SEISMIC HAZARD OF ROMANIA: DETERMINISTIC APPROACH

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Abstract

The seismic hazard of Romania is estimated in terms of peak ground motion values (displacement, velocity, design ground acceleration DGA) computing complete synthetic seismograms, which are considered to be representative of the different seismogenic and structural zones of the country. Special attention is paid to the Vrancea intermediate-depth earthquakes that control the seismic hazard level almost over the whole territory. The analysis of different possible scenarios shows the non negligible effect of the source parameters. The numerical results are in fairly good agreement with the macroseismic and strong motion data available for the major Vrancea events.

1. Introduction

The seismic hazard of Romania is relatively high, mainly due to the intermediate-depth earthquakes located in a confined focal volume at the Eastern Carpathians arc bend, in the Vrancea region. Two-three shocks with $M_w > 7$ occur here each century and are felt over a very large territory, from the Greek islands to Scandinavia, and from Central Europe up to Moscow. The largest and the most damaging subcrustal events reported from the beginning of the 19-th century occurred on October 26, 1802 ($M_w = 7.9$), November 26, 1829 ($M_w = 7.3$), January 11, 1838 ($M_w = 7.5$), November 10, 1940 ($M_w = 7.7$), and
March 4, 1977 ($M_w = 7.4$). On the other end, the crustal seismicity is moderate ($M_{\text{max}}$ observed on the Romanian territory is 6.4) with only a few isolated active areas (Shabla, Făgăraș-Câmpulung, Banat, Crisana-Maramures).

Several studies have been carried out to evaluate the seismic hazard of Romania, all based on probabilistic approaches (e.g., RADU and APOPEI, 1978; MĂNDRESCU, 1984; MĂNDRESCU, 1990; LUNGU et al., 1996). A totally different approach, developed by COSTA et al. (1992, 1993), is applied in the present paper to obtain a first order mapping of the seismic hazard of Romania. The computations are performed using the modal summation method (PANZA, 1985; FLORSCH et al., 1991) at a regional scale, for one-dimensional average structural models and scaled double-couple sources (GUSEV, 1983; RADULIAN et al., 1998b). The maximum ground acceleration, velocity and displacement in a given frequency range or any other parameter relevant to seismic engineering which is extracted from observed time series, can be estimated from simulated theoretical signals. This procedure allows us to obtain a realistic determination of the seismic hazard also in those areas for which scarce (or no) historical or instrumental information is available, and to perform relevant parametric analyses. The peak values of the modelled ground motion, tested against the few available recorded values, are used for the estimation of the seismic hazard level.

2. Input data

Two kinds of input data are required by the computation algorithm: the structural and the source parameters. The Romanian territory is divided into regional polygons where average layered structures are specified (Figure 1). The polygon boundaries, defined by RADULIAN et al. (1998a), roughly follow the contact between different tectonic units, or separate different lithosphere's properties. The structures at the political borders are correlated with data taken from OROZOVA-STANISHKOVA et al. (1996) for Bulgaria, and BUS et al. (1998) for Hungary. The models (depth, density, P- and S- wave phase velocities and quality factor) are given in Figure 2. The average upper crust properties are defined on the basis of data from oil industry boreholes (GAVĂT, 1939; PARASCHIȘV, 1976, 1979). The depth of the Conrad and Moho discontinuities and the depth of the lithosphere-asthenosphere boundary are adopted considering geophysical (SOCOLESCU et al., 1963; SOCOLESCU et al., 1964; CONSTANTINESCU et al., 1972; SOCOLESCU et al., 1975; CORNEA et al., 1981; LAZARESCU et al., 1983; ENESCU et al., 1988; RĂDULESCU, 1988; RĂILEANU et al., 1994), and seismological data (DEMETRESCU and ENESCU, 1960; IOSIF and IOSIF, 1973; ENESCU, 1987; ENESCU, 1992; ENESCU et al., 1992).
For the structure below the lithosphere-asthenosphere boundary, a standard continental model (HARKRIDER, 1970) is adopted, with a low-velocity layer down to a depth of 200 km. The density is 3.35 g/cm$^3$, and the parameters in the low-velocity channel are: P-wave velocity, $a = 8.1$ km/s, S-wave velocity, $b = 4.25$ km/s, and quality factors, $Q_a = 220$ and $Q_b = 100$. Structure number 6 corresponds to the Vrancea region where a highly confined focal volume, in the 60 — 200 km depth range, of subducted lithosphere is present. The low-velocity channel is, therefore, absent here and the parameters are: $\alpha = 8.1$ km/s, $\beta = 4.62$ km/s, $Q_\alpha = 1100$ and $Q_\beta = 690$.

The seismic sources are supposed to be distributed within the seismogenic zones defined by RADULIAN et al. (1998a), on the basis of geological, tectonic and seismicity information (Figure 3). A representative focal mechanism is associated with each seismogenic zone. The scalar seismic moment associated with each source is obtained by discretized and smoothed magnitude distribution, according to the procedure defined by COSTA et al. (1993). An updated version of the Romanian earthquake catalogue is considered by merging the catalogue of MUSSON (1996) for the Circum Pannonian region and the recent catalogue of ONCESCU et al. (1998). The catalogue of fault plane solutions compiled by RADULIAN et al. (1997) for the Romanian earthquakes which occurred between 1929 and 1995 is used to extract the focal mechanism information. The characterisation of the seismogenic zones is discussed in detail by RADULIAN et al. (1998a, this issue).

3. Seismic hazard computation

Starting from the structural models and seismic sources, P-SV- and SH-waves, synthetic seismograms are computed on a dense grid ($0.2^\circ \times 0.2^\circ$), by modal summation method (PANZA, 1985; FLORSCH et al., 1991) for the frequency range from 0.005 to 1.0 Hz. For a given site, all the potentially dangerous sources are taken into account and, as a measure of the seismic hazard level, the largest design ground acceleration, DGA, and the resultant value among the N-S and E-W components of horizontal displacement and velocity are considered.

The computations are made separately for shallow earthquakes ($h < 60$ km), and intermediate-depth earthquakes ($60 \leq h < 200$ km). For the shallow events, this deterministic technique has been successfully applied to several other areas, such as Italy (COSTA et al., 1993), Algeria (AOUDIA et al., 1996) or Bulgaria (OROZOVA-STANISHKOVA et al., 1996). For the Vrancea intermediate-depth events, due to the highly confined focal volume, a single epicentral location is assumed to be representative. To account for possible depth-dependent effects, two plausible focal depth values are considered: $h=90$ km and $h=150$ km.
The synthetic seismograms are scaled to the assumed scalar seismic moment: (a) for the shallow events, all with $h=10$ km for $M_w < 7$, and $h=15$ km for larger events, we use Gusev’s (1983) empirical spectral laws, as reported by AKI (1987); (b) for the intermediate-depth earthquakes, we modified Gusev’s (1983) curves to account for the possible difference in the corner frequency between shallow and deep earthquakes (AKI and RICHARDS, 1980). For Romanian events with $M_w > 6$, the analysis of observed spectra indicates that, for a given magnitude, the corner frequencies of deep events are one order of magnitude higher than those of shallow earthquakes (RADULIAN et al., 1998b). With this same scaling MOLDOVEANU and PANZA (1998) did model, for microzonation purposes, the seismic strong motion along a cross-section, representative of the geological settings of Bucharest, due to the May 30, 1990, Vrancea event ($M_w = 6.9$).

The deterministic modelling can be extended to frequencies greater than 1 Hz by using the existing standard design response spectra (PANZA et al., 1996). The design ground acceleration (DGA) values are obtained by scaling the chosen normalised design response spectrum (normalised elastic acceleration spectra of the ground motion for 5% critical damping) with the response spectrum computed at frequencies below 1 Hz.

For the shallow earthquakes we use Eurocode 8 design response spectrum for class A soil (EC8, 1993).

For the intermediate-depth events we consider the results of LUNGU et al. (1996) who analysed the strong ground motion records of the major Vrancea earthquakes of March 1977 ($h = 94$ km, $M_w = 7.4$), August 30, 1986 ($h = 131$ km, $M_w = 7.1$), May 30, 1990 ($h = 89$ km, $M_w = 6.9$), and May 31, 1990 ($h = 79$ km, $M_w = 6.4$), and proposed two characteristic design response spectra, one, with regional validity, for the Moldova region, and the other, with local validity, for Bucharest city, shown in Figure 4.

4. Seismic hazard mapping

The seismic hazard, expressed in terms of peak ground displacement, velocity, and DGA values, corresponding to the shallow earthquakes is shown in Figure 5. The largest values are obtained in the south-eastern part, at the border with Bulgaria: 10 cm maximum displacement, 27 cm/s maximum velocity and 0.25 g DGA (where g is the gravity acceleration), which imply a macroseismic intensity VIII, according to the MSK-76 scale, given in Table 1 (MEDVEDEV, 1977). These values are due to the events in Shabla zone (Bulgaria). The up-to-date Romanian standard for seismic zoning (SR 11100, 1993), given in Figure 6, completely ignores the seismic activity in the Shabla zone and consequently, in the south-east of Romania, it indicates intensity VII, the intensity value which is due to the Vrancea earthquakes. The seismic hazard is high all along the
southern part of Dobrogea, between the Black Sea shoreline and the bending to
the north of the Danube river (0.16 g close to Calărași city). Relatively high
values are obtained in the Câmpulung–Făgăraș region (0.09 g; 25°E, 45°N),
Banat region (0.11 g; 20.4°E, 46.0°N), and Crișana-Maramureș region (0.08 g;
22.0°E, 47.2°N), corresponding to intensity VII. For all the rest of the territory the
dGA values are below 0.05 g.

For the Vrancea strong subcrustal earthquakes two typical sources are
analysed: (i) a source located in the upper part of the slab, at 90 km of depth
with $M_w = 7.4$, corresponding to the March 4, 1977 event, and (ii) a source
located in the lower part of the slab, at 150 km of depth with $M_w = 7.7$,
corresponding to the November 10, 1940 event. The two focal depths selected
in the computations are typical average depths for the Vrancea earthquakes,
and correspond to the maxima observed in the depth distribution of the
earthquake energy release (TRIFU and RADULIAN, 1991; ISMAIL-ZADEH et
al., 1977). The observed focal mechanisms of the two events are close to each
other, and we consider for both cases an average mechanism with the following
parameters of the fault plane: 225° strike, 60° dip and 80° rake. The choice of a
common fault plane solution is fully justified by the fact that 90% of the studied
events, regardless of their magnitude, are characterised by a reverse faulting
mechanism with the T-axis almost vertical and the P-axis almost horizontal
(ENESCU, 1980; ENESCU and ZUGRĂVESCU, 1990; ONCESCU and TRIFU,
1987).

The seismic hazard map corresponding to source (i) is shown in Figure
7. The highest amplitudes are visible south-eastward of the epicentral area.
DGA values above 0.3 g are distributed over an area that extends to Galati city
to the east (0.39 g DGA, 85 cm/s maximum velocity and 32 cm maximum
displacement at 28.0°E, 45.4°N) and to Târgoviște city to the west (0.32 g, 45
cm/s maximum velocity and 23 cm maximum displacement at 25.6°E, 44.8°N).
The maximum values are obtained in the area of Ploiești city, 50 km north of
Bucharest (0.47 g DGA, 92 cm/s velocity and 33 cm displacement at 26.4°E,
44.8°N). In Bucharest the peak ground motion parameters are: 0.23 g, 27 cm/s
and 18 cm. High values are seen in the south-eastern part of the Transylvanian
basin: 0.34 g DGA, 69 cm/s velocity and 25 cm displacement at 25.4°E, 46.0°N.
Values greater than 0.2 g are spread to the N-NE close to the border with the
Republic of Moldova, to the S-SE to the latitude of 44.4°E, affecting almost all
the eastern sector of the Moesian platform (between 26°E and 28°E longitude),
with the exception of Dobrogea, and to the NW in the Transylvanian depression
reaching the Târgu Mureș city (24.6°E, 46.6°N).

The seismic hazard map computed for source (ii) is shown in Figure 8.
Generally, the distribution of the amplitude values is similar to the previous case.
Two effects of the focal depth are however visible: the area of the near-
epicenter local minimum is more developed, and the area of the largest values is shifted to larger epicentral distances (0.63 g DGA, 124 cm/s maximum velocity, 43 cm maximum displacement at 27.4°E, 44.4°N). The ground motion in Bucharest area is particularly large: 0.52 g DGA, 105 cm/s maximum velocity, 42 cm maximum displacement. DGA values greater than 0.3 g are seen over an extended area in the Moesian and Scythian platforms, oriented NE-SW. Similar values are obtained in the Transylvanian depression, (the maximum value of 0.55 g DGA, 116 cm/s velocity and 40 cm displacement at 24.8°E, 46.8°N) and in the northern part of Moldova (0.58 g DGA, 114 cm/s velocity and 48 cm displacement at 26.2°E, 47.4°N). Significantly lower DGA values, in the range 0.25 g-0.06 g, are visible in an area situated to the NW of Vrancea.

The design response spectrum proposed by LUNGU et al (1996) for Moldova region (Figure 4) is adopted to compute the DGA values for the subcrustal earthquakes. To test the influence of the selected design response spectrum on the computed DGA values, considering source (ii), we use the design response spectrum proposed for Bucharest city, which is specific for a soft soil. As we could expect, the DGA values, obtained in this way (Figure 9), are lower than the values shown in Figure 8.

5. Synthetic model against observations

Strong motion data are available in Romania since the 1977 major shock, when a SMAC-B accelerometer was operating in Bucharest. The maximum peak values (horizontal component) recorded in Bucharest in 1977 are: 15 cm, 65 cm/s and 194 cm/s², and the corresponding computed values are: 18 cm, 27 cm/s and 225 cm/s² respectively. Many accelerometers (SMA-1) were installed after 1977 and some of them triggered during the shocks of August 30, 1986, May 30 and May 31, 1990 (Table 2). For each of these events we have available more than 10 digitized accelerograms, therefore we compute DGA, maximum velocity and displacement in correspondence of the sites of the strong motion stations, and we compare them with the values obtained from the records (Figures 10-12).

For these events the computed DGA values are generally smaller than the observations, while velocities and displacements turn out to be more evenly distributed around the straightline with slope 1. The large scatter in the data is compatible with strong local effects, already reported in the literature. The systematic underestimate of DGA can be reduced considering either smaller depths or larger magnitudes, as shown, for example for the event of May 30, 1990, in Figures 13 and 14.

There is a large amount of macroseismic information related to Vrancea earthquakes. Reliable knowledge of earthquakes dates back to the 14-th
century. The identification of the historical Vrancea intermediate-depth events is easier than that for the shallow earthquakes, since the felt area associated to Vrancea shocks is extremely large. In all cases the maximum intensity is observed within a NE-SW elongated area, located south-eastward of the epicenter. This area often includes several important cities, like Bucharest, Ploiesti, Buzău, Galati, Brăila, Focsani, Bârlad. Such a trend is well reproduced by our computations, especially for the 1977 case. When the focal depth increases, the maximum values are shifted toward SE (Figure 8). In all cases, the computed maximum intensity occurs outside of the epicentral area, in agreement with the observations.

The deterministic approach gives, in the Transylvanian depression and north Moldova, intensity values that are at least one degree higher than the corresponding values proposed by the Romanian seismic zoning standard (SR 11100, 1993). The instrumental data are very scarce in these regions. It is therefore of crucial importance to install new strong motion instruments and to intensify macroseismic investigation of historical events before any conclusion can be reached about the seismic hazard level here. In fact, the inspection of the available macroseismic data reveals the observation of intensity values in the Sibiu area (24°E, 46°N) similar with those recorded in Bucharest (26.1°E, 44.4°N), Galati (28.1°E, 45.5°N) or Iasi (27.6°E, 47.2°N), and in agreement with our computations.

6. Discussion and Conclusions
Using numerically simulated ground motion, a first order deterministic evaluation of seismic hazard of Romania is proposed. Several simplifying assumptions are adopted in the computation: scaled point sources with prescribed average focal mechanism and depth for each seismogenic zone, and one-dimensional modelling of the structure. The design ground acceleration is estimated by extrapolating the long period part of the response spectrum ($T > 1$ s), determined from the synthetic signal, with the design spectrum recommended by standard building codes.

The seismic hazard due to shallow earthquakes is generally moderate, with DGA values less than 0.1 g, with the exception of the south-eastern part at the border with Bulgaria (Shabla zone). Other few limited areas are characterised by DGA values around 0.1 g: Făgăras-Câmpulung zone in the Southern Carpathians, and Banat and Crisana-Maramures zones at the eastern margin of the Pannonian basin.

The seismic hazard level of the Romanian territory is almost completely controlled by the Vrancea intermediate-depth seismicity. We consider two typical cases associated with the largest and most damaging earthquakes recorded this century: November 10, 1940 ($M_w = 7.7$) and March 4, 1977
(\(M_w = 7.4\)). DGA values greater than 0.3 g are obtained over an extended surface. The distribution of the peak values numerically determined correlates well with the values recorded in the area situated eastward and southward of the Carpathians arc. As our results show, it is of extreme importance to install new strong motion instruments in Transylvania to constrain the seismic hazard level in this area, since, according to our modelling, the ground motion values due to the Vrancea earthquakes (especially for the deeper events) could be higher than believed, on the basis of very poor observations.

Therefore in SE Romania and Transylvania the seismic hazard may be higher by one degree of MSK than predicted by the up-to-date Romanian standard for seismic zoning (SR 11100, 1993), which is obviously requiring a significant revision.

Further investigations are necessary to establish if the strong asymmetrical distribution of the motion amplitude on the NW-SE direction, across the Carpathians arc, is real. For this purpose two lines of research will have to be pursued: (a) systematic analysis of macroseismic data, including historical documents; (b) introduction of sources with finite dimensions, to account for possible effects on the radiation pattern.

The comparison with the instrumentally recorded accelerograms shows that satisfactory predictions of the ground motion can be made even allowing a few degrees of freedom for the source and medium. To take into account the uncertainties associated with the input parameters, extensive parametric analysis is required. Possible scenarios can easily be constructed for different source and structural parameters, which can be subsequently considered by civil engineers in the design of new seismo-resistant constructions and in the reinforcement of the existing built environment. As our study confirms, the seismic hazard level is very sensitive to the variation of the maximum magnitude, average depth and focal mechanism of the source. Therefore much attention has to be paid to the possibility of properly defining these parameters by geophysical and seismological constrains.

The technique we have used allows significant improvements that may be required by an even more realistic modelling of the ground motion. It can, in fact, deal with (i) laterally varying structures, using either the hybrid method, which combines, for the description of wave propagation in anelastic heterogeneous media, the modal summation with the finite difference techniques (FAEH et al., 1990; FAEH, 1992), or the fully analytical modal summation method, extended to laterally varying media (VACCARI et al., 1989; ROMANELLI et al., 1996; ROMANELLI et al., 1997); and (ii) extended sources that account for possible complexities of the rupture process, and are represented as a superposition of sub-events properly weighted and shifted in time (VACCARI et al., 1990). The full exploitation of these possibilities of the
method requires the production and collection of a large amount of data and evidences that are presently in progress.

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References


SOCOLESCU, M., POPOVICI, D. and VISARION, M. (1963), Mohorovicic surface in eastern Carpathians and Transylvanian basin, resulted from gravimetric data, St. Cerc. Geofiz., 1, 1-10 (in Romanian).


SR 11100 (1993), Seismic zoning. Macrozoning of the territory of Romania, Institutul Român de Standardizare (IRS, in Romanian).


Figure captions
Fig. 1. Structural polygons. The boundaries are plotted as solid lines. The numbers of the structural units correspond with those given in Fig. 2.

Fig. 2. Average lithospheric structures for the regional polygons. The P- and S-wave velocities - in km/s, density - in g/cm³, and the corresponding quality factors, are shown for the first 100 km of depth.

Fig. 3. Seismogenic zones (solid contours): BD - Barlad Depression, PD - Petrodobrean Depression, SH - Shabla, IM - Intramoesian Fault, D - Dobrogea, EV - East Vrancea, VR - Vrancea, FC - Făgăras-Câmpulung, TD - Transylvanian Depression, DA - Danubian Depression, BA - Banat, CM - Crisana-Maramures. For each seismogenic zone the maximum observed magnitude and typical fault plane solutions are shown.
Fig. 4 Comparative representation of different design response spectra used to construct the DGA maps for Romania: (a) Eurocode 8, soil A (EC 8, 1993) - dotted line; (b) Moldova region (LUNGU et al., 1996) - dashed line; (c) Bucharest city (LUNGU et al., 1996) - solid line. Spectra (b) and (c) are obtained from the Vrancea intermediate-depth earthquakes.

Fig. 5 Seismic hazard map for shallow earthquakes.
(a) resultant displacement in cm for 1 Hz upper frequency;
(b) resultant velocity in cm/s for 1 Hz upper frequency;
(c) DGA, expressed in units of gravity acceleration (g).

Fig. 6 Standard seismic zoning of the Romanian territory (Romanian standard SR 11100/1, 1993). The intensity isolines (MSK scale) are represented by solid contours.

Fig. 7. Seismic hazard map corresponding to source (i):
(a) resultant displacement in cm for 1 Hz upper frequency;
(b) resultant velocity in cm/s for 1 Hz upper frequency;
(c) DGA, expressed in units of gravity acceleration (g).

Fig. 8. Seismic hazard map corresponding to source (ii):
(a) resultant displacement in cm for 1 Hz upper frequency;
(b) resultant velocity in cm/s for 1 Hz upper frequency;
(c) DGA, expressed in units of gravity acceleration (g).

Fig. 9. Seismic hazard map (DGA values) corresponding to source (ii) when the design response spectrum of Bucharest is used.

Fig. 10. Computed DGA, maximum velocity and maximum displacement values versus homologue observed values for the August 30, 1986, Vrancea earthquake (h = 130 km, Mw = 7.1). The velocity and displacement are integrated from the available accelerograms. The slope-1 line is shown for reference.

Fig. 11. Computed DGA, maximum velocity and maximum displacement values versus homologue observed values for the May 30, 1990, Vrancea earthquake (h = 89 km, Mw = 6.9). The velocity and displacement are integrated from the available accelerograms. The slope-1 line is shown for reference.
Fig. 12. Computed DGA, maximum velocity and maximum displacement values versus homologue observed values for the May 31, 1990 Vrancea earthquake (h = 79 km, Mw = 6.4). The velocity and displacement are integrated from the available accelerograms. The slope-1 line is shown for reference.

Fig. 13. Computed DGA, maximum velocity and maximum displacement versus homologue observed values for the May 30, 1990 Vrancea earthquake, Mw = 6.9, h = 90 km (●), h= 60 km (□). The velocity and displacement are integrated from the available accelerograms. The slope-1 line is shown for reference. The depth of 60 km, consistent with the upper bound of the CMT hypocentral determination, improves the modelling of the observed ground motion field, and it is consistent with the waveform modeling made by MOLDOVEANU and PANZA (1998).

Fig. 14. Computed DGA, maximum velocity and maximum displacement versus homologue observed values for the May 30, 1990 Vrancea earthquake, h=90 km, Mw=6.9 (●), Mw=7.4(□). The observed velocity and displacement are integrated from the available accelerograms. The slope-1 line is shown for reference.

Table 1.
The Intensity scale MSK-76 and associated average peak values of ground motion (Medvedev, 1977).

<table>
<thead>
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<th>Intensity (degree)</th>
<th>Acceleration (cm/s²)</th>
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<th>Displacement (cm)</th>
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### Table 2
Source parameters of the Vrancea major earthquakes, in this century.

<table>
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<th>Date</th>
<th>Time</th>
<th>Lat.(^1) (°N)</th>
<th>Lon.(^1) (°E)</th>
<th>Depth(^1) (km)</th>
<th>Depth(^2) (km)</th>
<th>M(_w)(^2)</th>
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<th>Dip</th>
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<td>19:21</td>
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<td>26.8</td>
<td>94</td>
<td>90</td>
<td>7.4</td>
<td>225</td>
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<td>1986 08 30</td>
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<td>7.1</td>
<td>227</td>
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Note: 1 Oncescu and Bonjer (1997); 2 values used in the computations of the synthetic seismograms.
Fig. 2
Structure 7 - West Moesian platform

Structure 8 - Southern Carpathian

Structure 9 - Eastern Pannonian margin

Fig. 2
Structure 10 - Apuseni Mountains

Structure 11 - Crisana

Structure 12 - Transylvanian depression

Fig. 2
Fig. 2
Fig. 5a
Fig. 5b

Velocity (cm/s)

- ▲: 15.0 - 29.6
- ◯: 8.0 - 15.0
- □: 4.0 - 8.0
- ○: 2.0 - 4.0
- ■: 1.0 - 2.0
- ▲: 0.5 - 1.0
- ◯: 0.0 - 0.5
Fig. 5c
Fig. 7b

Velocity (cm/s)
- 120.0 - 123.7
- 60.0 - 120.0
- 30.0 - 60.0
- 15.0 - 30.0
- 8.0 - 15.0
- 4.0 - 8.0
- 2.0 - 4.0
- 1.0 - 2.0
Displacement (cm)

- 30.0 - 59.6
- 15.0 - 30.0
- 7.0 - 15.0
- 3.5 - 7.0

Fig. 8a
Fig. 8c
Fig. 10
90.05.31

Fig. 12
Fig. 13