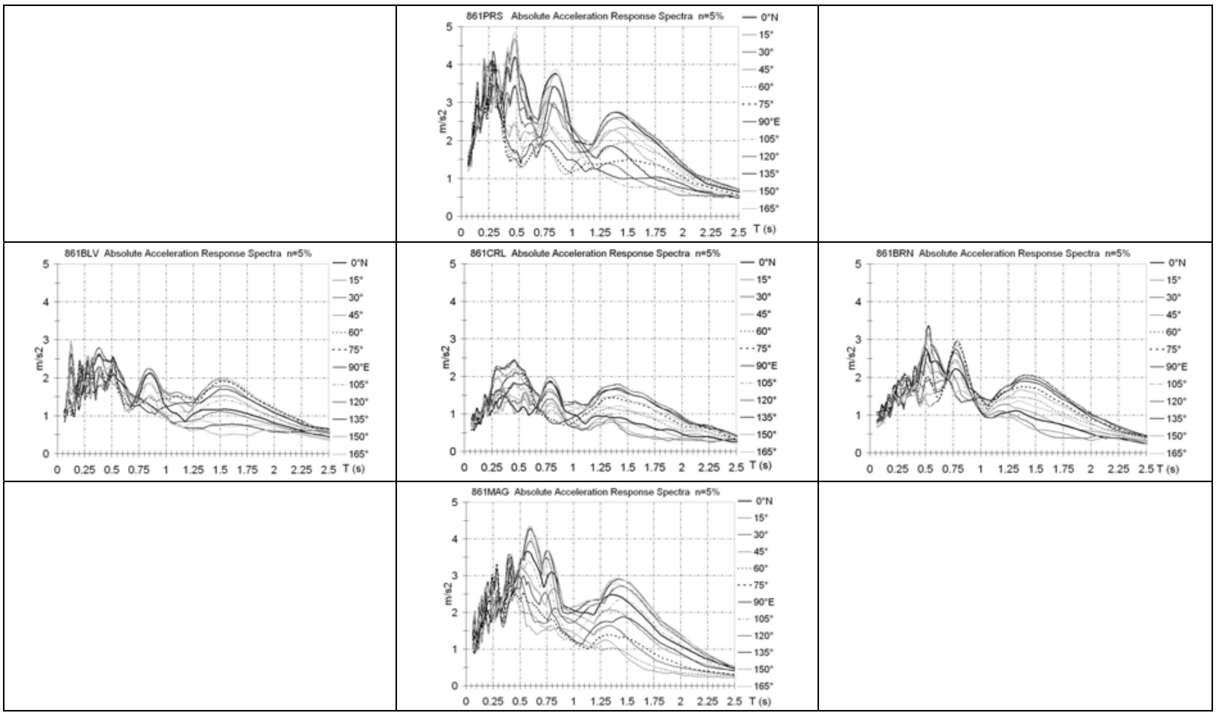


Fig. 11 – Response spectra for 12 azimuthally equidistant directions, for stations arranged as in Table 6, for the event of 1986.08.30.

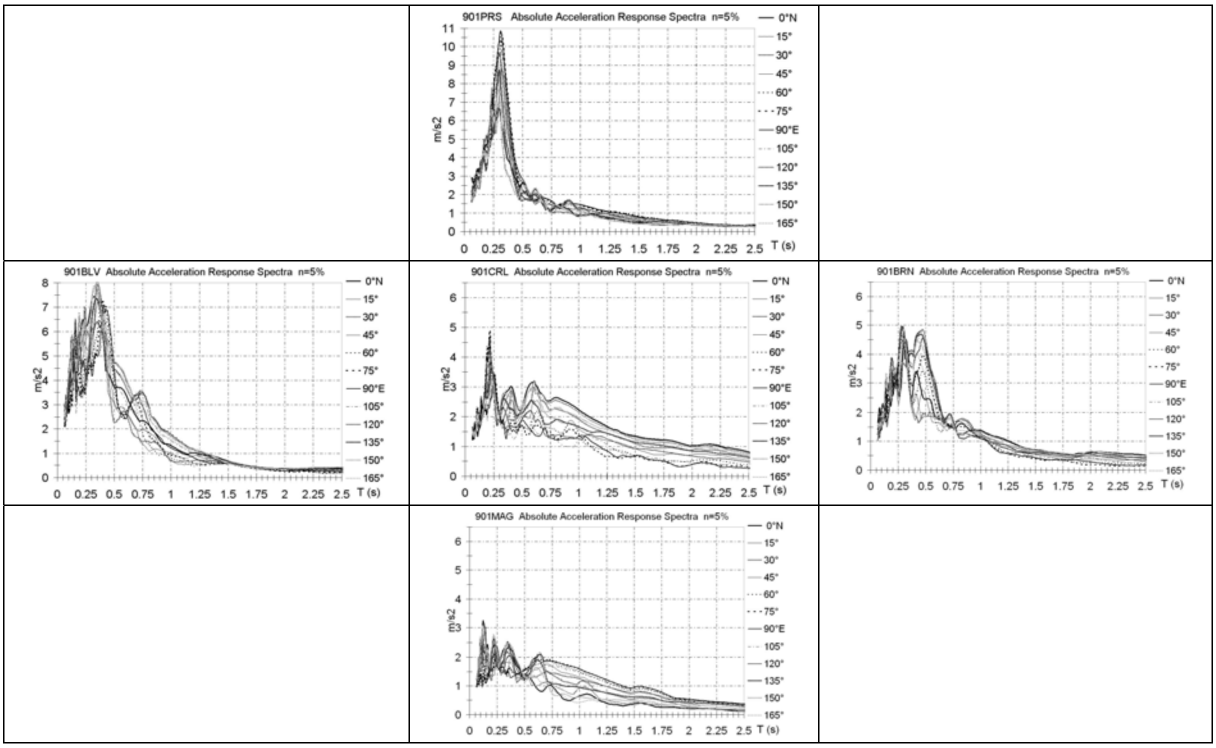


Fig. 12 – Response spectra for 12 azimuthally equidistant directions,
for stations arranged as in Table 6, for the event of 1990.05.30.

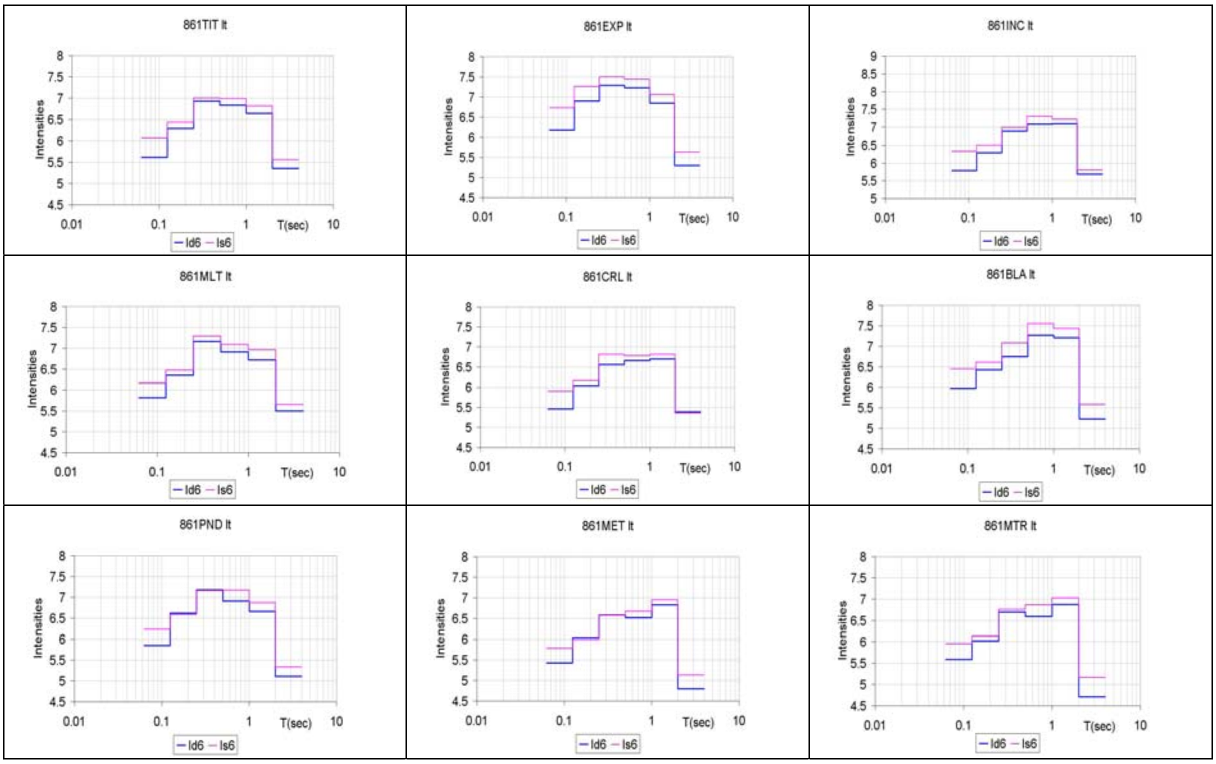


Fig. 13 – Averaged intensity spectra is˜(φ', φ'') (Is6) and id˜(φ', φ'') (Id6), for 6 dB intervals,
for stations arranged as in Table 5, for the event of 1986.08.30.

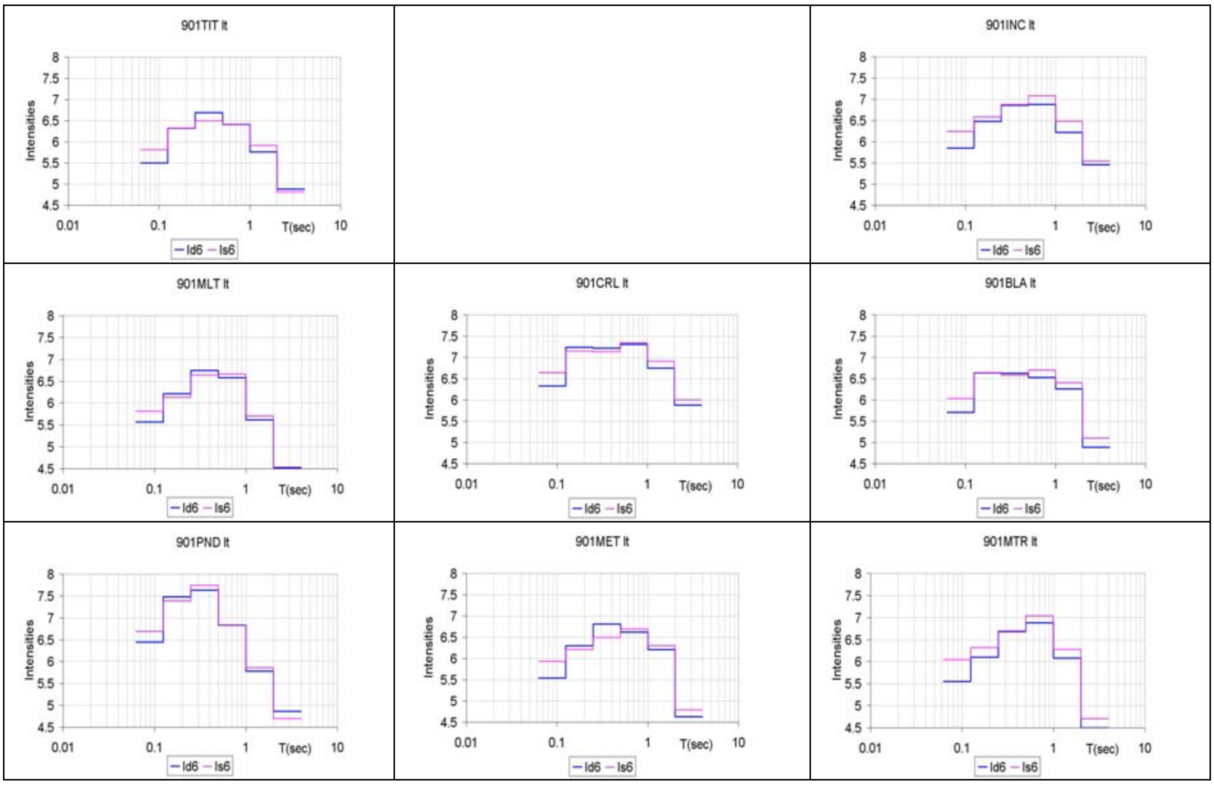


Fig. 14 – Averaged intensity spectra $\tilde{is}(\varphi', \varphi'')$ (Is6) and $\tilde{id}(\varphi', \varphi'')$ (Id6), for 6 dB intervals, for stations arranged as in Table 5, for the event of 1990.05.30.

5. DISCUSSION ON THE CAUSES OF EARLIER ZONATION SHORTCOMINGS

Summarizing now the data, results and conclusions presented, one may conclude that:

1. The macroseismic information obtained on the basis of the surveys organized subsequently to the two destructive Vrancea earthquakes of 1940.11.10 and 1977.03.04 occurred during the twentieth century was convergent in putting to evidence more severe effects inside Bucharest than in the outskirts.

2. In absence of other sources of information concerning the features of ground motion, the belief on more severe ground motion inside Bucharest than outside appeared to be justified, even if geological information at hand did not justify such a conclusion.

3. The information of instrumental nature having become available subsequently to the strong earthquakes of 1977, 1986 and 1990 showed that:

– the most severe earthquake effects were due to the longer period spectral components (in the range of 1 s to 2 s) of ground motion;

– the amplitude of the response spectra in the range of relatively long periods (of about 1.0 to 2.0 seconds), which had the main contribution to the destructive potential of ground motion, varied quite simultaneously, from one event to the other, for a wide area including Bucharest and surroundings;

– under these conditions, it is highly credible that the type of response spectrum of the first column of Fig. 7 was relevant for a wide area, covering Bucharest as well as the outskirts;

– given these facts, the modification of the zonation map from the version presented in Fig. 3 to the version presented in Fig. 4, where a higher intensity island for Bucharest no longer appears, was justified.

4. Looking now at the intensity spectra given, it turns out that in case of the record of 1977.03.04 of Fig. 7, the intensity is about one unit higher for relatively flexible structures (having fundamental natural periods of about 1 s or more), frequently met in the central zone of Bucharest, than for relatively stiff structures (having fundamental natural periods of about 0.2 … 0.4 s), met practically exclusively in the area surrounding Bucharest.

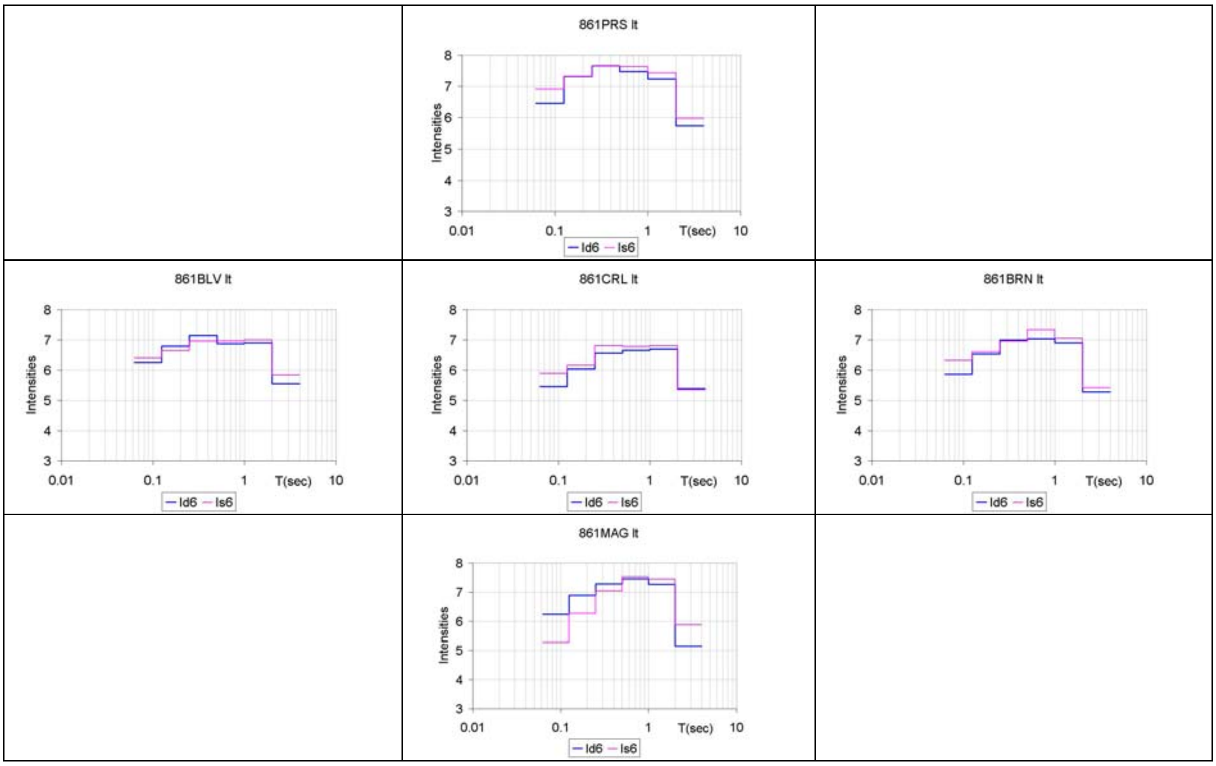


Fig. 15 – Averaged intensity spectra $i_s^{\sim}(\varphi', \varphi'')$ (Is6) and $i_d^{\sim}(\varphi', \varphi'')$ (Id6), for 6 dB intervals, for stations arranged as in Table 6, for the event of 1986.08.30.

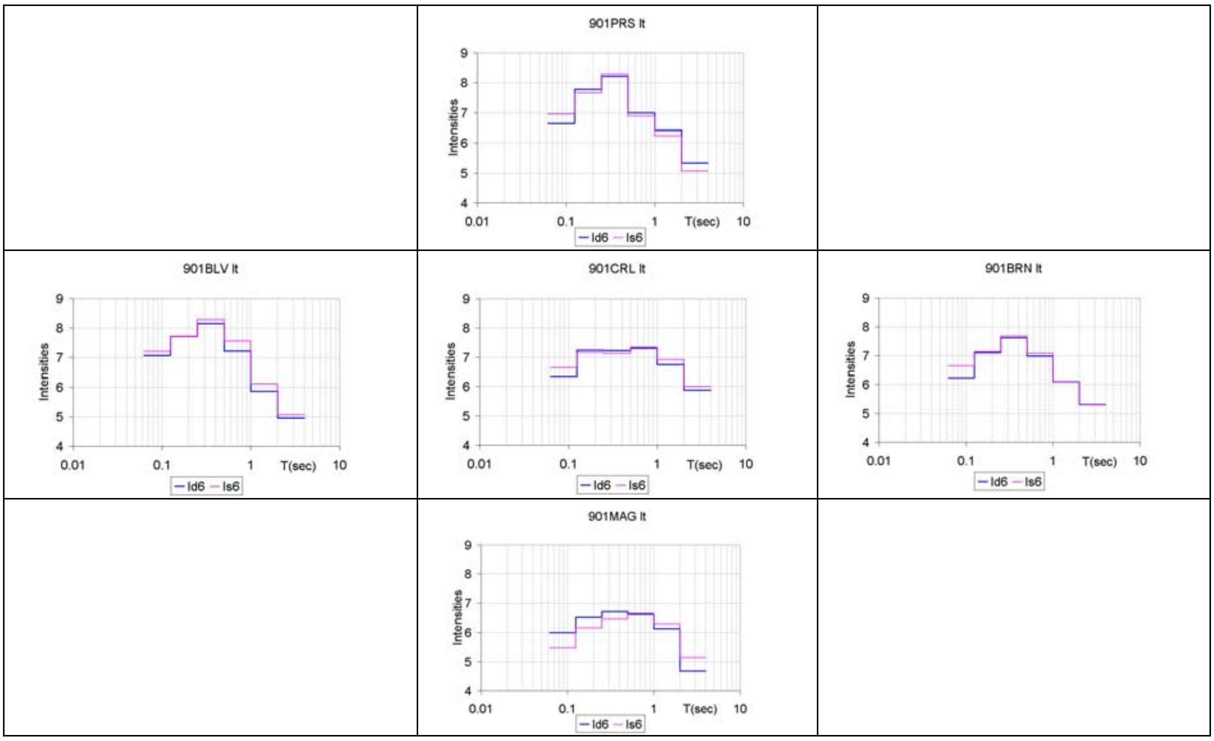


Fig. 16 – Averaged intensity spectra $i_s^{\sim}(\varphi', \varphi'')$ (Is6) and $i_d^{\sim}(\varphi', \varphi'')$ (Id6), for 6 dB intervals, for stations arranged as in Table 6, for the event of 1990.05.30.

This explains why, in the maps of Figs. 1 and 2, islands of higher assumed intensity that led to the erroneous zonation of Fig. 3, appear for Bucharest. *These remarks and conclusions provide strong arguments in favour of a reconsideration and updating of the concept of intensity.*

To end this section, some concluding remarks may be presented as follows:

– the case study presented puts to evidence the causes of erroneous zonation involved by the use of traditional macroseismic estimate techniques;

– a strong argument in favour of a radical revision of the concept of macroseismic intensity was brought.

6. CONCLUDING CONSIDERATIONS

1. The experience of the destructive Vrancea earthquake strongly put to evidence the need to pay attention, during post-earthquake studies, to the spectral features of ground motion.

2. Starting from this experience, a flexible and comprehensive system of in depth evaluation of the ground motion features, briefly referred to in Section 2, was gradually developed.

3. The history of earthquake zonation in Romania, for an area including Bucharest, briefly presented in Section 3, puts to evidence the need of revision of the solution based on traditional macroseismic surveys when relevant instrumental became available. The outcome of this revision was in agreement with the information concerning the geological features of the area.

4. The data at hand, briefly presented in Sections 3 and 4, made it possible to investigate in analytical terms, and to summarize in Section 5, the causes of erroneous zonation that was based on traditional macroseismic surveys.

5. The studies presented emphasized some of the possible serious consequences of the use of traditional macroseismic assessment of ground motion severity. The results obtained represent a strong argument in favour of revising the concept and the ways of assessment of the intensity of earthquake ground motion. The primary need in this connection is represented by a consideration of the spectral features of ground motion.

6. As a consequence, a modern scale of seismic intensity should be developed by a Joint Working Group in which engineers should have the same authority as seismologists.

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ON THE INTERDECADAL VARIATION OF MAGNETOSPHERE DIMENSIONS (1964–2007)

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An attempt is made to assess the size of magnetosphere cross-section in the solar wind, based on instrumental solar wind data and geomagnetic dipole moment values. The stand-off magnetosphere distance shows a solar cycle variation of ~12 % between maxima and minima and a long-term variation of ~6 % in the last four solar cycles (1964–2008).

Key words: magnetosphere stand-off distance, solar wind dynamic pressure, temporal evolution, space climate.

1. INTRODUCTION

In the last years a new line of research has been developed within the frame of the Institute of Geodynamics of the Romanian Academy, namely the study of several aspects of the solar-terrestrial and heliospheric physics, such as: the long-term solar signatures in the evolution of geomagnetic activity (Demetrescu, Dobrică, 2008) and climate (Dobrică *et al.*, 2009, 2010), and the long-term evolution of heliospheric and magnetospheric parameters (Demetrescu *et al.*, 2010), contributing to the field of space climate and space weather research. The space climate concept refers to long-term change in the Sun, and its effects in the heliosphere and upon the Earth, including the atmosphere and climate; the space weather regards the short-term variations in the different forms of solar activity, their prediction and effects on the near-Earth environment and technology.

The magnetosphere shape and dimensions (the surface and radius of the magnetosphere cross-section in the solar wind) are a result of the equilibrium between the magnetic pressure of the geomagnetic field and the dynamic pressure of the solar wind in which the Earth and its magnetosphere are embedded. According to Schield (1969), the sunward part of the magnetosphere can be viewed as a half sphere of radius

$$l_o = \left(f^2 M^2 / (2\mu_o P_w)\right)^{1/6} \qquad (1)$$

where M is the magnetic moment of the Earth's dipole, Pw is the dynamic pressure of the solar wind at magnetopause, μ_o is the permeability of the vacuum, and f is a constant which depends on the character of the interaction of the solar wind particles with the magnetopause (f = 2.44). l_0 is also called 'the stand-off distance of the magnetopause'.

In the present paper we discuss the variation of l_o during the time span since *in situ* measurements of the solar wind parameters have been performed by various space missions (1964).

2. DATA

2.1. The magnetic moment of the terrestrial dipole can generally be expressed by means of the first order coefficients of a spherical harmonic model of the main field (*e.g.* Chapman, Bartels, 1940) as

$$M = \frac{4\pi R_E^3}{\mu_o}\sqrt{\left(g_1^0\right)^2 + \left(g_1^1\right)^2 + \left(h_1^1\right)^2} \qquad (2)$$

where R_E is the Earth's mean radius (6372 km).

The coefficients are determined by a spherical harmonic analysis of measured data for a certain geomagnetic epoch, from geomagnetic observatories, repeat stations and geomagnetic surveys – at the Earth's surface, and from dedicated space missions – at altitudes of several hundred kilometers.

At present several models describing the evolution of the main field are available (Olsen *et al.*, 2007), of which gufm (Jackson *et al.*, 2000), IGRF (Maus *et al.*, 2005) and CM4 (Sabaka *et al.*, 2004) cover longer timespans: 1590–1990, 1900–2010, and, respectively, 1960–2002. For our study the coefficients of the three models, available at http://www.epm.geophys.ethz.ch/~cfinlay/gufm1/model/gufm1, http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html, and http://core2.gsfc.nasa.gov/cm/ for each year, were used.

2.2. The dynamic pressure of the solar wind is given by

$$P_w = m\,N\,V^2 \quad (3)$$

where V is the solar wind speed, N is the solar wind density and m is the mass of the particles constituting the solar wind. Data on these parameters can be found at http://omniweb.gsfc.nasa.gov/form/dx1.html.

3. RESULTS AND DISCUSSION

The evolution of the dipole magnetic moment calculated according to eq. (2) is plotted in Fig. 1, where the three models are superimposed. One can notice that in about 100 years (the 20th century) the magnetic moment decreased by about 8%. A close look reveals, in addition to the long-term variation, the existence of fluctuations, with smaller amplitudes, of periods of 11, 22 and ~80 years. Such variations have been shown to be present in the evolution of geomagnetic elements (Demetrescu, Dobrica, 2005, 2011) too. The evolution of the ingredients of the magnetic moment is illustrated, for the three models considered, in Fig. 2.

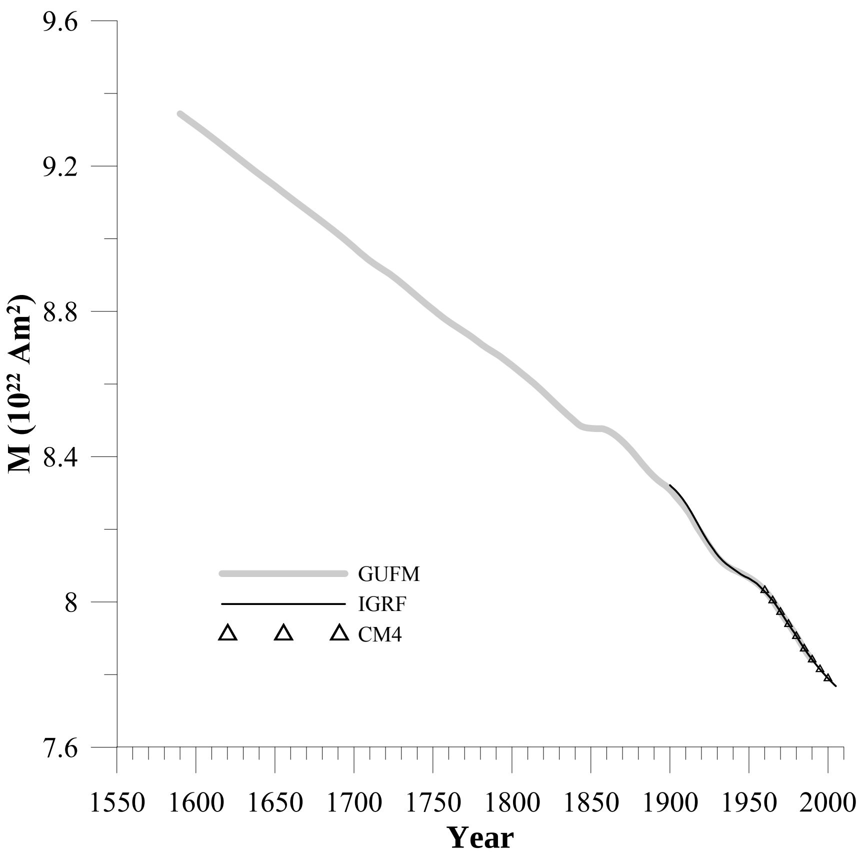

Fig. 1 – The variation of the geomagnetic dipole moment given by three geomagnetic models with long time-span.

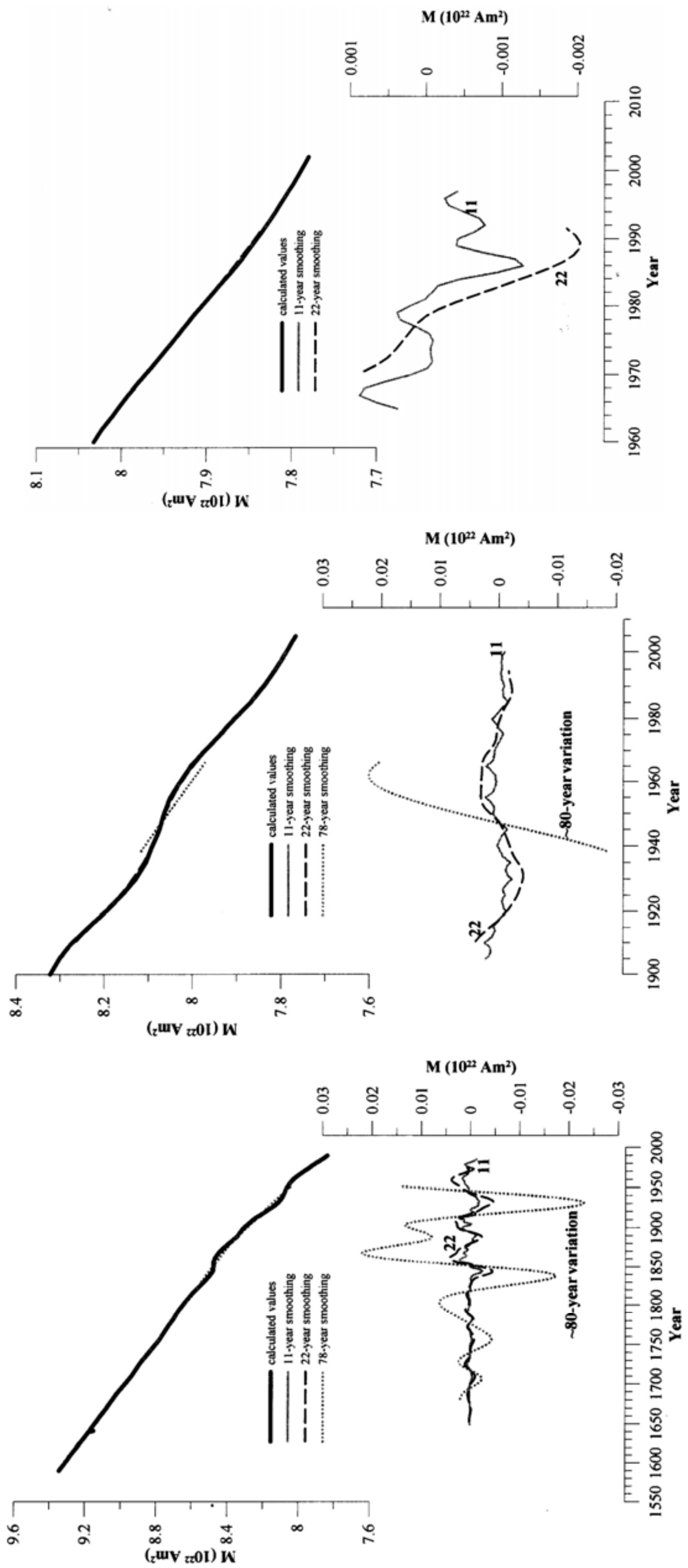

Fig. 2 – The ingredients of the magnetic moment as revealed by the three main field models.
From left to right: gufm1, IGRF, CM4.

The 22-year variation has a relatively small amplitude ($0.5 \cdot 10^{20}$ Am^2), without effect on the solar wind coupling with the magnetosphere. However, the ~80-year variation, with an amplitude of $2.3 \cdot 10^{20}$ Am^2, can influence that coupling.

In Fig. 3 we illustrate the variation of the solar wind parameters and of the dynamic pressure in the space era by means of annual averages calculated from hourly data. They all show a solar cycle effect. The latter is eliminated by filtering the time series with 11-year running averages, also shown superimposed in the figure. It can be noticed that the long-term evolution of the dynamic pressure is controlled mainly by the solar wind density and only to a much lesser extent by the solar wind speed.

The evolution of the radius of magnetosphere cross-section, as calculated according to eq. (1) is plotted in Fig. 4. A variation with the 11-year solar cycle is quite obvious, with a difference of about 12 % between maxima and minima. A variation of ~6 % characterizes the long-term evolution, superimposed in the same figure. In terms of Earth's radius, R_E, these variations are of about 1.2 R_E and 0.6 R_E, respectively. The latter seems to be part of the solar magnetic cycle signature in data (Demetrescu *et al.*, 2010).

According to eq. (1), l_0 should increase with increasing M and decrease with increasing P_w. This is indeed the case, as it can be seen in Fig. 5 and, respectively, 6. The 11-year variation is most probably caused by corresponding variations in P_w.

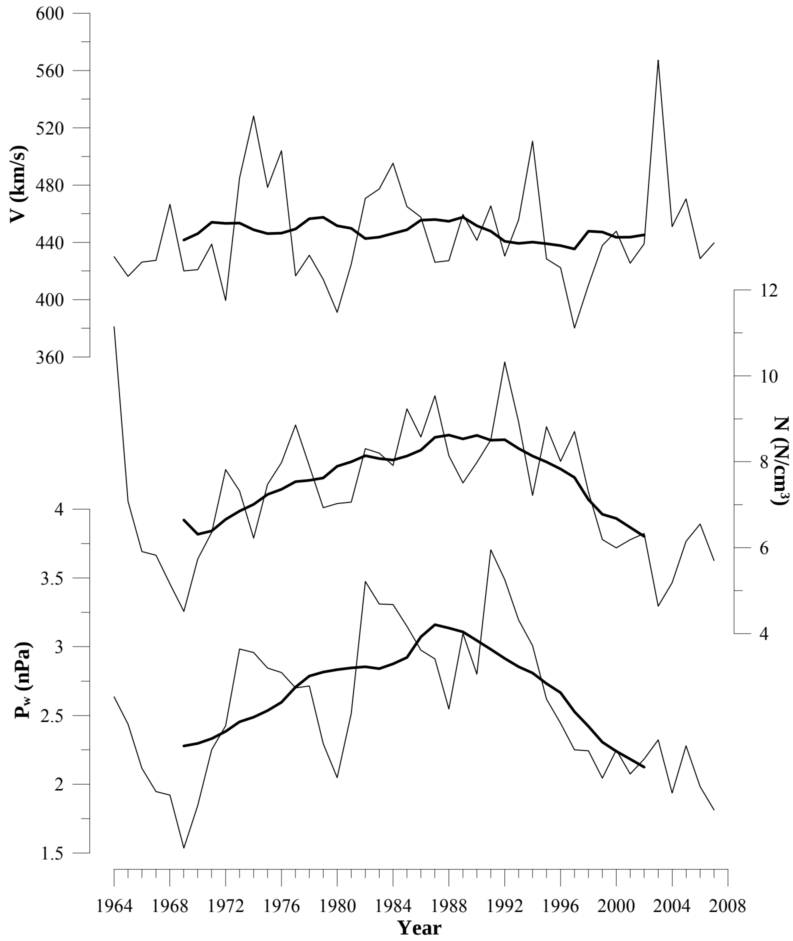

Fig. 3 – Evolution of the solar wind parameters in the space (instrumental) era. Top: solar wind velocity; middle: solar wind density; bottom: solar wind dynamic pressure on magnetosphere. Thin line – annual means; thick line – 11-year running averages.

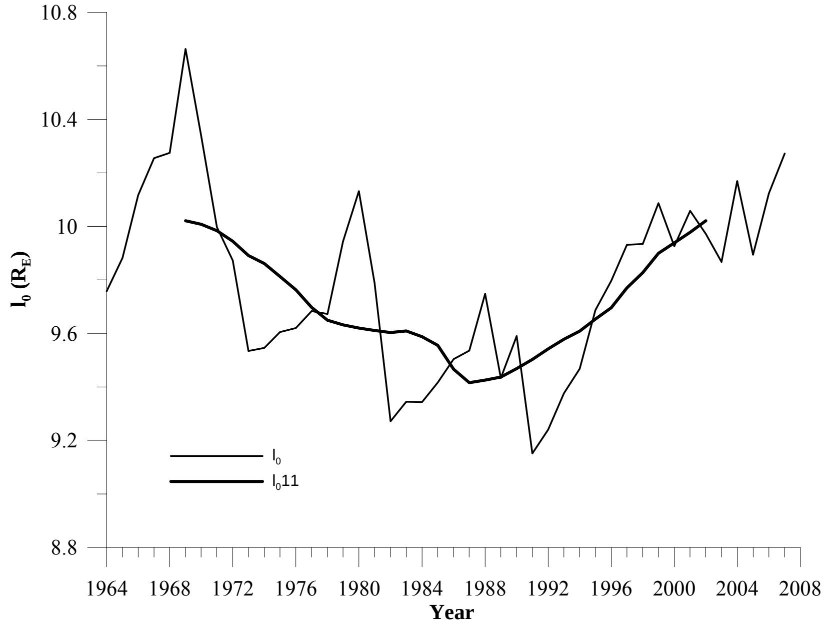

Fig. 4 – Evolution of the magnetosphere stand-off distance in the space (instrumental) era. Annual values (thin line) and 11-year running averages (thick line).

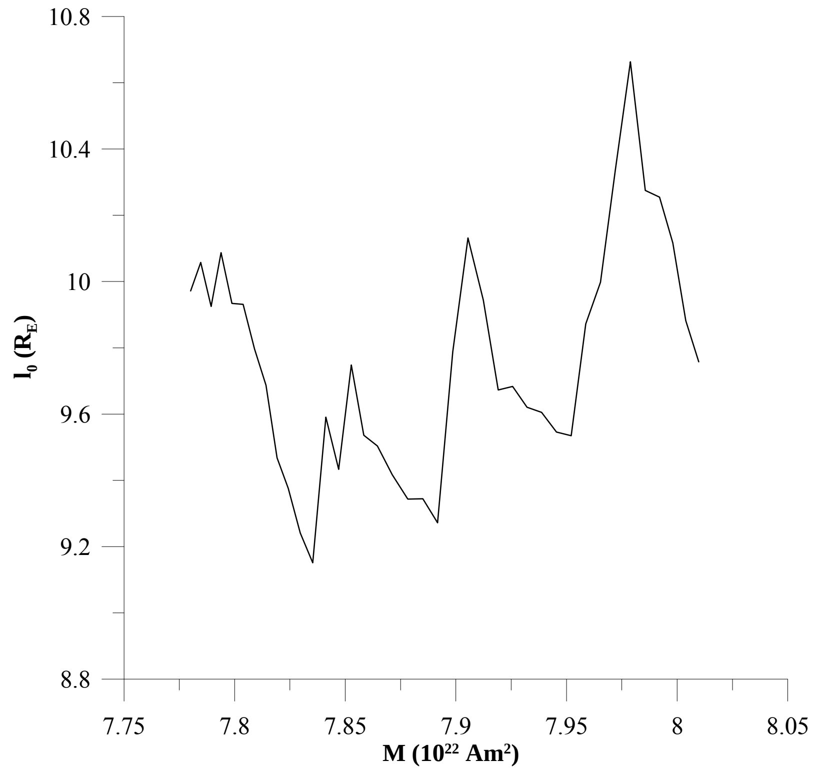

Fig. 5 – Dependence of the magnetosphere stand-off distance on the terrestrial dipole magnetic moment.

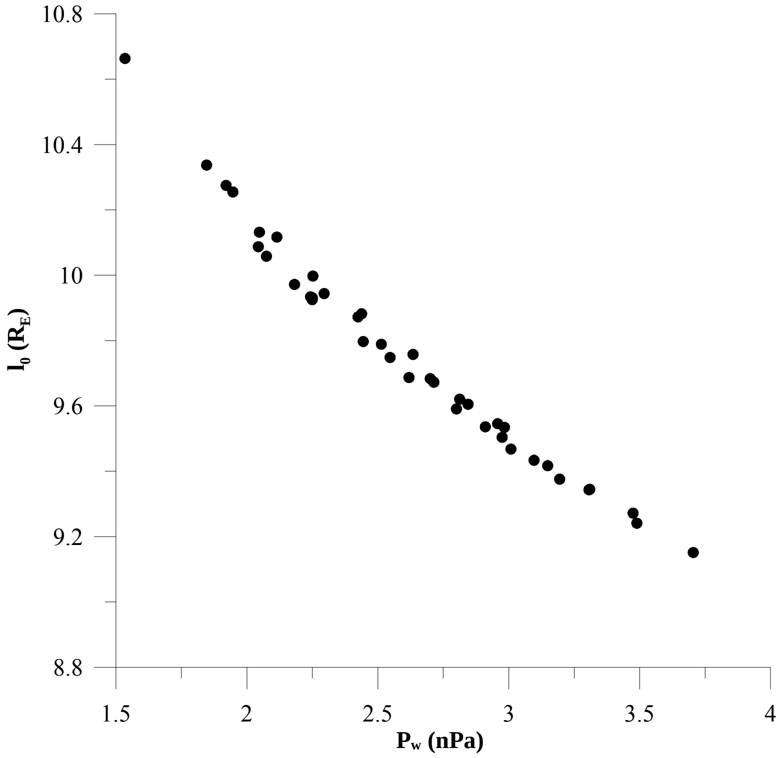

Fig. 6 – Dependence of the magnetosphere stand-off distance on the solar wind dynamic pressure.

4. CONCLUSIONS

The long-term evolution of several heliospheric and magnetospheric parameters (solar wind speed and density, solar wind dynamic pressure on magnetosphere, and, respectively, dimmensions of the magnetosphere cross-section in the solar wind), based on data from the last four solar cycles, was discussed in connection with variations of the Earth's dipole magnetic moment.

The solar wind dynamic pressure seems to be controlled mainly by the solar wind density, showing at the interdecadal timescale, solar-cycle-related amplitude variations of ~12 %.

In the study time interval (1964–2007), the values of the magnetopause stand-off distance varied with the solar cycle, showing differences of ~12 % between maximum and minimum values (~1.2 R_E). Also, a longer-term variation of ~6 % (~0.6 R_E) characterizes the evolution of the cross-section radius during the last four solar cycles. According to Demetrescu *et al.* (2010), that variation is part of the solar magnetic cycle signature in data.

The present study brings new information in the field of space climate research.

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GEOTHERMAL INTERPRETATION OF RECENT TOMOGRAPHY IMAGES OBTAINED FOR THE SOUTHERN PART OF THE HARGHITA MOUNTAINS

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The thermal structures of the upper mantle along two geotraverses crossing the Carpathian Arc bend, obtained by the conversion of seismic S-wave velocities into temperature, are presented and interpreted. The results of investigation evidence distinctive signatures of the tectonic processes in the study area: low temperatures down to the depths of 170 km, representative for the episode of the slab paleosubduction beneath the Vrancea region and the possible existence of melting fractions higher than 1% in the two recent volcanic zones, Ciomadul (Harghita Mountains) and Perşani Mountains.

Key words: temperature of the upper mantle, seismic velocity-temperature conversion, Harghita Mountains.

1. INTRODUCTION

The seismic wave velocity – temperature conversion technique could be a useful tool in assimilating the available information supplied by tomographic seismic data, in order to improve our understanding about the thermal structure of the main tectonic units of the Romanian territory (Tumanian, 2008).

The conversion procedure of the seismic wave velocities to temperatures includes the perturbing effect of the composition variability with depth and the corrections for the effect of anelasticity and for the melt and water presence in the mantle rocks.

In this study we use the two dimensional V_S models obtained by local tomography inversion beneath the Southern part of the Harghita Mountains area, of Popa *et al.* (2011), to infer temperature and melt distribution in the upper mantle, down to 220 km. Some characteristics of the obtained thermal structures and melt distributions are clearly marked out and in accordance with independent geophysical models of the study area.

2. CONVERSION PROCEDURE

The conversion of the seismic wave velocity to temperature is based on the relationship between the seismic velocity and the thermal and mechanical properties of the propagation medium. The effect of temperature on seismic wave velocity and elastic parameters of rocks samples has been well documented in laboratory experiments. The composition variability of the upper mantle, indicated by xenoliths, is considered of minor importance in comparison to the effect of temperature on seismic wave velocity. In this study we use the seismic velocity-temperature conversion method formulated by Goes *et al.* (2000) for the shallow mantle, in which the effect of compositional variations and corrections for the anelastic behaviour of the mantle rocks are considered.

In the conversion procedure the main rock of the upper mantle (peridotite) is assumed to be composed of eight minerals: olivine, orthopyroxene, clinopyroxene, garnet, spinel, jadeite, phlogopite and amphiboles (Table 1). The sensitivity of the seismic wave velocity to temperature decreases with increasing depth, while the compositional variability gains influence (Cammarano *et al.*, 2003). Consequently, the upper mantle cannot be treated as uniform in terms of composition. Here we take into account the compositional variability with increasing depth by evaluation of the average elastic parameters (shear modulus, bulk modulus) and density for a given composition, as a function of temperature, pressure, iron content and the volumetric proportion of each individual mineral λ_i (Table 1), using the Voight-Reuss-Hill (VRH) averaging scheme.

In the study area the knowledge of the upper mantle composition has been improved by petrological and geochemical analyses of mantle xenoliths hosted by alkali basalts erupted in Quaternary (1.2–0.6 Ma) at the eastern edge of the Transylvanian Basin (Perşani Mountains). The dominant rock in the xenoliths is spinel-lherzolite (Szabo *et al.*, 2004). The geochemical and isotopic examinations of the calc-alkaline magmas from the Eastern Carpathians (Mason *et al.*, 1996) evidenced an important crustal contamination process during magma genesis and trace element patterns very similar to those from the Aeolian and Aegean arcs (Mediterranean Basin). These Mediterranean arcs are considered to have been developed from a source modified by sediment subduction and subsequently, by intra-crustal contamination.

Based on the results obtained by Mason *et al.* (1996), Tumanian *et al.* (2012) and the suggestions for the volumetric proportion of each individual mineral of the spinel-lherzolite given by Goes *et al.* (2000), we propose a reference model for the upper mantle composition at the eastern edge of the Transylvanian Basin and its variability with depth (Table 1). The compositional model takes into account the solid-solid phase transition in the mantle peridotites from spinel to garnet.

Table 1

Reference mantle composition (spinel-lherzolite) in the study area

Minerals λ_i (%) / **Depth range (km)**	**Olivine**	**Opx.**	**Cpx.**	**Gt.**	**Sp.**	**Ja.**	**Phlo.**	**Amfib.**
Moho-80 km	56	24	12	0	2	0	1	5
80–180 km	58	24	12	2	0	0	4	0
180–220 km	62	24	12	2	0	0	0	0

The nonlinear velocity-temperature relationship is also influenced by several perturbing factors as the presence of material melt and fluids in the upper mantle (Priestley and McKenzie, 2006). Consequently, here we used an extended procedure of the seismic velocity – temperature conversion proposed by Tumanian *et al.* (2012), in which a correction for the presence of the partial melt in the upper mantle has been introduced. Following the parameterization for hydrous melting developed by Katz *et al.* (2003), the extended technique provides additional information about the melt fraction in the mantle, MF, corresponding to the temperature value inferred by conversion and to the bulk water content of the hydrous mantle rock. The addition of water to a peridotite system, such as in zones affected by subduction processes, increases the degree of melting, in proportion to the dissolved water fraction (wt %). In the subduction zones (like the Southeastern Carpathians) the upper mantle may contain traces of hydrous phases, such as amphiboles and phlogopite, down to its stability limits (200 km), as a result of dehydration of the subducted slab. The results reported by Szabo *et al.* (1995) and mentioned by Szabo *et al.* (2004) indicated the enrichment of the peridotite xenoliths in both anhydrous phases (clinopyroxenes and orthopyroxenes) and hydrous minerals (amphiboles and phlogopite). Szabo *et al.* (2004) mentioned that amphiboles occur as interstitial phases and veins and are more common than phlogopite. In our analysis the bulk water content of the upper mantle is assumed constant (0.4 %) down to depths of about 180 km, while at larger depths it is maintained at a small value of 0.1 %. For another perturbing factor of the seismic velocity – temperature relationship, the sensitivity of the velocity with respect to the presence of melt (DVC), a value taken from literature, DVC = 4, is assigned (Goes *et al.*, 2000).

3. RESULTS OBTAINED BY SEISMIC VELOCITY – TEMPERATURE CONVERSION FOR THE SOUTHERN PART OF THE HARGHITA MOUNTAINS

Here we present the obtained thermal models of the upper mantle beneath the Southeastern Carpathians, along two geotraverses, using the conversion technique of the seismic S-wave velocities into the temperatures. The velocity models are derived from tomographic inversion of the local earthquake data (Popa *et al.*, 2011), by means of LOTOS–09 code (Koulakov, 2009). The tomographic algorithm started with preliminary source locations based on the initial 1D velocity model used by the National Institute of Earth Physics for routine earthquake locations. The source locations were then corrected in iterative steps in accord with an optimized 1D velocity model. The tomographic images reconstruct the depth-velocity structure beneath the Carpathian Arc bend, with special focus on the southern part of the Harghita Mountains (Ciomadul volcano), considered as the area with the most recent volcanic activity in the entire Carpathian – Pannonian region. The latest eruptions have been emplaced in post-collisional regime and they occurred during a short time interval in Quaternary (42–10 Ka). Some geophysical peculiarities of this region like the important thermal anomaly with the temperature values of 800^{o}C at depth of 20 km (Demetrescu and Andreescu, 1994), the enhancement of the local seismicity beneath the Ciomadul volcano area, assumed by Prof. Vasile Lăzărescu (*fide* Popa *et al.*, 2011) and confirmed by recent seismic monitoring, and the attenuation of the seismic waves coming from the Vrancea earthquake foci, suggest the presence of the unconsolidated state of the magma chamber beneath Ciomadul volcano (Popa *et al.*, 2011).

The tomographic images (Popa *et al.*, 2011, Fig. 5) indicated the presence of a high velocity anomaly in the crust and upper mantle, which coincides with the rock volume where the most earthquake hypocenters are located, but also an extension of the anomaly to the SW (Sinaia area) and to the NE (in a zone adjacent to Ciomadul volcano). A low-velocity anomaly has been delineated beneath that part of the Harghita Mountains where no seismic event has been reported. The Ciomadul volcano is located above a low-velocity anomaly, which is laterally separated from the descending material corresponding to Vrancea region by a horizontal succession of low and high velocity anomalies. This alternating structure could be interpreted as suggesting the possibility of the ascending movement, respectively, a gravitational descending of the upper mantle (Ismail-Zadeh *et al.,* 2005).

Koulakov *et al.* (2007) concluded that the seismic velocity anomalies obtained by tomographic inversion seem to be more robust than the absolute velocity values and that the incomplete knowledge about the reference model does not harm the relative velocity perturbations. Taken into account that the two reference velocity models, initial and optimized, display excessive large velocities at subcrustal depths, in contrast with other accepted reference models (like PREM, Anderson, 2007) and the conclusion of Koulakov *et al.* (2007) concerning the absolute velocity models, we first investigate and interpret the three reference models (initial, optimized and PREM) by the conversion to temperatures of these velocity models.

In Fig. 1 we present the three analysed velocity models (Fig. 1a) and the derived geotherms obtained by conversion, corresponding to each velocity models, for two different composition types: a composition in which the presence of hydrous minerals are taken into account, as in the compositional model presented in Table 1 (Fig. 1b), respectively, when this fact is ignored (Fig. 1c). The mean stratigraphic column for the study area is also shown, in terms used by Brandmayr *et al.* (2010).

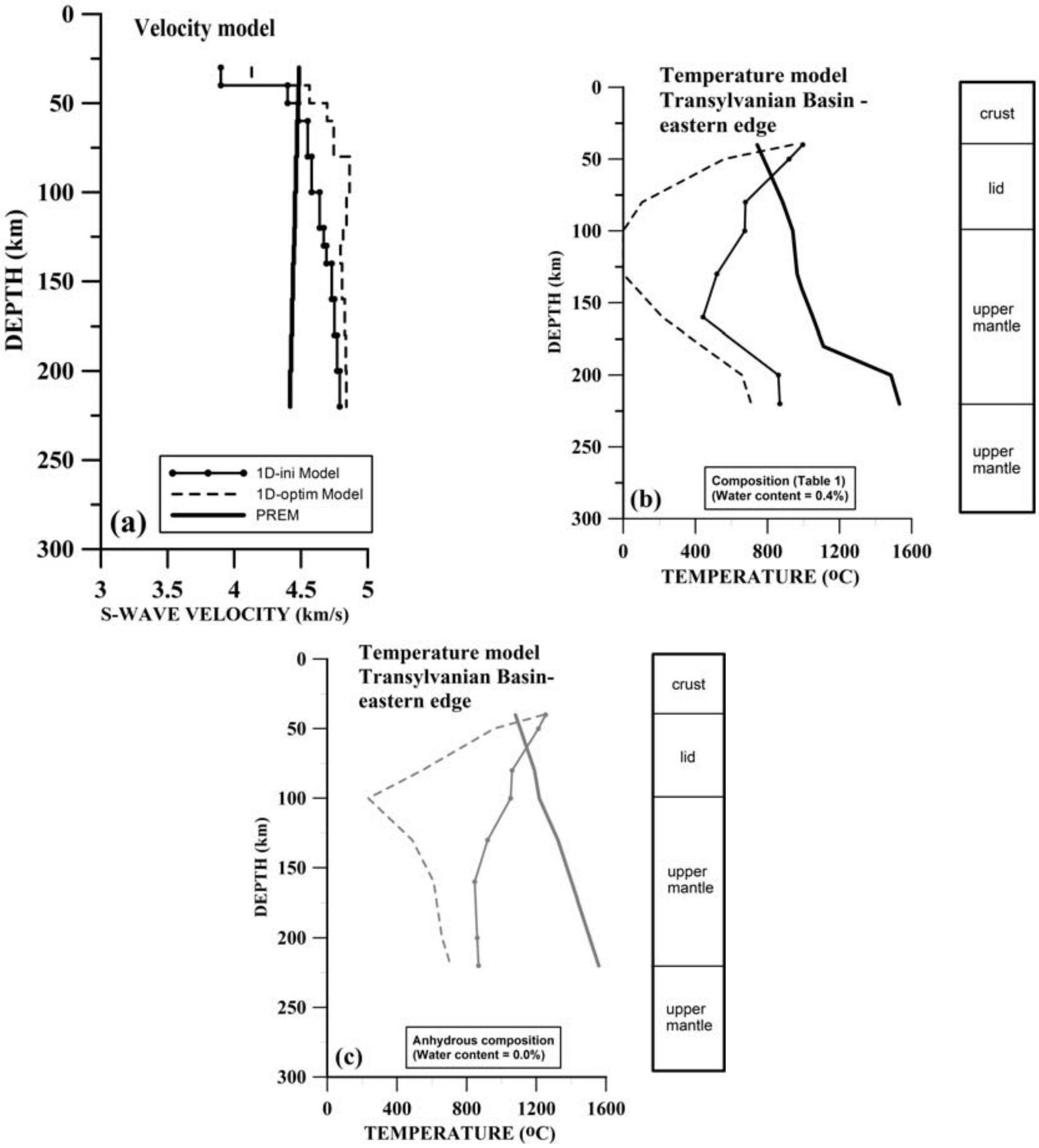

Fig. 1 – Three reference velocity models (a); derived geotherms for the compositional model presented in Table 1 (b); derived geotherms for the anhydrous compositional model (c).

The examination of the derived geotherms indicates extreme high temperatures at the top of the upper mantle in case of 1D initial and optimized velocity models (dotted line and short-dashed line), for the two composition types (Fig. 1b and 1c), while at larger depths in the upper mantle the temperatures decrease in a way corresponding to the subducted slab. In our opinion this fact suggests that the 1D velocity model, used as reference model for the velocity anomalies derived by LOTOS–09 procedure, is strictly appropriate for subduction regions and it is not suitable to achieve the absolute velocity models along the two geotraverses crossing at the Ciomadul volcano zone. Conversely, the conversion of the PREM model supplies a proper geotherm (black thick line, Fig. 1b) for the composition shown in the Table 1, and consequently, in the following interpretation the PREM and the composition from Table 1 have been assumed as reference models. We proceeded to transform the velocity anomalies obtained by Popa *et al.* (2011) into absolute velocity structures, and then, to convert the last ones to temperature structures along the investigated geotraverses. The result of this approach is shown in Fig. 2 for the section directed SW–NE and in Fig. 3 for section directed NW–SE. To illustrate some features of the temperature fields the isolines are drawn at unequal intervals, using a high density of the isolines in the depth domain where the melting process of the upper mantle has been noticed. At the top of the sections we marked the position of the Ciomadul volcano by a black full triangle. On the Romanian territory the Ciomadul volcano is placed in the southern part of the Neogene volcanic chain Călimani–Gurghiu–Harghita, 60 km NW from the Vrancea seismic area.

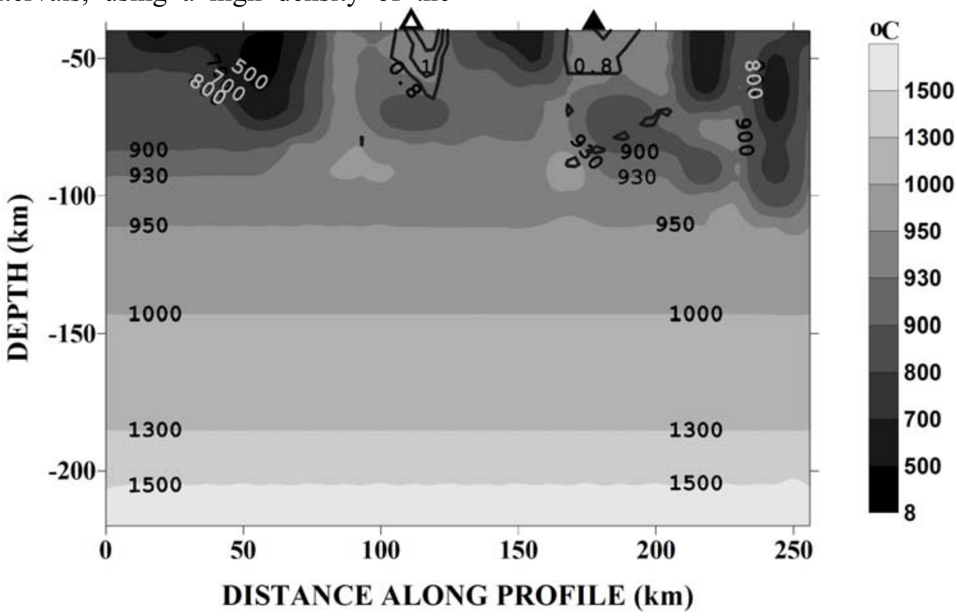

Fig. 2 – Temperature structure of the upper mantle and melt fraction distribution along the section directed SW–NE.

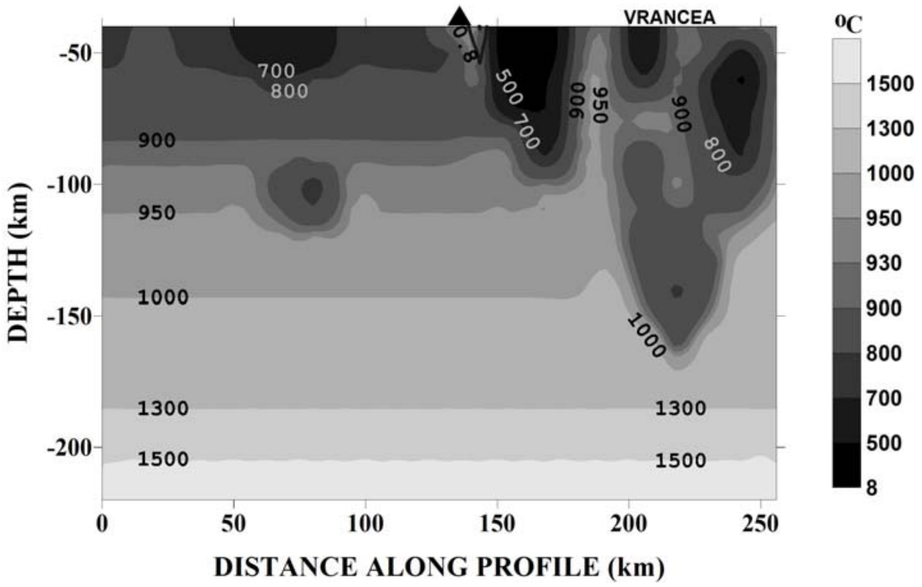

Fig. 3 – Temperature structure of the upper mantle and melt fraction distribution along a profile directed NW–SE, perpendicular to the Eastern Carpathians bend.

The petrological and geochemical analyses indicated that magmatic activity in Ciomadul volcano area has the origin in the upper mantle, at depths of 85–105 km, but the magmatic chamber is located at crustal depths (5–15 km) (Mason *et al.*, 1996). Beneath the Ciomadul volcano, at depths of 100 km we evaluate temperature values of about 930–950°C, which are close to the estimations obtained in this depth interval for the Perşani Mountains, located in Fig. 2 as marked by a black open triangle. We consider these evaluations in agreement with the results obtained by Szabo *et al.* (1995), which indicated equilibrium temperatures of about 1000–1050°C at depths of 130 km, beneath the Perşani Mountains zone. We also noticed that only in the two volcanic zones, Ciomadul and Perşani Mountains, the melting fractions in the upper mantle reach higher values than 1 %, a level which explains the development of igneous provinces (Anderson, 2010).

The temperature field for section directed NW–SE (Fig. 3) clearly delineates a zone with low temperatures down to depths of 170 km in the Vrancea seismogenic region, representative for a subducted slab. This result is in accordance to the previous evaluations of the convergence process modelling for the bending area of the Eastern Carpathians (Demetrescu and Andreescu, 1994; Andreescu and Demetrescu, 2001). We could also notice the thermal features of the possible ascents of the upper mantle in front, as well as in the backside of the subducted slab, in agreement with results of the seismic tomography.

4. CONCLUSIONS

Geothermal interpretations of the information provided by seismic tomography obtained for the Southern part of the Harghita Mountains confirmed the thermal structure of the upper mantle in the study area and certified that the conversion technique of the seismic velocity to temperature is able to improve the thermal modelling evaluations, especially for the active tectonic areas. In addition, this investigation pointed out a deficiency of the tomographic inversion which applies LOTOS–09 code in estimation of the robust absolute values for the seismic velocities, as a consequence of the non-unique solution for the 1D reference velocity model. Consequently, we consider that a complex approach of the upper mantle structure, from both seismic and geothermal perspectives, could offer a better knowledge of the geophysical characteristics of the investigated area.

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CORRELATION BETWEEN THE VRANCEA SEISMICITY AND ANOMALOUS BEHAVIOUR OF SOME ELECTROMAGNETIC PARAMETERS

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In the last decades the electromagnetic data supplied a large body of information regarding the deep structure of the seismic active Vrancea zone and surrounding areas necessary for understanding its peculiar geodynamics. By finding out how the propagation of the electromagnetic (EM) field of external origin is influenced by the variation of the geophysical properties of the lithospheric structure, we have tried to reveal possible correlations between the electrical conductivity changes due to the seismic activity in the intermediate depth interval (70–180 km) and the anomalous pre-seismic behaviour of the normalized resistivity (ρn) having an invariant character in non-seismic condition. The ρn parameter was extracted from the EM data sets acquired in 2011 by using a monitoring system, placed at the Geodynamic Observatory Proviţa de Sus, and the results have been correlated with seismic events of M > 3.5. According to this information it is revealed that some days before an earthquake, the daily mean variation of the ρn parameter, taken throughout the frequency range less than 1.66E–2 Hz, displays a significant enhancement versus its normal distribution identified in non-seismic conditions. Before all the earthquakes of M ≥ 3.6 the ρn distribution exhibit significant enhancements and the pre-seismic lead time is between 4 and 35 days.

Key words: Vrancea zone, geodynamics, normalized function ρn, earthquake mechanism.

1. INTRODUCTION

Recent catastrophic earthquakes occurred in Asia and America (Sumatra–Andaman, 2004; Sichuan–China, 2008; Haiti, 2010 and Japan, 2011) have provided and renewed interest in question of the existence of precursory signals related to earthquakes. In these circumstances, the EM science community is struggling on how to provide early information related to the occurrence time of such events in order to reduce the loss of human life and property. Previous papers published by Fraser-Smith *et al.* (1990); Hayakawa and Fujinawa (1994); Freund *et al.* (1999); Gotoh *et al.* (2002); Hayakawa and Molchanov (2002); Liu *et al.* (2004); Tramutoli *et al.* (2005); Varotsos (2005); Hattori *et al.* (2006); Ouzounov *et al.* (2006); Parrot *et al.* (2007); Stănică and Stănică (2007); Stănică and Stănică (2010, 2011), etc. have shown that some precursory signals observed on ground and in space might be associated with earthquakes. As the seismic active Vrancea zone is a very "hot" subject in the Eastern Europe related to the upper mantle strong seismicity, this paper is focused on a specific EM approach able to emphasize the short-term precursory parameter associated to the earthquakes, as a complementary alternative to the satellite observations. It means that in this paper a specific EM methodology, centered on both pattern recognition and anomalous pre-seismic behaviour of the normalized resistivity ρn (Stănică and Stănică (2010, 2011) linked to seismic events with M > 3.5 occurred in a span of four months in 2011, has been applied.

2. GEODYNAMICS AND POSSIBLE EARTHQUAKE MECHANISMS

The seismic active zone Vrancea (Fig.1) is placed within the Carpathians Arc Bend at the contact of three tectonic plates and it is considered as a very complex one owing to its peculiarities of both the deep geodynamic structure and earthquake mechanisms.

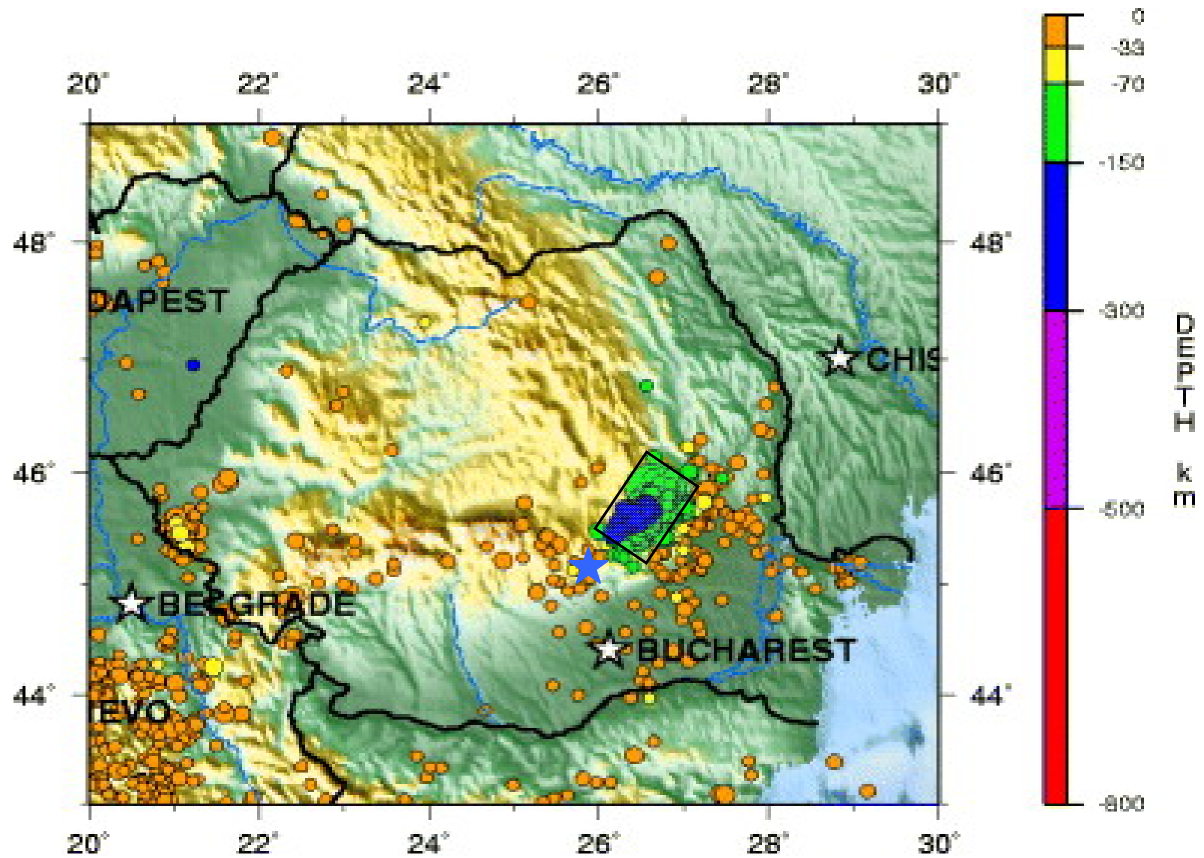

Fig. 1 – Map of the seismicity in Romania (modified after http://earthquake.usgs.gov./earthquakes/world). Black rectangle – the seismic active Vrancea zone; blue star – Geodynamic Observatory Proviţa de Sus; colored circles – the epicenters of earthquakes of various depths.

In the last years, several geodynamic models related to the triggering mechanism of the intermediate depth earthquakes have been elaborated for this area.

Oncescu *et al.* (1984), proposed a double subduction model on the basis of 3-D seismic tomographic images. In their interpretation, the intermediate-depth earthquakes are generated within a vertical surface separating the sinking slab from stable lithosphere.

Ismail-Zadeh *et al.* (2000) supposed that the viscous flows due to the sinking seismogenic slab together to dehydration-induced faulting can be considered as possible triggering mechanism explaining the intermediate-depth seismicity in Vrancea.

Stănică *et al.* (2004) show, on the base of the three-dimensional (3D) resistivity tomographic image based on magnetotelluric data, that the possible triggering mechanism of the intermediate-depth earthquakes in the Vrancea zone may be the rock response to the active torsion processes sustained by the descending asthenospheric currents and the irregular shape of the relic slab. In their opinion, this torque effect may generate the increased shear stress and drive faulting process within the rigid slab (Fig. 2).

Sperner and the Collaborative Research Center [CRC] 461 Team (2005) proposed four possible configurations for the Vrancea zone: (i) subduction beneath the suture zone; (ii) subduction beneath the foredeep area; (iii) two interacting subduction zones; (iv) subduction beneath the suture, followed by delamination.

Various types of slab detachment or delamination have been proposed to explain the present-day seismic images of the descending slab (Girbacea and Frisch, 1998; Gvirtzman, 2002; Sperner *et al.*, 2001; Wortel and Spakman, 2000).

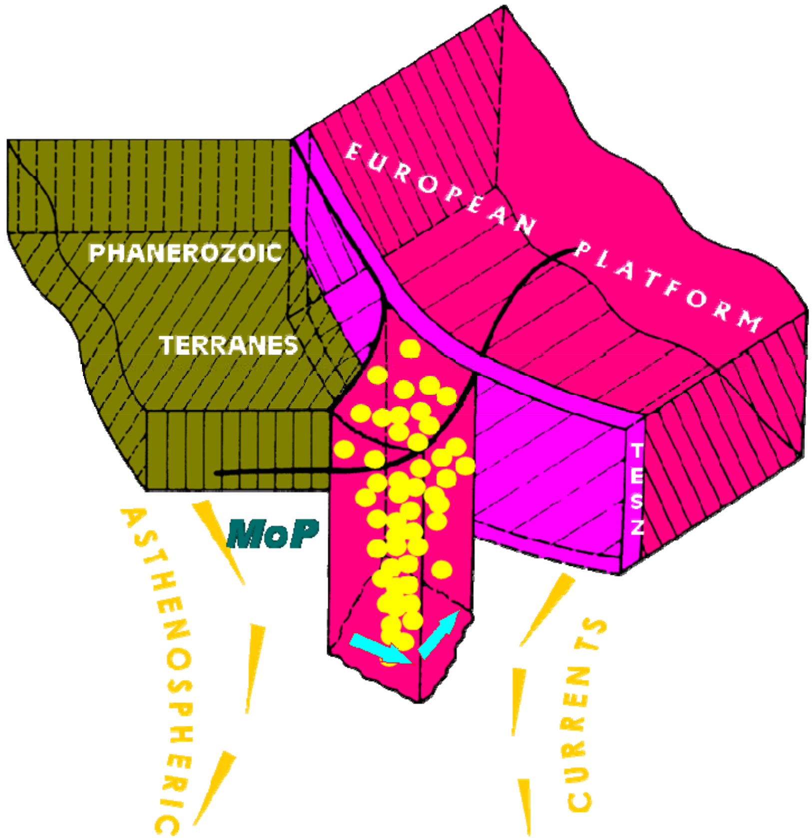

Fig. 2 – Lithospheric model of the Vrancea seismogenic zone and its surrounding areas. Yellow full circles – earthquake hypocenters; MoP – Moesian Platform; TESZ – Trans-European Suture Zone; thick black line – Carpathian electrical conductivity anomaly (CECA). Blue arrows indicate the torsion direction of the seismogenic volume (relic slab).

3. ELECTROMAGNETIC METHODOLOGY

3.1. Theoretical base of the cause (earthquake)-effect (normalized resistivity ρn) relationship

Unlike other type of information (electric or seismic), the electromagnetic data are more convenient for tackling the short-term precursory parameters, because they are restricted neither to narrow high conducting paths – as the electric data, nor to a short time before the earthquakes – as the seismic ones. It means that a specific EM methodology centered on the pattern recognition and on the anomalous pre-seismic behaviour of the ρn parameter (Stănică *et al.*, 2006, D. Stănică and M. Stănică, 2007) linked to seismic events is to be taken into consideration. The idea to use the EM methodology for studying earthquakes precursors was based on the fact that at the Earth surface the vertical geomagnetic component Bz is entirely secondary field and its existence is an immediate indicator of lateral inhomogeneity. Supplementary, for a two-dimensional (2D) structure Bz is produced mainly by B⊥ (horizontal geomagnetic component perpendicular to the geological strike) and consequently a normalized function Bzn defined as:

$$Bzn = Bz/B_{\perp}, \tag{1}$$

should be time invariant for a given 2D structure in non geodynamic conditions (Word *et al.*, 1970), and it becomes unstable due to the geodynamic processes (Stănică and M. Stănică, 2007; Stănică and D.A. Stănică, 2010, 2011). In order to identify cause (earthquake)-effect (normalized resistivity ρn) relationship, we may compute the following magnetotelluric relations valid for a 2D geoelectric structure:

$$\rho_z = 0.2\ T\ \left| E_{\parallel}/Bz \right|^2 \qquad (2)$$

and

$$\rho_{\parallel} = 0.2\ T\ \left| E_{\parallel}/B_{\perp} \right|^2, \qquad (3)$$

where: ρ_z is the vertical resistivity, $E_{\parallel}$ and $\rho_{\parallel}$ are the electric field and the resistivity parallel to the geoelectric strike and T is period (sec.).

Thus, the normalized function Bzn may be estimated as:

$$\left| Bzn \right| = (\rho_{\parallel}/\ \rho_z)^{1/2}, \qquad (4)$$

Equation (4) demonstrates that Bzn could be linked to variation of the electric conductivity into the lithosphere. Its right part leads to the normalized resistivity, defined as:

$$\rho n = \rho_{\parallel}/\ \rho_z \qquad (5)$$

It is important to point out that all the above relations are valid if the 2D geoelectric structure condition is fulfilled. In our methodology, it was also supposed that pre-seismic conductivity changes, due to the fluid migration through the faulting system, may generate changes of the ρn parameter, having variations in magnitude proportional to the intensity of anomalous current concentrations through high conductivity path (according to the equation 5).

3.2. Real time data collection

The Provița de Sus Geodynamic Observatory (GOPS, Fig.1) is located at about 100 km towards south-west of seismic active Vrancea zone and the criteria of selection as monitoring site are: (i) existence of logistic base able to supply optimal EM data; (ii) placement on the Carpathian electrical conductivity anomaly (CECA) where, ideally, the conditions for both the 2D type geoelectric structure and high conductivity path connected with Vrancea zone are fulfilled; (iii) there is the possibility for real time wireless data transfer to the central office (Institute of Geodynamics, Bucharest) for data processing and analysis.

In order to select the frequency range where the equation (5) is valid (*i.e.*, existence of a 2D geoelectrical structure and its strike orientation), as a first step in our EM methodology, at the GOPS we made a magnetotelluric sounding (MTS) using the equipment GMS-06 (METRONIX – Germany). This geophysical system has 5 channels (two electric Ex, Ey and three magnetic Bx, By, Bz components), 24 bit resolutions, GPS, low frequency range (4096sec.-1kH) for data acquisition and "MAPROS" software packages for data processing. The MAPROS software packages include all the mathematical relations for robust estimation of the magneto-telluric transfer functions, real time evaluation, display of the time series and all important electromagnetic parameters ($\rho_{\perp}$, $\rho_{\parallel}$, skewness and strike, etc.).

On the basis of MTS results, a 2D geoelectrical structure has been identified on the frequency range less than 1.66 E-2 Hz where skewness < 0.3 (Stănică and D.A. Stănică, 2011) and average strike orientation is N96^{0}E. According to equation (6), this frequency range is also associated with the intermediate-depth earthquakes interval (70–180 km) where EM precursors are generated.

$$\delta_1[\mathrm{km}] = \frac{1}{2\pi}\sqrt{\frac{10\rho_1[\Omega\mathrm{m}]}{f[\mathrm{Hz}]}}\ , \qquad (6)$$

where: δ_1 is the penetration depth; ρ_1 is the resistivity of geological structure between the earthquake hypocenter and measuring site GOPS.

The next step in our study was to set up a continuous monitoring of the geomagnetic components ($B_{\perp}$, $B_{\parallel}$, Bz) using the acquisition module MAG-03 DAM (Bartington-England), with 6 channels, 24 bit resolution and three axis magnetic field sensor MAG-03 MSL (frequency range: DC – 1kHz). In order to obtain the component of the geomagnetic field $B_{\perp}$, one of the horizontal components of the three axis magnetic sensor must be oriented perpendicular to the average strike orientation (N96^{0}E) obtained previously.

The parameters of the data acquisition card are under software control and additional program collects information at each five seconds and stores them, every 60 seconds, on the PC HD. Using the wireless connection, all the data are transferred from GOPS to the central unit, placed at the Institute of Geodynamics in Bucharest, for real-time data processing and analysis in both time and frequency domains.

3.3. Time domain processing of the geomagnetic data

The geomagnetic digital time series collected by the monitoring system are analyzed in the time domain to obtain the daily mean values of the **ρn** parameter and its standard deviation (STDEV), on the frequency interval less than 1.66E-2 Hz, imposed by equations (1) and (5), when the 2D structure condition is fulfilled.

The geomagnetic time series recorded at the GOPS for 7 days (September 28, 2011 – October 4, 2011), including both the occurrence time of the earthquake of M4.8 (October 4, 2011) and pre-seismic disturbance of the vertical component Bz (October 01, 2011), are presented in Fig. 3.

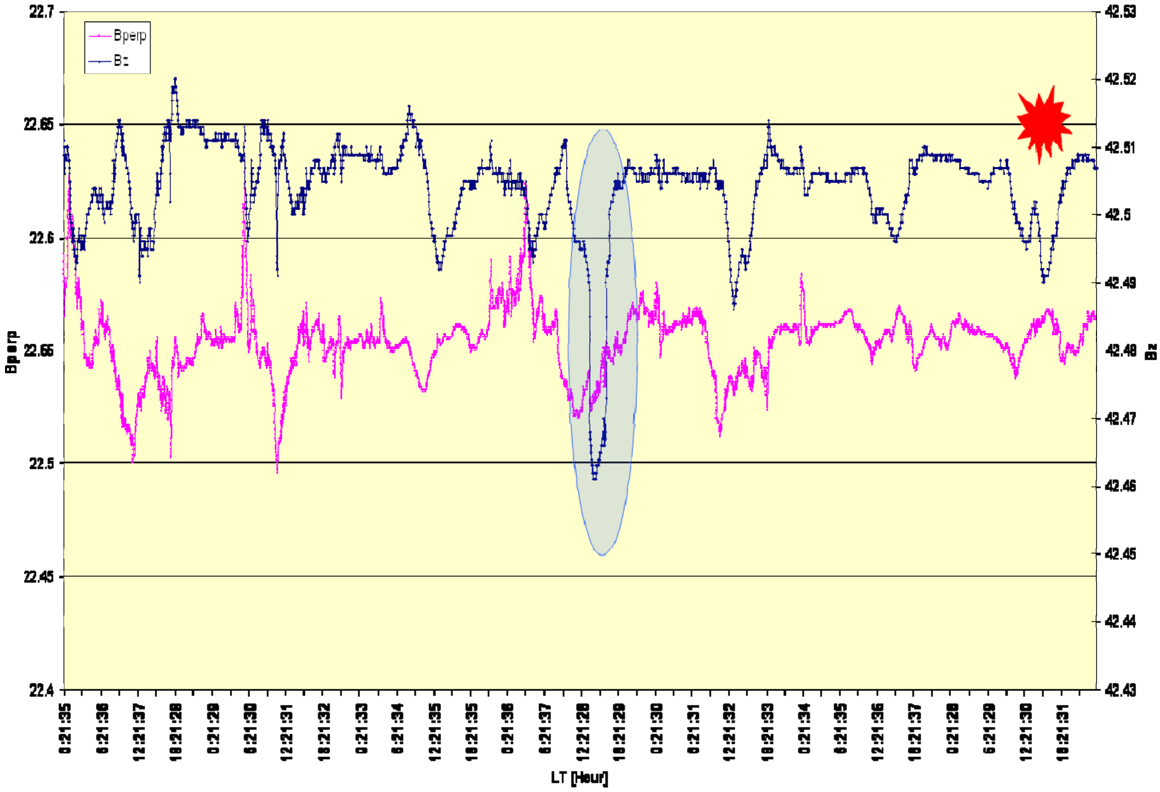

Fig. 3 – Geomagnetic time series (Bperp and Bz) recorded at the GOPS with the sampling rate Δt = 60s in a time window of 7 days (September 28, 2011 – October 4, 2011). Bperp – $B_{\perp}$; star – earthquake of M 4.8. The ellipse marks a pre-seismic disturbance of the vertical component (Bz) of geomagnetic field (lead time is about 3 days before the earthquake).

4. RESULTS

In this paper, daily mean distribution of the normalized resistivity ρn and its standard deviation (STDEV) are determined in the frequency range less than 1.666E-2 Hz, where 2D structural condition is fulfilled. The concept of this analysis is based on the idea that the signal associated with solar-terrestrial origin is constant, according to equation 1, while the lithospheric origin pre-seismic signal generated by the underground current flowing along the conductivity path (CECA) is considered to have a vertical component (see Fig. 3). In other words, according with the equations (4) and (5), the normalized resistivity ρn shows a small and certain value for its normal trend (in non seismic condition) and increased values in pre-seismic conditions.

To have a comprehensive view on the applied methodology one example of ρn distribution acquired in a span of four month (July 01 – October 31, 2011) is shown in Fig. 4 in correlation with the intermediate depth earthquakes of magnitude (Mw) higher than 3.5, selected from the catalogue issued by National Institute of the Earth Physics–Bucharest. It is easily visible (Fig. 4) that there are two domains characterized by increased values of ρn which can be correlated with earthquakes of magnitudes oscillating between 3.6 and 4.8: the first one, with ρn values comprised between 3.508 and 3.559 through the interval July13 – September 8, and a second one, in the September 10 – October 25 interval, having values between 3.535 and 3.567.

Pre-seismic lead time of the ρn parameter related to its relative maximum values in both domains (3.559 on August 8 for the Domain I and 3.620 on October 27 for the Domain II) is between 4 and 25 days.

As in the analyzed interval the local variation of the earthquakes energy was growing due to a lot of earthquakes of M > 3.5 occurring at short intervals, a continuous enhancement of the ρn parameter was observed (Fig. 4). Therefore, in order to examine the singularity (anomaly) of the ρn distribution through the interval analyzed, it was necessary to introduce a new function (ρn*) which was obtained as ratio between ρn and its monthly standard deviation (STDEV). The evolution of the function ρn* for the interval July – October 2011 is presented in Fig. 5. This function ρn* is considered to be the threshold for anomaly using standard deviation and, for this paper, the criterion of pre-seismic anomaly is set at 1.5 STDEV.

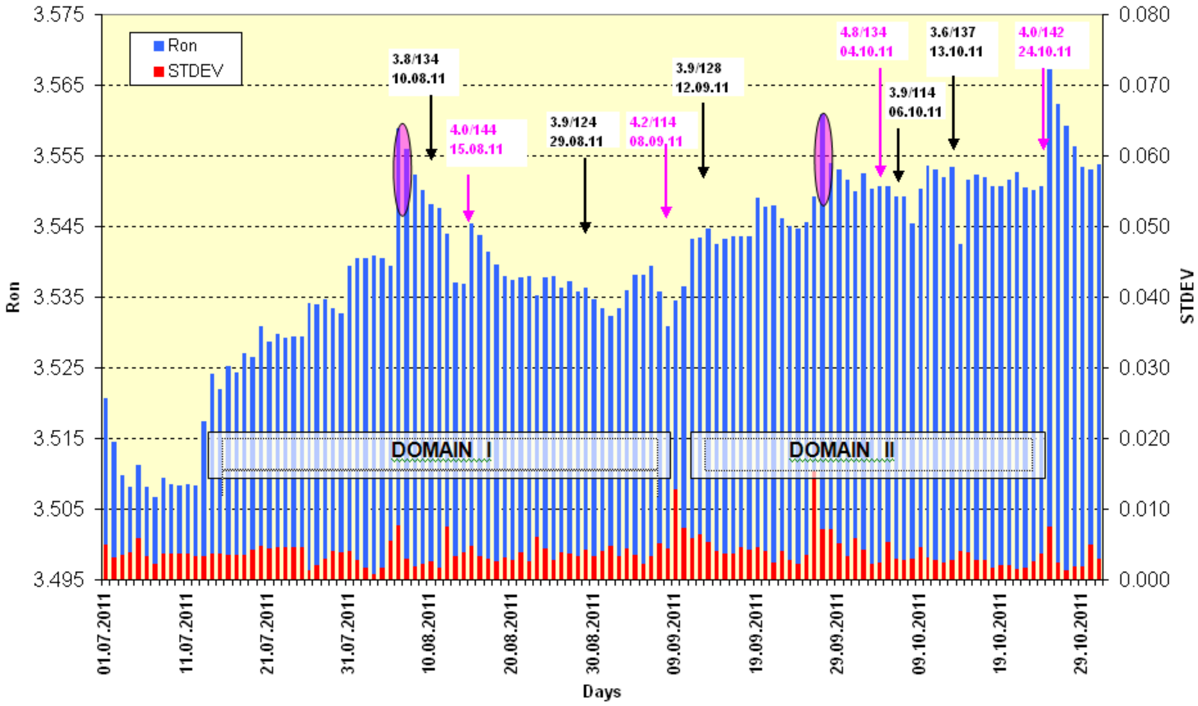

Fig. 4– Distributions of the ρn and STDEV within the interval July 01 – October 31, 2011. Vertical arrows – earthquakes; the ratio 4.0/144 is the magnitude/hypocenter depth of earthquake in km; pink ellipses mark pre-seismic lead time.

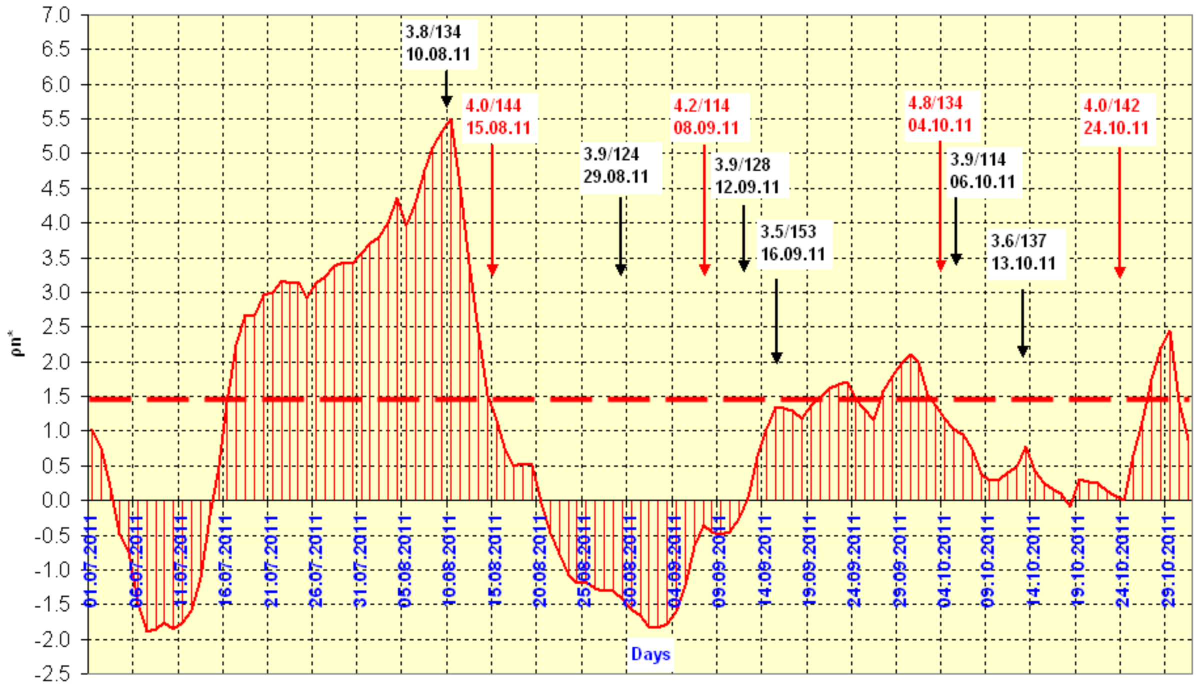

Fig. 5 – Distribution of the function ρn* obtained for the interval July – October 2011.

5. CONCLUSIONS

The results obtained in this paper are based on the hypothesis according to which the pre-seismic conductivity changes, due to the fluid migration through faulting system, may generate increased values of the normalized resistivity (ρn) proportionally with the intensity of anomalous current concentrations through the high conductivity path (CECA).

The ρn parameter monitored at GOPS in the interval July–October 2011 has been analyzed in order to detect its pre-seismic anomalous behaviour related to the intermediate depth earthquakes with M ≥ 3.6.

Before all the earthquakes of 3.6 ≤ M ≤ 4.8 the ρn distribution exhibits significant enhancements and the pre-seismic lead time is between 4 and 25 days (related to the two peaks of the anomalous domains recorded on August 10th and October 1st, Fig. 5).

The level of the peak belonging to the anomalous pre-seismic domain, extended on the interval July 16 – August 18, is very high in relation with the magnitude of the earthquakes at which it is reported. One explanation could be that in this interval two crustal earthquakes have occurred in the surrounding areas (*i.e.*, M4.1/4km on August 5 in northern Bulgaria and M3.7/4km in Black Sea).

When the anomalous and normal domains are much closer, due to a multitude of earthquakes occurred at short time intervals, then an anomalous pre-seismic superposition effect have been observed. Therefore, for this paper the threshold of the pre-seismic anomaly related to an earthquake of M ≥ 3.6 was established at ρn* = 1.5 (red dashed line in Fig. 5).

Acknowledgements. The authors are rendering homage to Prof. Dr. Dorel Zugrăvescu, the first who put the foundation stone of the Institute of Geodynamics of the Romanian Academy, at his 80th birthday anniversary.

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QUANTIFICATION OF EARTHQUAKE ACTION ON STRUCTURES

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1. INTRODUCTION

This introductory part represents at the same time a brief reference to the volume *Quantification of earthquake action on structures* and an homage to Professor Dorel Zugrăvescu, who, among so numerous and valuable activities and achievements, provided conditions for this work to develop. It also introduces the subsequent paper, *A major reason to fundamentally revise the traditional concept of macroseismic intensity: to avoid possible zonation mistakes. An illustrative case*, the last one of the volume referred to, which presents quite dramatic arguments in favour of a radical updating of the concept of seismic intensity.

The concept of *intensity of the seismic ground motion*, which has already existed for a rather long time, in order to evaluate the severity of seismic ground motion during one earthquake, at a certain geographic point (or upon a limited geographic area, for which this severity is believed to be about the same), is widely popular. However, the ways in which this concept is understood may differ considerably. One could even observe a scale of the levels of understanding of this concept. We have at one end laypersons and, unfortunately, quite frequently, some mass media agents, who do not even make a difference between the concepts of ground motion intensity and of earthquake magnitude. At the other end we have the professionals, who would like to adapt this concept in a way to make it as suitable as possible to the requirements of their activities. The volume referred to, *Quantification of earthquake action on structures*, is addressed to people of this latter orientation.

This volume relies on two main sources. Firstly, we have the long term and fruitful activities of the Russian school of seismology, for which the group of the Institute of Physics of the Earth of Moscow played a dominant scientific role, contributing considerably to the gradual improvement of knowledge and achievements related to the traditional concept of seismic intensity. Secondly, we have the activities of a group that first came into existence in INCERC (National Building Research Institute) Bucharest, in response to the impact of the destructive Vrancea earthquake of 1977.03.04, with the task of carrying out an in depth post-earthquake survey.

An immediate incentive to organize cooperative activities on this theme was due to a meeting held in Moscow in 2004 under the auspices of the NATO Programme Security through Science (NATO – Russia Joint Scientific and Technological Cooperation), on the theme "Disaster Forecast and Prevention", in which Horea Sandi participated. He was encouraged by the organizer of the meeting, Dr. Frederick Krimgold, Director, Center for Disaster Risk Management, Virginia Tech., to apply to the NATO Office of Brussels, in his capacity of scientist of a NATO member country, for support required by the development of a project in this field. Soon thereafter, during a meeting held in Bucharest, hosted by Prof. Dorel Zugrăvescu, corresponding member of the Romanian Academy, Director of the Institute of Geodynamics, Academician Alexandr Gliko, Director of the Institute of Physics of the Earth, Moscow, agreed to set up a joint project aimed to contribute to developments in the domain of quantification of seismic intensity. He nominated Prof. Felix Aptikaev, who was leading research activities in this field, as a counterpart on behalf of his institute. During subsequent contacts, it was agreed to invite the Institute of Geology and Seismology of Chişinău, Moldova (Director and counterpart: Dr. Vasile Alcaz), to join the project. The application forwarded to the NATO Office was accepted and NATO provided the Collaborative Linkage Grant No. 981619 for the Project *Quantification of earthquake action on structures*.

The cooperative activities in this framework lasted from 2005 to 2008. They included meetings in Bucharest, Chişinău and Moscow and led to the drafting of some joint papers. The main participants in these activities were the authors of this volume. Finally, the NATO Office agreed to provide support for the publication of the volume.

2. PAPERS INCLUDED IN THE VOLUME

The volume includes the following papers (the papers P.1 to P.8 reproduced from previous publications; the papers P.9 to P.12 newly drafted) on which some comments are due:

P.1. Sandi, H., Floricel, I. (1998), *Some alternative instrumental measures of ground motion severity.* Proc. 11th European Conference on Earthquake Engineering, Paris.

P.2. Aptikaev, F. (2005), *Instrumental seismic intensity scale*. Proc. Symposium on the 40th anniversary of IZIIS, Skopje.

P.3. Aptikaev, F. (editor) (2006), *Project of Russian Seismic Intensity Scale RIS-04*. Proc. First European Conference on Earthquake Engineering and Seismology, Geneva, Switzerland, (Paper No. 1291).

P.4. Sandi, H. (2006), *Bridging a gap between seismologists and engineers: possible restructuring of the intensity scale(s*), Proc. First European Conference on Earthquake Engineering and Seismology, Geneva, Switzerland, (Paper No. 571).

P.5. Sandi, H., Aptikaev, F., Alcaz, V., Borcia, I.S., Drumea, A., Erteleva, O., Roman, A. (2006), *A NATO project on deriving improved (instrumental) criteria for seismic intensity assessment*. Proc. First European Conference on Earthquake Engineering and Seismology, Geneva, Switzerland, (Paper No. 581).

P.6. Sandi, H., Borcia, I.S. (2006), *Damage spectra and intensity spectra for recent Vrancea earthquakes.* Proc. First European Conference on Earthquake Engineering and Seismology, Geneva, Switzerland, (Paper No. 574).

P.7. Aptikaev, F.F., Mokrushina, N.G., Erteleva, O.O. (2008), *The Mercalli Family of Seismic Intensity Scale*. Journal of Volcanology and Seismology, 2008, vol. **2**, no. 3, pp. 210–213, Pleiades Publ., Ltd.

P.8. Aptikaev, F., Borcia, I.S., Erteleva, O., Sandi, H., Alcaz, V. (2008), *Development of instrumental criteria for intensity estimate. Some studies performed in the frame of a NATO project.* Proc. 14th World Conference on Earthquake Engineering, Beijing, China (Paper No. 02-0042).

P.9. Borcia, I.S., Sandi, H., *Techniques and results of processing of macroseismic and instrumental information for sample events, in relation to the calibration of instrumental criteria*.

P.10. Alcaz, V., Borcia, I.S., Sandi, H., *Some data and results concerning ground motion in Moldova during recent strong earthquakes of 1986 and 1990.*

P.11. Borcia, I.S., Sandi, H., Aptikaev, F., Erteleva, O., Alcaz, V., *Some statistical results related to the correlation of macroseismic estimates with instrumental estimates of seismic intensity.*

P.12. Sandi, H., Borcia, I.S. (2011), *A major reason to fundamentally revise the traditional concept of macroseismic intensity: to avoid possible zonation mistakes. An illustrative case.*

3. SOME REFERENCES TO THE ACTIVITIES OF RUSSIAN SEISMOLOGISTS

One of the main starting points of the activities carried out in the project framework was represented by recent seismological research of Russia, in which considerable attention was given to the use of instrumental information. Numerous seismic intensity scales were developed and proposed along time by various authors. The scales discussed at this place pertain to the "Mercalli family", as referred to in P.3 (Aptikaev *et al.*, 2006). Out of them, two scales, which were successively endorsed by the European Seismological Commission, are considered here as a reference to scales of this family, which rely, at least mainly if not exclusively, on visual observation or on oral information, gathered during post-earthquake surveys: the scales MSK-64, updated in 1977 (Medvedev, 1977), and EMS-98 (Grünthal, 1998).

The developments of P.7 (Aptikaev *et al.*, 2008) refer, among other, to the following ranking system (of increasing relevance) of the scales pertaining to this family: nominal scales, class scales, ordinal scales, interval scales, ratio (or absolute) scales.

While stating that the magnitude scale is an absolute scale, it is concluded in that paper that "The seismic scales of the Mercalli family are in the class of interval scales".

Comments of the authors:

– the rich and valuable results of P.2 (Aptikaev, 2005) concerning the distributions of several kinematical parameters of instrumental data recoded during earthquakes create a background for re-ranking (at least gradually) the seismic intensity scale to a ratio scale;

– the papers P.2, P.3 and P.7, together with their lists of references, convincingly illustrate the long term and valuable scientific work of the Russian school of seismology, which has brought numerous contributions of fundamental scientific importance in this field.

4. SOME REFERENCES TO ACTIVITIES IN ROMANIA

Another starting point of the project activities was represented by the scientific impact of the destructive Vrancea earthquake of 1977.03.04. The in depth post-earthquake survey initiated led to the development of statistical damage spectra (Bălan *et al.*, 1982) for various reference areas of the City of Bucharest. The results obtained made it clear that in depth analyses of the features of earthquake ground motion deserve to be carried out in the frame of post-earthquake surveys. Earlier models on how to *quantify seismic intensity on the basis of instrumental records* were provided by publications of earthquake engineering experts like Arias (1970) and Housner (1970). This stimulated analytical and numerical research carried out initially in the frame of INCERC (National Building Research Institute, Bucharest). The outcome of this work was summarized first by the developments of P.1 (Sandi, Floricel, 1998) and by the overview Table 2 of P.8 (Aptikaev *et al.*, 2008). The system developed is flexible, making it possible to quantify the intensity according to needs, in global terms or, in a more detailed manner, in spectral and/or directional terms.

The last paper of this volume, P.12 (Sandi, Borcia, 2010), illustrates through a dramatic case study the errors that may be caused by the use of scales of the Mercalli family.

In case one looks back at the ranking system reproduced from P.7 (Aptikaev *et al.*, 2008), one may state that this system of intensity quantification pertains at least to the last class, namely that of absolute scales. On the other hand, one may state that the system exceeds the classes listed, since it introduces a *new way of multi-dimensional quantification of ground motion severity*, richly illustrated by the intensity spectra presented in P.9 (Borcia, Sandi, 2010).

5. COMMENTS ON THE INSTRUMENTAL INFORMATION AND ON ITS USE

The progress in the field of acquisition of data during earthquake occurrence is well-known. Firstly, accelerographs were gradually improved, reaching at present the stage of digital data acquisition, with all the potential advantages derived. Secondly, the accelerographic networks gradually extended, reaching a stage in which, for some areas, the territory is quite well covered, in which some dense arrays are working, in which an increasing number of structures became well equipped. Given the advantages of instrumental information, of complete characterization of seismic motion at recording sites, of accuracy and certainty, making use of instrumental becomes compulsory from the scientific point of view. And yet, the most recently endorsed intensity scale, EMS-98 (Grünthal, 1998), *makes no use of instrumental information*. In the comments added to that scale, it is recognized that a good record fully characterizes the seismic motion at the recording site, but, since no working criterion is widely accepted in literature in order to quantify seismic intensity, the solution adopted was to skip the problem. Consequently, the assessment of intensity may be related no longer to a desired site, but to an area for which a kind of homogeneity of ground motion is implicitly assumed, and for which the intensity estimate has a kind of statistical sense. Therefore, the available techniques of gathering information that are accessible, influenced the definition of the object of investigation itself.

The group of the Institute of Physics of the Earth of Moscow, involved in the project, undertook a sustained work in order to check (and, following the results obtained) to recalibrate the parameters of ground motion used for intensity assessment, as shown in P.2 (Aptikaev, 2005). The parameters considered were the (absolute) peak values of ground acceleration, ground velocity, ground displacement and (kinematic) power. It turned out that the ratios of geometric progressions are no longer the same as used in the frame of the MSK scale, where the unique value 2.0 had been assumed.

The group of Bucharest proceeded in a different (but compatible) way. A system of new kinematic criteria was postulated and calibrated. This means that the ground motion intensity has been radically redefined, P.1 (Sandi & Floricel, 1998), and this was done in a way that had to cover (and actually did) the technical needs of engineers involved in the earthquake protection of structures. More precisely, perhaps the most important achievement consisted of the fact that the system of definitions adopted made it possible to deal not only with *global intensities*, but also with newly introduced concepts, like that of *intensity spectra*.

6. CLOSURE

Given the stake raised by the development of the concept of seismic intensity and by the corresponding adaptation of post-earthquake survey techniques, as well as by the other functions of the concept of seismic intensity, a Joint Working Group (JWG), or Joint Task Group (JTG), in which the sub-groups of seismologists and engineers should be quite equal in size and in influence, should be established by the European Seismological Commission and by the European Association of Earthquake Engineering, in order to support progress in this field.

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