



An automatic procedure for earthquake analysis using real-time data

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Abstract

The seismicity of Romania is mostly represented by earthquakes produced by the Vrancea seismic source with intermediate depth events (3 shocks/century with magnitude M_W greater than 7.0). The seismic activity in Romania also includes crustal earthquakes. The crustal seismicity is more scattered and moderate compared to the intermediate-depth one. A stable and automatic method has been implemented in the real-time data acquisition and processing system ANTELOPE to estimate the seismic moment, the moment magnitude and the corner frequency of events recorded by the velocity sensors, using spectral analysis applied to S waves. The main goals are the independent estimation of the seismic moment and the common characterization for all events recorded by the National Seismic Network. The main target of this paper is represented by the fast estimation of moment magnitude M_W and ground motion parameters that are derived using Gallo et al. (Bull Earthquake Eng 12:185–202, 2014) methodology and their validation with other magnitude determination algorithms existing at the National Institute for Earth Physics (NIEP). To test this new methodology, we have analyzed 331 seismic events, most of them being automatically located, and afterwards added a new, manually processed solution for events with $M_L \geq 4.5$, to obtain a larger interval of magnitudes.

Keywords Earthquakes · Moment magnitude · Corner frequency · Ground motion parameters

1 Introduction

The concept of the seismic moment was introduced by Aki (1966), but it took 13 years before the moment magnitude scale was designed. It took too long because the necessary spectra of seismic signals had to be derived by hand at first, which required personal attention to every event. Caltech seismologists Hanks and Kanamori (1979) introduced the moment magnitude scale to address the shortcomings of the Gutenberg and Richter (1942, 1956) scale while maintaining consistency. In this case, for medium-sized earthquakes, the moment magnitude values should be similar to Richter values.

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This scale is based on the physical properties of the earthquake, specifically the seismic moment. Unlike other magnitude scales, the moment magnitude scale does not saturate at the upper limit. Anyway, this has the side effect that the scales diverge for smaller earthquakes (Kanamori 1978, 1983).

Many studies about the scalar seismic moment and magnitude estimations for local events were carried out in the past years. We won't entirely review these studies, but only point out a few important ones such as: Mayeda (1993), Mayeda and Walter (1996), Mayeda et al. (2003) obtained an empirical calibration method to compute seismic source moment-rate spectra derived from local and regional coda envelopes using broadband recordings. Lancieri and Zollo (2008) estimated the local magnitude from peak displacement measurements. Ottemoller and Havskov (2003) used an automatic method to estimate the moment magnitude from the displacement spectra of the local seismic events. Also, Edward et al. (2010) computed moment magnitude by using a spectral fitting procedure. Raykova (2020) described a similar procedure for estimating earthquake source parameters (seismic moment, source radius, stress drop) by applying the Brune model for the 2012 seismic cluster in the Sofia seismogenic zone. Satriano (2022) developed a tool to compute earthquake source parameters (seismic moment, corner frequency, radiated energy, source size, stress drop) from the inversion of P-wave and S-wave displacement spectra.

In this paper is proposed a methodology for moment magnitude estimation, combined with ground motion parameters (PGA-peak ground acceleration; PGV-peak ground velocity; PSA-0.3, 1.0 and 3.0 s -Pseudo Spectral Acceleration; Arias Intensity and Housner coefficient), developed by Gallo et al. (2014), which uses the spectral analysis of the S waves, according to Andrews (1986).

This methodology, developed by the SeisRaM (Seismological Research and Monitoring group) of the Department of Mathematics and Geosciences (DMG) of the University of Trieste, was adopted because it was designed to be fastest possible analysis of seismic source parameters and ground motion parameters in Antelope Environmental Monitoring Software by Kinematics Inc (<http://www.brrt.com/software.html>), using data from the real-time seismic network, Antelope being the NIEP's real-time data acquisition and processing system.

Fast estimation (approx. 5 min) of source parameters (M_w -moment magnitude, M_0 -seismic moment, f_0 -corner frequency) and ground motion parameters after strong earthquakes occur in Romania is essential to rapidly evaluate the potential damages in the areas affected by them and contributes to the mitigation of the seismic risk (Kronrod et al. 2013; Cioflan et al. 2016, 2022; Manea et al. 2021).

Romania has a high seismic activity, both crustal and intermediate depth with several moderate events ($M_w > 4.0$) occurring every year. Seismic activity at intermediate depth (60–180 km) in the Vrancea area is by far the most important due to its energy and effects (Knapp et al. 2005; Ismail-Zadeh et al. 2012). The seismic events occur within a small focal volume concentrated at the contact between three main tectonic units: East-European Plate, Intra-Alpine subplate and Moesian subplate (Knapp et al. 2005; Tugui et al. 2009; Radulian et al. 2000; Craiu et al. 2022), with 2–3 major earthquakes per century, which are felt over a massive and densely populated areas (Craiu et al. 2012, 2015, 2016; Manea et al. 2020).

Thus, precise estimations of the earthquake analysis from real-time data, represent a issue of great interest for the National Authorities for Civil Protection for a rapid assessment of the effects and characteristics of a strong earthquake.

2 Network and data

As part of the upgrade of the Romanian Seismic Network during the last decade, earthquake detection has increased since the number of seismic stations installed has also known an impressive rate, therefore we have obtained much more information about the earthquake source and ground motion parameters.

We processed earthquake data recorded by the National Institute for Earth Physics from Romania (NIEP) from 2004 to 2021. During this period, NIEP had undergone a steady upgrade from 44 strong motion sensors and 24 velocity stations (broadband and short-period) in 2005, up to 123 velocity stations (broadband and short-period) and 163 strong motion stations by the end of 2021 (Marmureanu et al 2021) (Fig. 1). The stations are distributed to cover the entire Romanian territory, with more stations located around the Vrancea seismic zone.

The automatic and manual data processing at the National Seismic Network is performed using Antelope system, which is a commercial-off-the-shelf data acquisition, analysis, and management software designed to provide a comprehensive set of environmental monitoring data and processed information in real-time.

Antelope software acquires and processes data from all existing network stations; at the end of processing, raw data and estimated parameters are archived into a complex database. The automatic data processing, event location and magnitude estimation

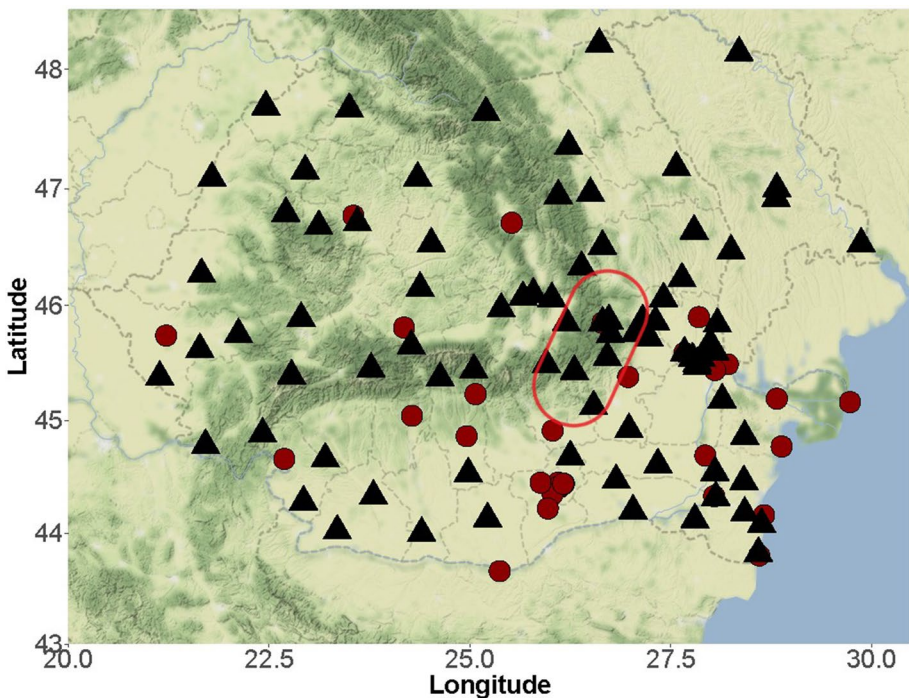


Fig. 1 The Romanian Seismic Network including broadband (black triangles) and short-period (red circles) stations used in this study. The red patch indicates the surface expression of the Vrancea seismic zone.

performed by Antelope system is described by Ionescu et al. (2020). The implemented location algorithm uses the IASP91 velocity model (Kennett and Engdahl 1991).

The algorithm for estimating the seismic source parameters (M_0 , f_0 and M_w) and ground motion parameters has been installed and configured in Antelope for Vrancea intermediate-depth earthquakes and for the crustal seismicity of Romania and is currently running at the National Institute for Earth Physics.

We have analyzed 331 seismic events with $1.7 \leq M_L \leq 6.0$, recorded in Romania during 2004–2021 (Annex 1), using the broadband and short-period sensors from the National Seismic Network department of the National Institute for Earth Physics (NIEP).

3 Methodology

The University of Trieste has developed a fast automatic algorithm for rapid and broadband data analysis. This software has been implemented in the Antelope real-time system, running at the National Institute for Earth Physics (NIEP).

The algorithm for the moment magnitude (M_w) estimation has been developed applying the methodology described in Andrews (1986). This methodology uses the Brune spectrum (Brune et al. 1970), the corner frequency and is applied to the S waves (method described in Gallo et al. 2014). The relative code is written in MATLAB and interfaced with the Antelope real-time system installed at NIEP, hereafter the Antelope system. The code reads the data (waveform, event location, instrumental calibrations, etc.) directly from the real-time database and adds two new tables (M_w -station magnitude, network M_w - the average magnitude for the event) to facilitate the interface with this new procedure and its results.

This algorithm requires the azimuth, epicentral distance, signal type (acceleration or velocity) and sampling rate. The average, trend, spike and instrumental response are removed, and then the epicentral distance is fixed at 100 km (Yao et al. 2019). A key pre-process tool implemented in this procedure is the automatic filter, which guarantees to process the seismic data only in the frequency range where the SNR (signal-to-noise ratio) is large enough.

The high-pass and low-pass cut-off frequencies are automatically fixed (Gallo et al. 2014) in a pre-selected frequency range (normally 0.1–50 Hz) and allows for a selection of the frequency domain with an SNR larger than 3. All the parameters are extracted after a Butterworth band pass filter is applied to obtain accelerations, velocities and displacements by doing the derivative or the integral of the signal. After this step, the procedure follows two different directions, seismic moment computation and ground-motion parameters determination.

To obtain the signal spectra, the Fast Fourier Transform is computed, and then the waveforms are corrected for geometrical spreading and intrinsic attenuation to retrieve the source spectra. The source spectra for both velocity and displacement are computed to obtain the seismic moment. M_w is estimated from the seismic moment using the Hanks and Kanamori (1979) relationship.

The ground motion parameters of the recorded data are extracted in real-time; this required the implementation of an automated earthquake processing system based on event identification and signal processing. The arrivals of P waves are detected and a trigger or pick is declared when the ratio of the short-term average to the long-term average (STA/LTA ratio) of the signal's function exceeds a threshold value.

A global velocity model of the area (IASP91) is used in the locations of events. Data processing is done in three different steps: the event location, the estimation of local moment magnitude and the computation of ground motion parameters. The most important requirement for obtaining optimal results is to use at least 10 active stations in the location procedure combined with their spatial distribution, the azimuthal gaps and the noisiness of the seismic network.

For the crustal seismicity in Romania, we used attenuation factor ($Q(f) = 80 \cdot f^{1.1}$), density ($\rho = 2.7 \text{ g/cm}^3$), S wave velocity ($v_s = 3.4 \text{ km/s}$) and displacement radiation pattern factor ($k = 0.63$) according to Console and Rovelli (1981). For Vrancea intermediate-depth earthquakes, we adopted a $Q(f) = 1000 \cdot f^{1.1}$, according to Oth et al. 2007, $\rho = 3.2 \text{ g/cm}^3$, $v_s = 4.5 \text{ km/s}$ and $k = 0.63$, which is an acceptable approximation following the seismic tomography results of Martin et al. (2006).

Following this procedure, also summarized in Fig. 2, all results are included in a report that is generated in approx. 5 min after the occurrence of a seismic event.

After a strong earthquake, rapid, precise and clear information from the seismic network to the authorities, that have the responsibility to take decisions on emergency management, is mandatory. This implies to record and transmit high-quality seismic data in a very short time and to maintain an efficient and complete procedure of earthquake analysis at the data center.

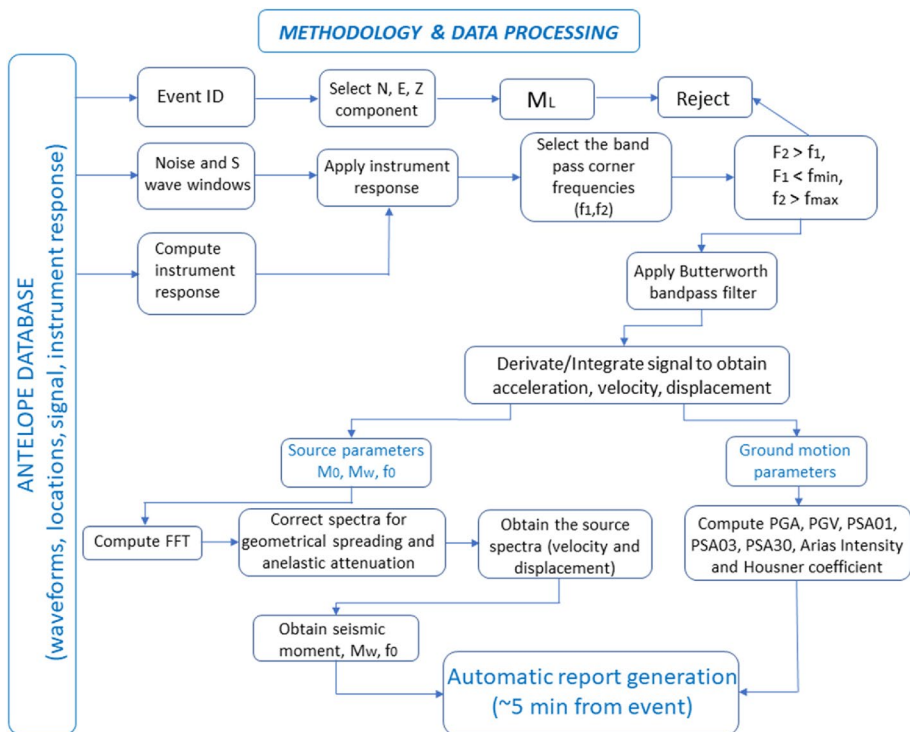


Fig. 2 Flowchart of the automatic data analysis running at National Institute for Earth Physics. M_L - represents local magnitude, mandatory for this procedure to run; f_1 , f_2 - low-pass and high-pass cut-off frequencies; f_{\min} requires $SNR > 3$, f_{\max} requires $SNR > 5$, $f_{\max} < 10 \text{ Hz}$; (F_1 , F_2) represents 0.1–50 Hz frequency domain

4 Results and discussion

4.1 Automatic earthquake source parameters estimation

The procedure, already optimized (adapted for Romania's seismic activity and local conditions) and installed in Antelope real-time data processing, produces fast estimations of moment magnitudes and ground motion parameters.

To validate our results, we computed the M_w magnitude ($1.7 \geq M_w \geq 5.9$) for the 331 seismic events, occurred during 2004–2021, with depth range between 5 and 150 km (Fig. 3).

By comparing the new M_w values with the local M_L magnitudes calculated by the Antelope system in real-time, the general tendency is that the M_L magnitudes are slightly overestimated (Fig. 4). The magnitude error is computed as in Gallo et al. (2014) for the number of seismic stations that are used in an event location within 100 km predefined epicentral distance. Larger magnitude errors tend to appear for the crustal earthquakes, where the limitation in epicentral distance plays a key role in magnitude determination (and due to the M_L relation that underestimates the magnitude values in the epicentral area).

Because the Vrancea area presents intense seismic activity and is of interest to our country, a considerable number of seismic stations have been installed here. Taking into account the good azimuthal coverage in this area (one of the important criteria for obtaining optimal results), in Fig. 4 we chose to compare the M_w magnitude, obtained following the procedure described in this article, with the M_L magnitude, only for intermediate depth seismic events from this area. We selected 74 seismic events with

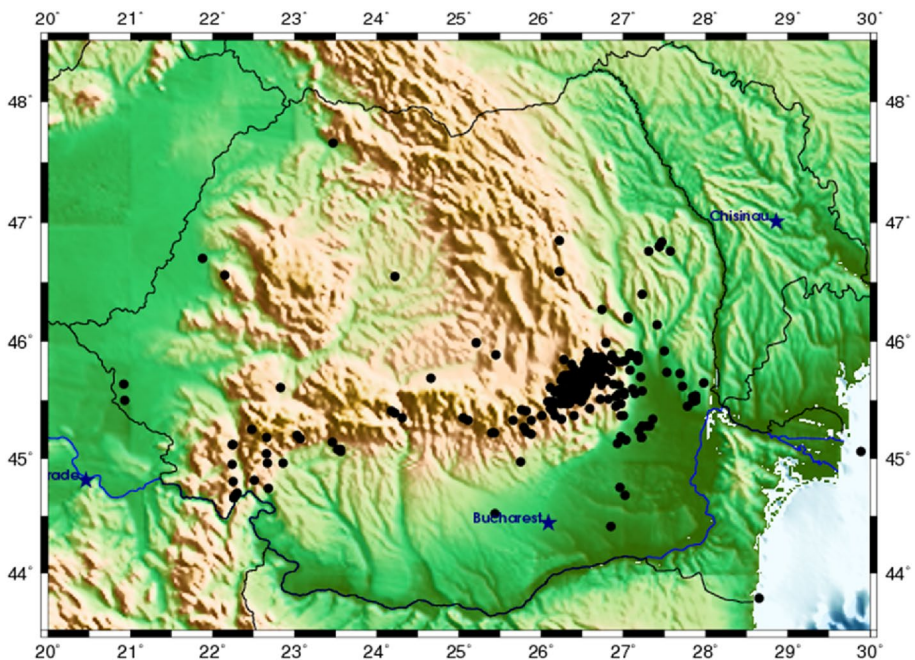
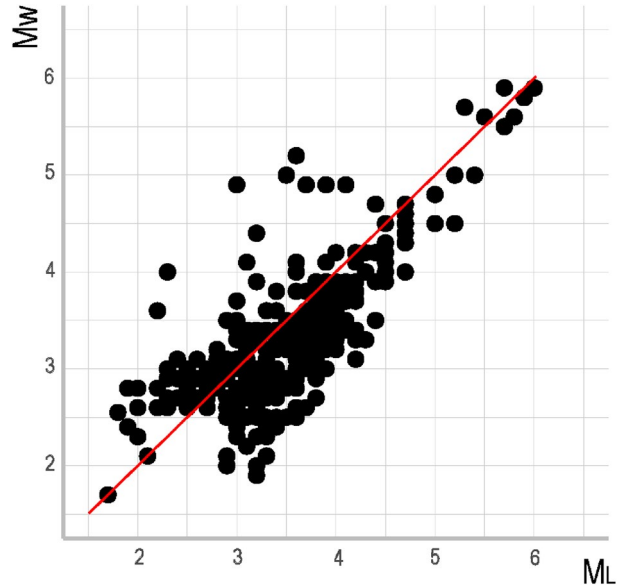


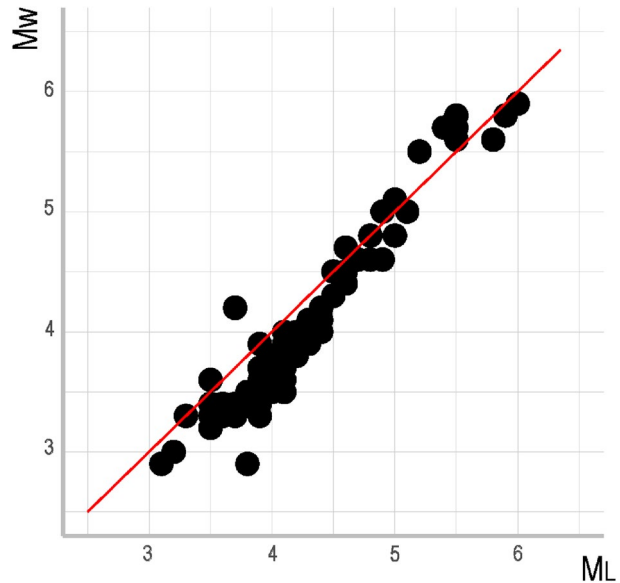
Fig. 3 The location of earthquake epicenters used in this study

Fig. 4 Comparison between the local magnitude M_L as estimated by Antelope (RSN) and the moment magnitude estimated by the procedure described in this study (M_w) for all 331 processed events in the 2004–2021 period. The red line represents equivalence



magnitude $M_L \geq 3.0$, in the 2004–2021 period. As far as we can notice, the magnitude errors for Vrancea intermediate-depth earthquakes are much smaller than in the case of shallow-depth ones (Figs. 4 and 5). This is because the local magnitude relation for intermediate depth events takes into account the hypocentral distance (Craiu et al. 2012) and, instead, for crustal seismicity, we used the Richter relation (1935), which tends to underestimate the magnitude in the epicentral area.

Fig. 5 Comparison between the local magnitude M_L as estimated by Antelope and the moment magnitude estimated by the procedure described in this study (M_w) for Vrancea intermediate-depth events, with $M_L \geq 3.0$, in the 2004–2021 period. The red line represents equivalence

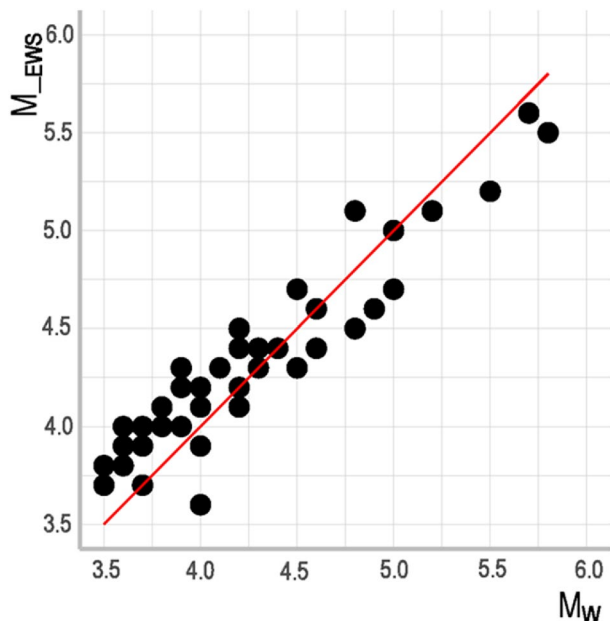


These events are automatically located and are not manually revised. This fact, combined with the network development (a larger number of seismic stations available for the latest events compared with the old ones) causes a scattering of the results (site effects, magnitude errors at different stations).

Presently, Romania operates one of the existing Earthquake Early Warning Systems (EWS) (active since 2013) (Clinton et al. 2016; Marmureanu et al. 2021), which uses 35 seismic stations for locating and estimating earthquake magnitude (M_{EWS}) for Romanian seismic events. In addition, we have decided to validate our results (only for Vrancea intermediate-depth events) by comparing the moment magnitude values with the EWS alerts (magnitude estimations). This validation was performed on a smaller set of seismic events (approximately 50), due to the fact that EWS alerts are issued only for a small number of events with higher magnitudes ($M_w > 3.5$) (Fig. 6). As we can observe, there are some small estimation errors that are less than 0.2 magnitude units. This behavior is generated mainly from the EWS methodology that uses only P waves to detect strong earthquakes using strong motion channels (Marmureanu et al. 2015). At low magnitudes (smaller than $M_w = 4.5$) and considerable earthquake depths (larger than 100 km), the initial P phase picks have greater uncertainties than for larger magnitudes, this is causing large errors in location depth and epicentral distance estimation compared to the other methodology.

Also, to validate the results, we have compared all 3 magnitude estimations, currently used within NIEP (M_w , M_{EWS} and M_L) (Fig. 7), and it can be observed that at lower magnitudes, M_w gives smaller values than M_L and M_{EWS} . This is because in our methodology, the epicentral distance is limited to 100 km, and only uses the stations around the epicenter, while in the estimation of the magnitude M_L , all the seismic stations of the National Seismic Network are used, and the errors are quite large with the increase of epicentral distance. Another explanation of the different estimates for the three magnitudes would be the different methodologies for magnitude computation, previously

Fig. 6 Comparison between the moment magnitude M_{EWS} as estimated by the Earthquake Early Warning System and the moment magnitude estimated by the procedure described in this study (M_w) for 50 events, with $M_L \geq 3.5$, in the 2004–2021 period. The red line represents equivalence



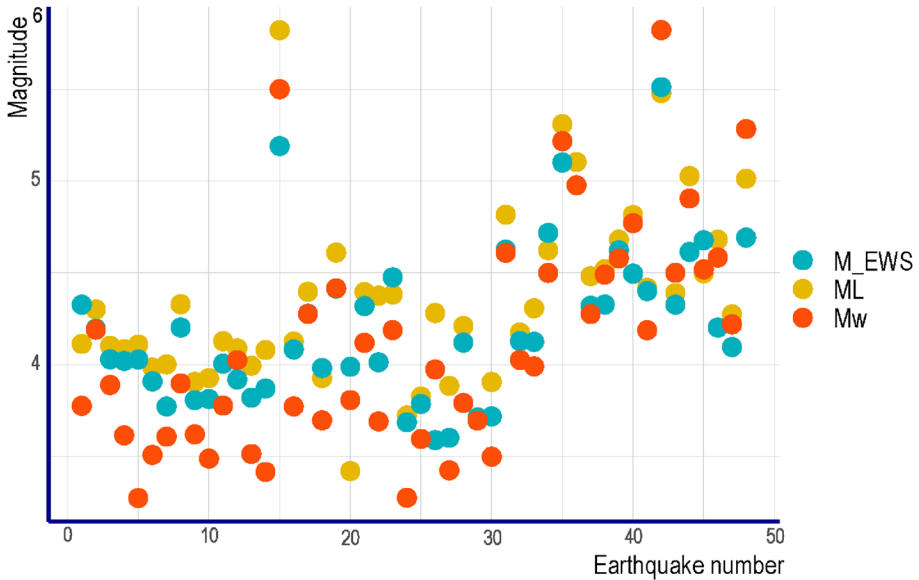


Fig. 7 Validation of the three magnitude scales currently operational at NIEP (moment magnitude as estimated by Earthquake Early Warning System- M_{EWS} , local magnitude as estimated by Antelope- M_L and the moment magnitude estimated by the procedure described in this study- M_w)

mentioned in the paper. However, at larger magnitudes the differences between the magnitudes are relatively small (0.1) and a certain trend does not prevail.

In Fig. 7 there are 2 seismic events that stands out as peaks (the first is a crustal event recorded in 22.11.2014 with $M_w=5.5$ and the second one an intermediate depth occurred in 27.12. 2016 with $M_w=5.7$). For the first event, the local magnitude $M_L=5.9$ is overestimated, our procedure estimated a $M_w=5.5$, in full agreement with other magnitude estimations (see Table 1) and the Earthquake Early Warning System provided a 5.2 magnitude value (underestimated). For the second seismic event, that occurred on 27. 12. 2016, all the magnitude estimations (M_w , M_L and M_{EWS}) are very close and also, in agreement with the magnitudes provided by the international centers (Table 1).

We have also validated our methodology with the magnitudes M_w obtained from the international agencies for earthquakes monitoring, like EMSC (European Mediterranean Seismological Center) and ISC (International Seismological Center). We selected the seismic events available with a magnitude $M_w \geq 4.3$, and compared them with the magnitude calculated from moment-tensor inversion by two international centers, EMSC (https://www.emsc-csem.org/Earthquake/index_tensors.php) and ISC (2022, <http://www.isc.ac.uk/iscbulletin/search/fmechanisms/>), (Table 1 and Fig. 8). As can be observed, there are no major discrepancies in the magnitude values, except for one event that occurred on August 5, 2009 in the Black Sea, and there is a difference of 0.5 degrees in magnitude between our estimate, $M_w=4.5$ (based on the estimates of two stations) and ISC estimation, $M_w=5.0$ (Fig. 8 and Table 1). In conclusion, the results obtained by implementing this procedure are well correlated with the magnitudes reported by the international seismological agencies (Fig. 8).

We should mention that this methodology for estimating the source parameters does not take into account the local effects on the spectral amplitudes. Even so, the data quality is

Table 1 The list of moment magnitudes ($M_w \geq 4.3$) estimated by different international agencies for earthquakes monitoring: Date (day/ month/ year), Time (hh:mm:ss), Lat (latitude north in degrees) and Long (longitude east in degrees), Depth (km), NIEP (M_w determined in this study), EMSC (M_w) and ISC (M_w)

Date	Time	Lat	Lon	Depth	NIEP	EMSC	ISC
27/10/2004	20:34:36	45.77	26.70	100	5.9	6	5.8
14/05/2005	01:53:23	45.64	26.53	150	5.2		5.2
13/12/2005	12:14:38	45.68	26.70	150	4.9	4.8	4.8
25/04/2009	17:18:49	45.67	26.61	100	5.6	5.3	5.2
05/08/2009	07:49:08	43.78	28.65	15	4.5	4.8	5
06/10/2013	01:37:20	45.66	26.57	140	5.6	5.4	5.3
31/10/2014	23:00:04	45.12	22.24	15	4.4	4.1	
22/11/2014	19:14:17	45.87	27.15	40	5.5	5.6	5.7
23/09/2016	23:11:19	45.71	26.61	100	5.8	5.7	5.7
27/12/2016	23:20:55	45.73	26.63	100	5.7	5.6	5.6
08/02/2017	09:52:06	45.77	26.63	140	4.3	4.5	
08/02/2017	15:08:20	45.49	26.27	140	4.8	4.4	
02/08/2017	02:32:12	45.59	26.33	150	5.0		4.8
28/10/2018	00:38:11	45.71	26.30	150	5.9	5.6	5.6
31/01/2020	01:26:47	45.75	26.69	140	5.0	4.7	
24/04/2020	22:04:18	45.92	27.50	30	4.5	4.6	
25/05/2021	21:30:37	45.59	26.50	150	4.5	4.4	

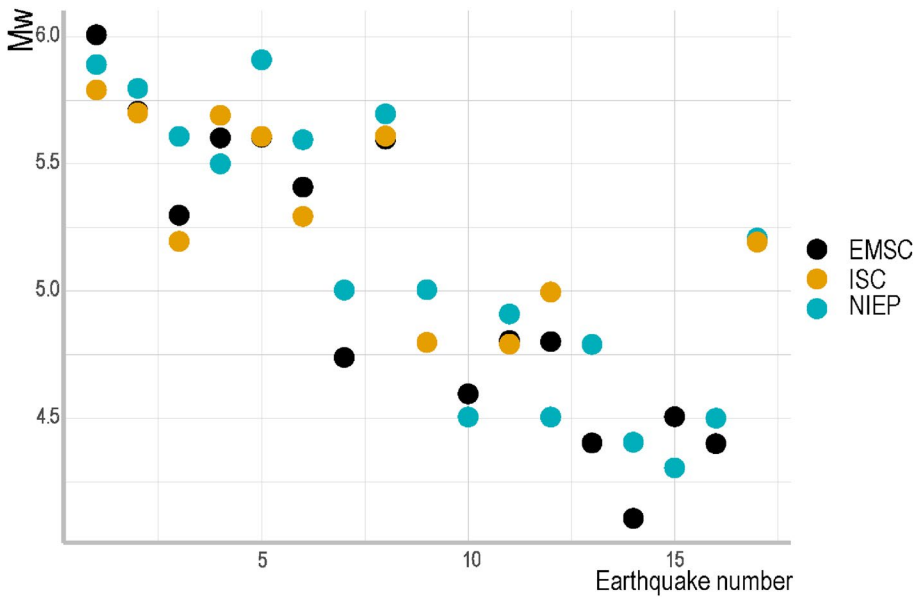


Fig. 8 Comparison between the moment magnitude estimated by the procedure described in this paper (NIEP) and other agencies (EMSC and ISC)

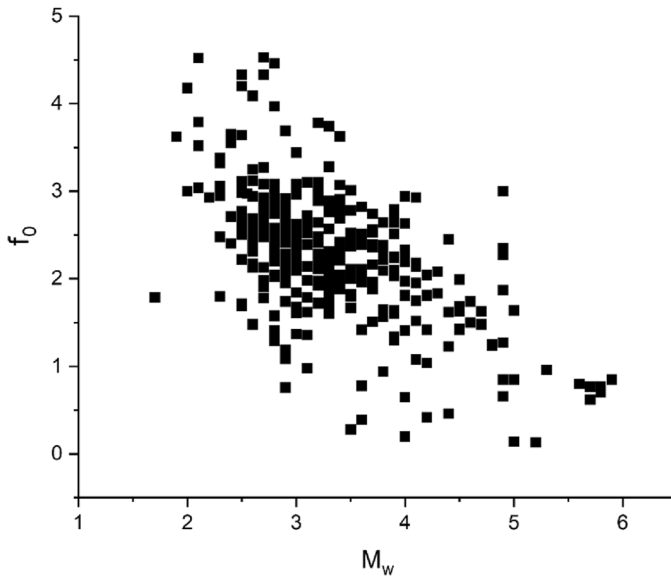


Fig. 9 The corner frequency dependency from the moment magnitude M_w (estimated by the procedure described in this study)

very good, and there is still an influence of site effects, which can be observed in the magnitude and corner frequency estimations (Fig. 9).

4.2 Automatic ground motion parameters estimation

Rapid (5 min) generation of maps of ground-motion parameters is achieved through advances in real-time seismographic data acquisition combined with newly developed relationships between recorded ground-motion parameters and expected earthquake intensity values (Wald et al. 2019).

Usually, in the network configuration, it is important to concentrate the instrumentation in the urban regions with high seismic hazard and to install a minor number of stations in other areas. In such a way, the results should be more accurate in the areas with higher seismic risk, while in the other areas, the use of ground motion relations is fundamental to supply the lack of real data. By filtering, integrating, or differentiating the real-time data from all available recordings, we extracted all the parameters: the peak ground acceleration (PGA), the peak ground velocity (PGV), and the response spectral acceleration amplitudes (PSA) (at 0.3, 1.0, and 3.0 s). In the procedure analyzed in this paper, the ground motion parameters are determined from the same signal window used for the seismic moment computation (Fig. 2). Based on these values of the ground motion parameters, a ShakeMap can be generated, which allows the rapid estimation of the ground motion due to an earthquake, highlighting areas exposed to a specific hazard level. These values can constitute input data for the system for the rapid estimation of seismic damage in Romania. Other applications in which this data can be used are: the estimation of seismic damage and socio-economic losses (with applications also in the insurance and reinsurance sector), seismological and earthquake engineering research, public education and outreach.

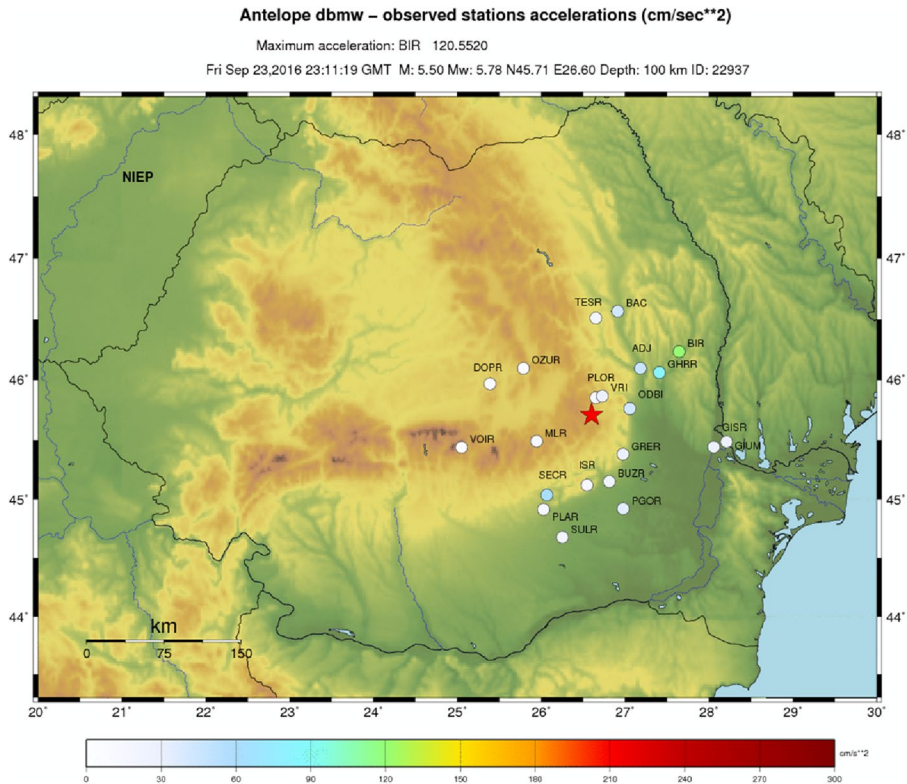


Fig. 10 PGA (Peak Ground Acceleration) map for the 23 September, 2016 $M_w=5.8$ Vrancea seismic event. The red star represents the epicenter and the colored points represent the higher acceleration values according to the scale

To have a rapid idea of the ground motion parameter characteristics, the related values are plotted in maps covering the epicentral area, at the same time, a report of the recorded earthquake is generated and sent by email to the civil protection authorities. For example, in Figs. 10, 11, 12, 13, and 14, the values of the ground motion parameters for the seismic event recorded on September 23, 2016, in the intermediate depth Vrancea zone, with a magnitude $M_w=5.8$, are extracted and displayed on the map.

The assessment of earthquake risk at the urban or regional scale constitutes an important element in the mitigation of economic and social losses due to earthquakes, planning of immediate post-earthquake actions and for developing of earthquake insurance procedures. Therefore, the rapid generation of ground motion parameters after the occurrence of a significant earthquake is an important element for emergency response agencies and critical users.

5 Conclusions

The procedure, developed by the SeisRaM group of the Department of Mathematics and Geosciences (DMG) of the University of Trieste, was installed and customized in 2015 at the data acquisition center of the NIEP. This processes the real-time data recorded by the

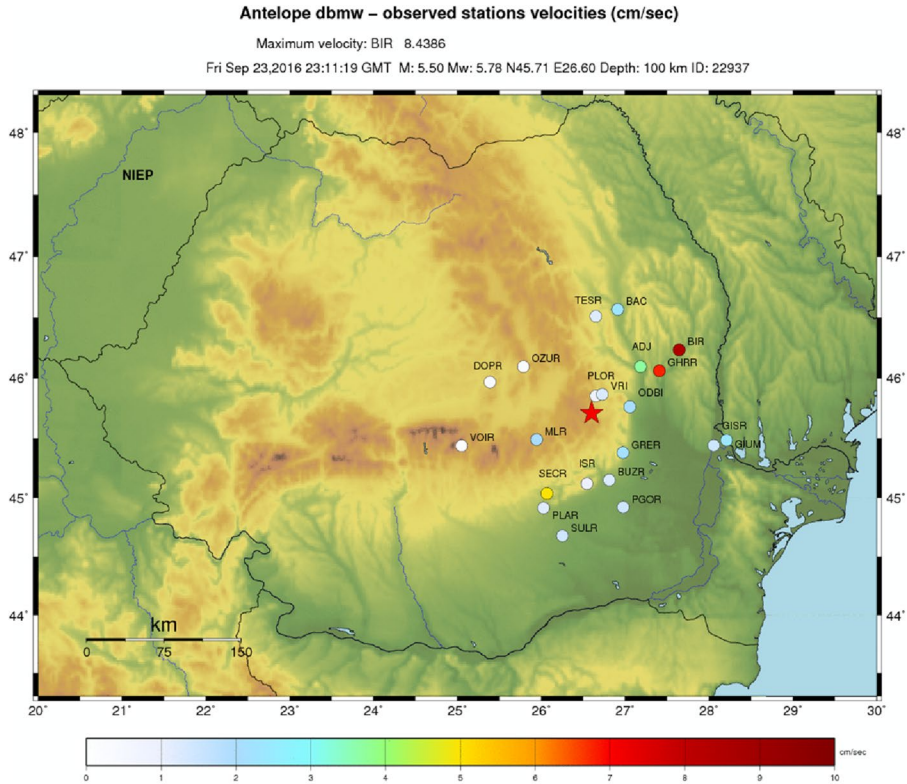


Fig. 11 PGV (Peak Ground Velocity) map for the 23 September, 2016 $M_w = 5.8$ Vrancea seismic event. The red star represents the epicenter and the colored points represent the higher acceleration values according to the scale

seismic stations and can exploit the related information during seismic emergencies for civil protection purposes. The procedure has been tested with success during the recent strong and intermediate-depth events that have occurred in Romania in the last years.

After testing the procedure on the entire data set (331 seismic events, with magnitude $1.7 \leq M_L \leq 6.0$) for both intermediate-depth and shallow earthquakes, we can say that, for earthquakes with $M_w \geq 4.0$, this methodology gives very reliable solutions and agrees with the magnitude estimated by Antelope, EWS system and international agencies for earthquake monitoring (EMSC, ISC). The larger differences appear at lower magnitudes and are due to the epicentral distance limitation of this procedure. At the same time, the magnitude errors for Vrancea intermediate-depth earthquakes are much smaller than in the case of shallow-depth ones, due to the different magnitude estimation relationships (shallow and intermediate-depth earthquakes).

Another function of the algorithm is to provide fast and robust information on the ground motion parameters from high-quality previously pre-processed data. The procedure has been tested during the last strong events that occurred in Romania.

Therefore, to have an immediate idea of the ground motion parameters measure, the relative values are depicted on maps that cover the epicentral zone. To give fast, complete

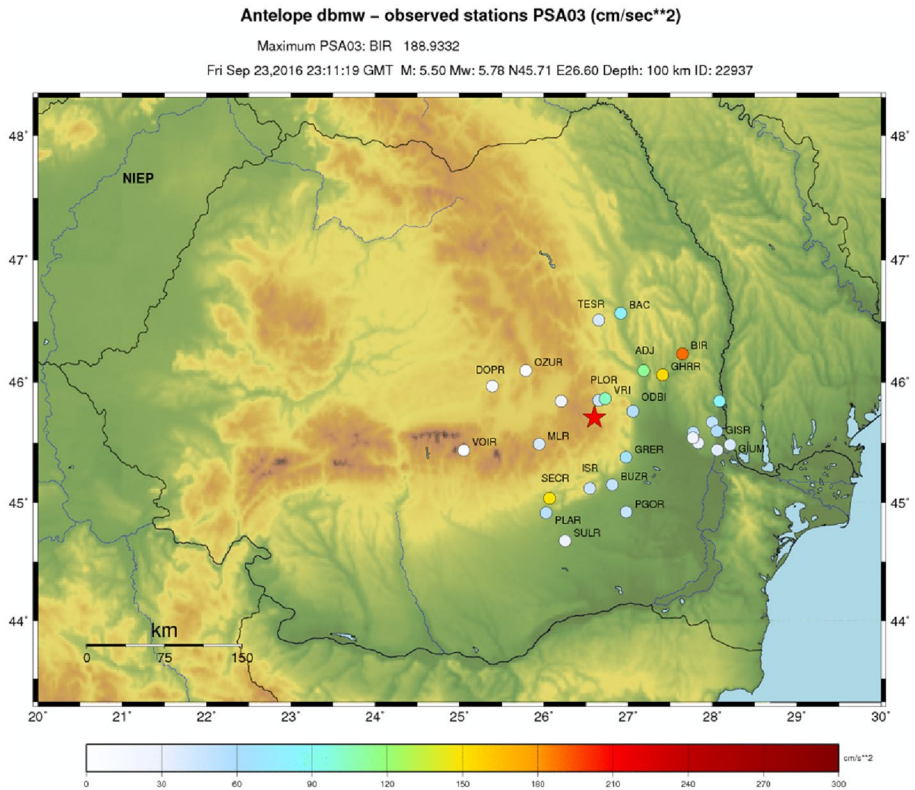


Fig. 12 PSA 03 (Pseudo Spectral Acceleration at 0.3 s) map for the 23 September, 2016 $M_w = 5.8$ Vrancea seismic event. The red star represents the epicenter and the colored points represent the higher acceleration values according to the scale

and clear information on the characteristics of the ground motion and source parameters during a strong earthquake and on its correlation with possible damage scenarios, an automatic procedure was implemented and tested in the NIEP data acquisition and processing system, to provide detailed reports. These reports are sent, by email, a few minutes after an event occurs, to the local users.

The rapid determination of earthquake source parameters is therefore of great importance for correctly determining shaking intensities or evaluating the strong motion distribution generated by a large earthquake. A major vulnerability of Bucharest and other important cities in Romania was observed during the last major events from 1940 November 10 ($M_w = 7.4$) and 1977 March 4 ($M_w = 7.2$) (Cioflan et al. 2016). Therefore, the rapid estimation of the earthquake source parameters for strong earthquakes can play a major role in reducing the negative impact of disastrous events on largely populated areas and, respectively, in mitigating the damage to critical structures and lifelines. Taking into account the information provided by this procedure in a very short period of time (approx. 5 min), it is a very useful tool in seismic risk mitigation.

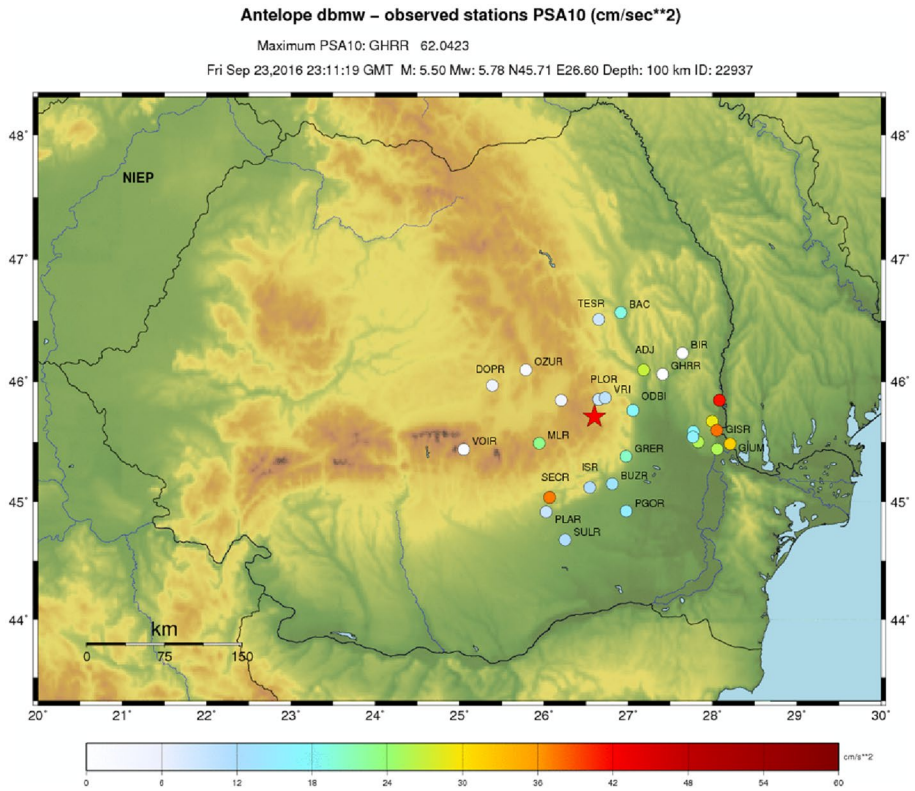


Fig. 13 PSA 1.0 (Pseudo Spectral Acceleration at 1.0 s) map for the 23 September, 2016 $M_w=5.8$ Vrancea seismic event. The red star represents the epicenter and the colored points represent the higher acceleration values according to the scale

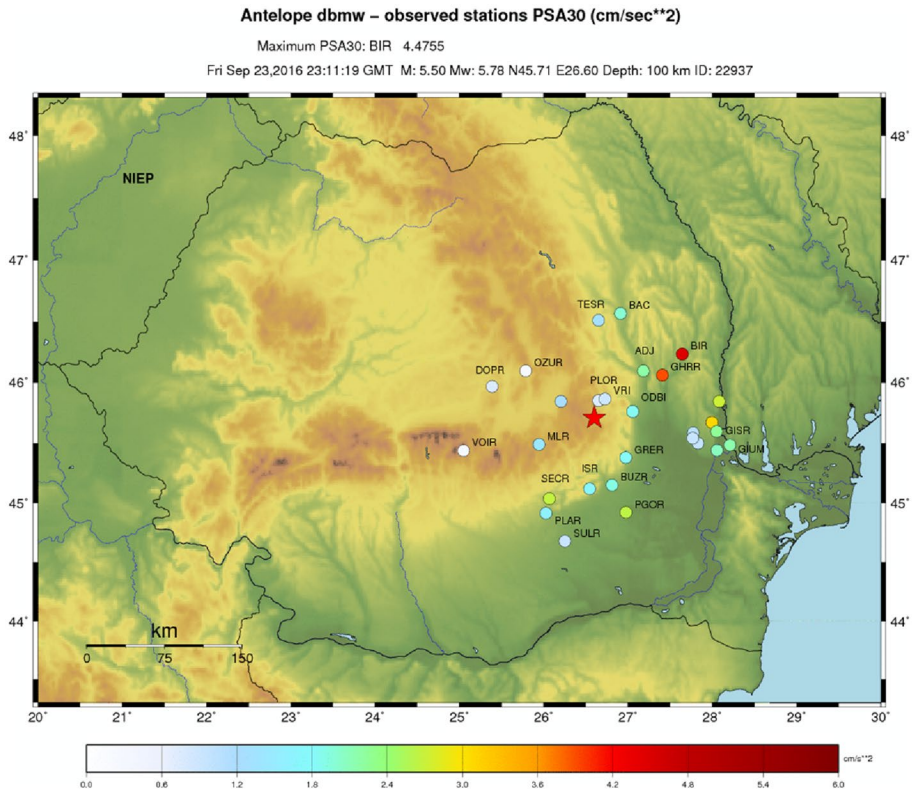


Fig. 14 PSA (Pseudo Spectral Acceleration at 3.0 s) map for the 23 September, 2016 $M_w=5.8$ Vrancea seismic event. The red star represents the epicenter and the colored points represent the higher acceleration values according to the scale

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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