IMPROVING LOCATION PARAMETERS FOR EARTHQUAKES IN ROMANIA USING JOINT HYPOCENTER DETERMINATION METHOD (JHD)

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Abstract. ANTELOPE revised locations, extracted from the INCDFP catalogue, were used as input data for relocation with JHD method. The basic idea behind this technique is to simultaneously determine an optimum 1-D structural model for the target area, to relocate the events and to fix a common set of station corrections. Under appropriate conditions, the station corrections reproduce the unmodelled velocity variations, and thus can significantly improve the location of events. These corrections are related to local effects characterizing the station site. The relocated earthquakes and quarry blasts using JHD better delimit specific clusters in comparison with routine catalog locations.

Key words: catalogue parameters, joint hypocenter location, optimum 1-D model.

1. INTRODUCTION

The major impact of strong earthquakes on modern society makes seismic hazard assessment for seismically prone areas in Romania a priority. For the seismotectonic characterization of a seismic region, a key factor is the seismic activity specific for that region. This is also a crucial input for assessing seismic hazard. Seismogenic zones are areas of clustered seismicity, where seismic activity and stress field orientation are considered relatively uniform in space and time. Initially, Romania was seismically divided into different seismogenic zones taking into account only the geographical distribution of seismic activity [1, 2]. A more recent characterization of the Romanian seismic zones and their classification was performed using tectonic and seismic information correlated with the main tectonic units, active faults and epicenter distribution [3, 4], representing the surface projection of the fault system. This zoning method has been used in probabilistic [5] and deterministic [6] seismic hazard assessment studies. Thus, using seismic catalogue data combined with available tectonic information the main seismic

zones for Romania were defined: Vrancea Zone, East Vrancea Zone, Făgăraş-Campulung, Danubian, Banat, Crişana Maramureş, Bârlad Depression, Predobrogean Depression, Intramoesic Zone, and Transylvanian Depression (Fig.1).

The specific characteristics of seismic activity in the defined areas: maximum expected magnitude, average earthquake occurrence rate, size distribution, time and space clustering of earthquakes, are determined by analyzing the catalogues. Therefore, any seismicity study starts from the earthquake catalogue associated with the study area which provides basic data for understanding the regional seismotectonics and for developing reliable seismic source models. The quality, homogeneity, completeness and accessibility of this information are reflected in the quality of the final seismic risk results.

Currently, the earthquake parameters such as magnitude, time of occurrence, epicentral location and depth, contained in the ROMPLUS catalogue of the National Institute for Earth Physics (NIEP), are obtained using the Antelope software developed by Kinemetrics. For the calculation of these parameters, at present, not all factors that may influence the accuracy of location determination are taken into account, such as possible local effects characteristic for different recording sites. Also, locations are carried out for a 1-D velocity model (IASPEI model, [8]) which was validated at global scale.

The main purpose of the present paper is to determine a new 1-D velocity model as the optimum model for Romania and to evaluate and introduce corrections in the location procedure that take into account the local effects at the seismic station site. In this way, we expect to better constrain the localization parameters, to ensure homogeneous locations on the scale of the whole country and to obtain the smallest possible errors for the events in the NIEP catalogue.

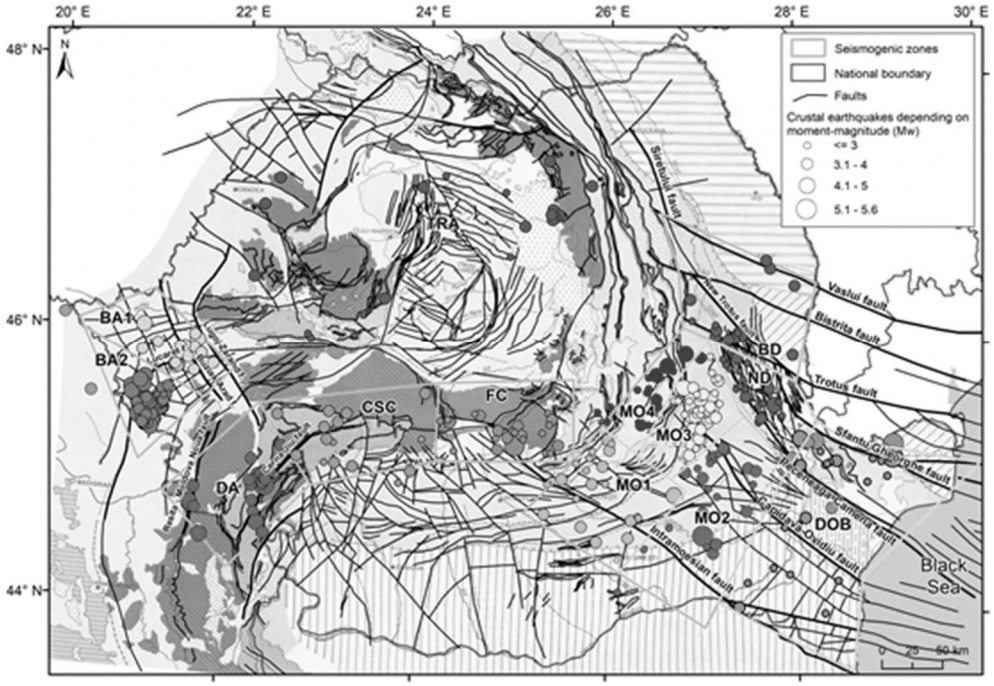

Fig. [1] - Seismogenic zones defined as polygons in the frame of tectonic settings after Săndulescu (1984): DOB—Dobrogea, ND—North Dobrogea orogeny, BD—Bârlad Depression, MO—Moesian Platform, FC—Făgăraş-Câmpulung, CSC—Central South Carpathians, DA—Danubian, BA—Banat, TRA—Transylvania [7].

2. DATA AND METHOD

The dataset selected for our analysis consists of events recorded in Romania during 2020-2021 according to the ROMPLUS catalogue. These locations were obtained using Antelope software [9] without taking into account possible propagation anomalies caused by lateral variation in the real structural model relative to the 1-D model adopted and local effects at the seismic stations sites.

For an efficient assessment of local effects on locations, the Joint Hypocentre Determination (JHD) method is applied. JHD was first introduced by [10] and further developed by Freedman [11, 12]. Thus, for earthquake location, the joint location technique takes into account lateral velocity variations not included in 1D velocity models used for locating seismic events.

The basic idea behind this technique is the simultaneous location for a cluster of earthquakes and the determination of a joint set of station corrections. Under appropriate conditions, the station corrections reproduce the unmodelled velocity variations, thus improving the localization of the events.

Published studies indicate that the JHD method consistently improves relative locations, while absolute locations may or may not be affected by some errors, depending on the nature of the lateral velocity variations. When these are large, as when sedimentary basins or crystalline rocks are interposed on the wave propagation trajectory from source to station, JHD locations may be affected by a systematic displacement from the true locations [12].

To apply this method, we used the VELEST software, a FORTRAN77 routine developed for running 1-D velocity models used in location procedures and as reference models for seismic tomography [13, 14]. The software was first developed in 1976 by Ellsworth and Roecker for seismic tomography studies, and later modified by Nowack, Thurber and Comer who implemented the layered "raytracer" model [15, 16]. The concept of the "minimal 1-D model", [13] and [17] provide several examples of applications, such as 1-D velocity model, for improved earthquake locations, but also as initial reference model for 3-D seismic tomography [18].

The input parameters of the VELEST program are: location coordinates of the events in the ROMPLUS catalogue, initial velocity model (IASPEI) and stations coordinates. For the analyzed time period (2020 - 2021), crustal or sub crustal events with at least 7 P readings and at least one S reading were selected. A total of 1200 events were thus chosen, out of which 323 of intermediate depth (> 60 km) and 877 shallow (< 60 km). The model consists of a 1-D velocity model (layered) and station corrections. The direct problem is solved by tracing rays from source to receiver, calculating the direct, refracted and (optionally) reflected rays passing through the 1-D model. In both ways, the inverse problem is solved by fully inverting the damped least squares matrix model [At A+L] (A= Jacobi matrix, At= transposed Jacobi matrix L=damping matrix). Since the inverse problem is nonlinear, the solution is obtained iteratively, where 1 iteration consists of solving both the complete forward and the inverse problem at once Fig. 2.

VELEST iteratively treats the problem of simultaneously determination of optimum velocity model and relocation for local earthquakes, quarry blasts, and other types of explosions (Fig. 2).

The final results consist essentially in a new velocity model (for which the computed travel times for P- and S-wave phases best approximate the observed times), location improvement and station corrections.

VELEST can be run for single-event localizations, but is very effective for large data sets based on the Joint-Hypocenter-Determination (JHD) simultaneous location technique.

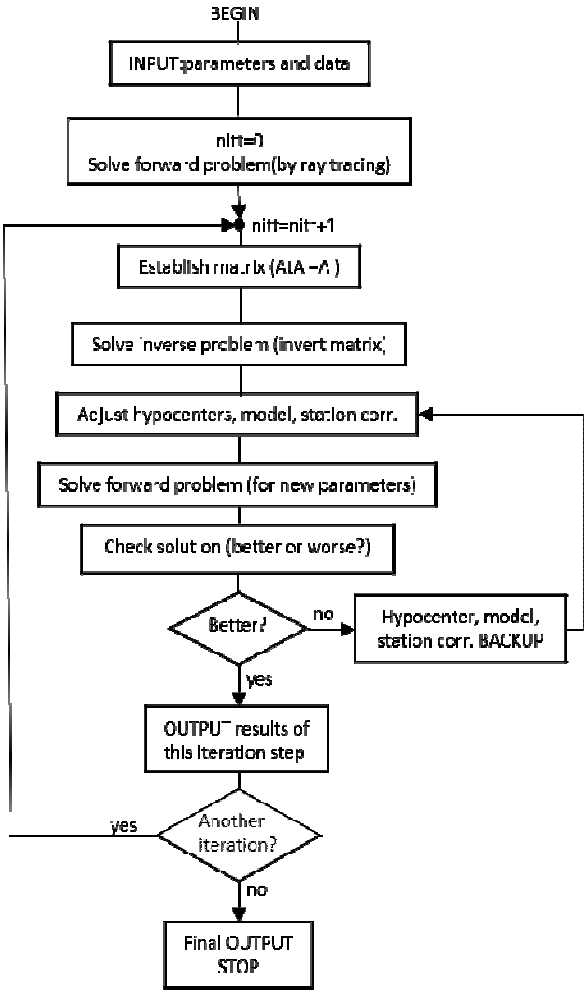

Fig. [2] - Algorithm of the VELEST routine [17].

3. RESULTS

The inversion program converged well in 6 iterations. Following the convergence, events with large errors (RMS > 1.5 s) were eliminated from the initial dataset and the inversion procedure was resumed. For the last inversion result, 1200 events were considered. The final output contains the new (optimum) 1-D model, the events relocalization, RMS errors and GAP and station corrections.

3.1. NEW OPTIMIZED 1-D MODEL

In Fig. 3 we represent the new 1-D velocity model (for P wave) in comparison with the model used for routine localization in ANTELOPE (IASP91 model). While the variations from one model to the other are minor in the crust (depth < 60 km), they become significant at greater depth. Obviously, the relative increase of velocity with depth is related to the presence of a high-velocity body in the mantle, beneath the Vrancea region, as revealed by all the tomography inversions [19].

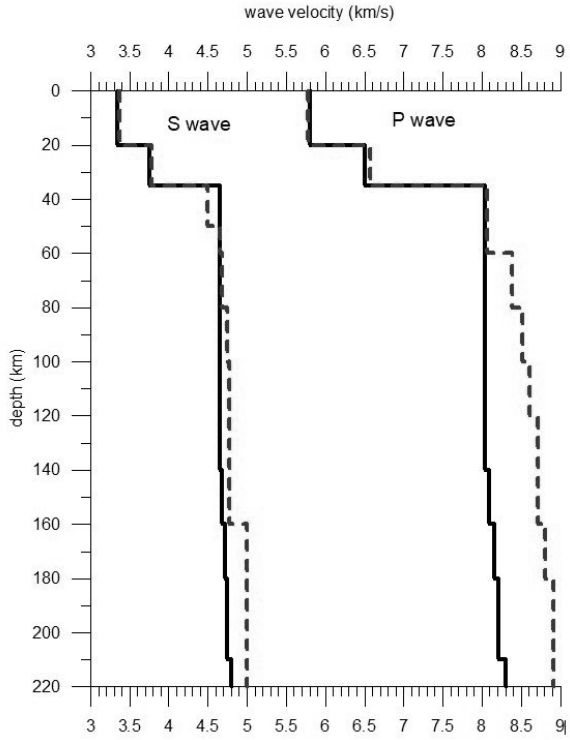

Fig.[3] - Comparison of the iasp91 velocity model (black solid line) and the New optimized 1-D model (red dotted line).

3.2. EVENTS RELOCATION

The relocations of hypocentres relative to the ROMPLUS catalogue locations are represented in the Fig. 4. Looking at the scale of the whole country, the differences between JHD locations and routine locations are relatively small. As shown in Fig. 4, crustal seismicity (depth less than 60 km) is extended over the entire Romanian territory, whereas the intermediate depth seismicity is confined to the Vrancea seismic zone. There are two distinct clusters of earthquakes: shallow

(crustal), at depths down to ~40-50 km, and intermediate depth, at depths ranging from ~60 to 180-200 km. For the intermediate-depth earthquakes, a bi-modal distribution is observed, with a first rather moderate concentration of seismicity ranging from ~60 to 100 km and a second one showing a significant increase in seismicity at depths ranging from ~100 to 180 km. The shallow (crustal) and intermediate-depth seismicity are separated by a "seismic gap" (an area characterized by a relative lack of seismic events) at depths of about 40/50 to 60 km.

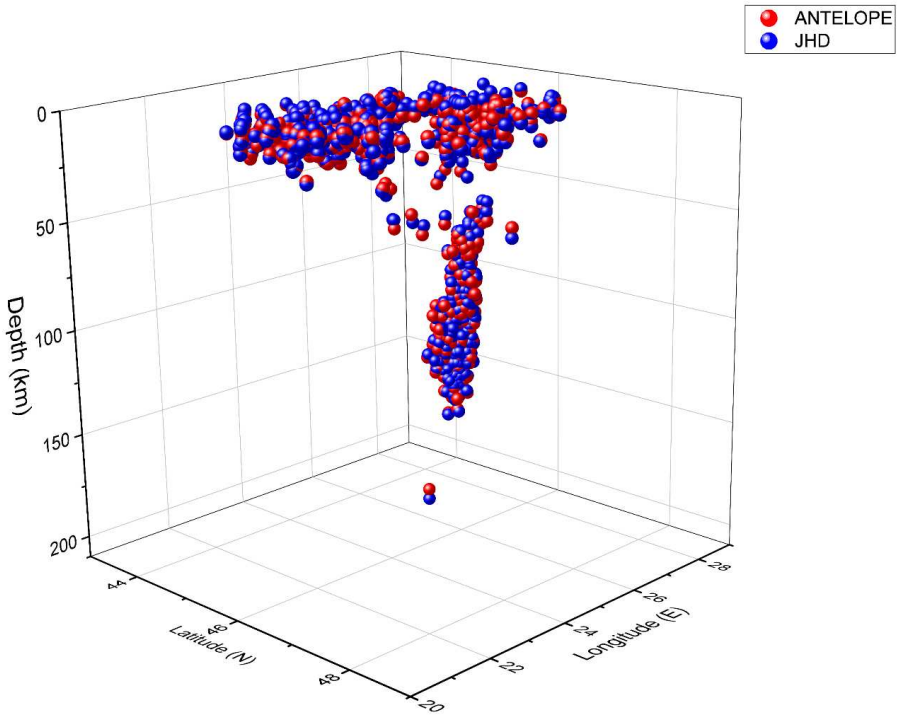

Fig. [4] - Depth distribution of Antelope/JHD compared locations.

The representation of location differences in epicenters is given in Fig. 5. Note a better constraint of epicenters for the Vrancea intermediate-depth earthquakes, while the differences are apparently insignificant for the crustal events (tectonic or quarry blast events), as shown in the three enlarged views, selected as examples. A more detailed investigation of the figure referring to the group of events from Harghita region reveals a systematic shift towards East of the relocated events compared with the initial (ROMPLUS) events. This deviation can be attributed to structural differences from the standard models, which were not taken into account by ANTELOPE. Regarding the grouping of events (assumed quarry blasts) in the

Deva area, we do not notice differences neither in terms of the form of distribution nor in the degree of constraint.

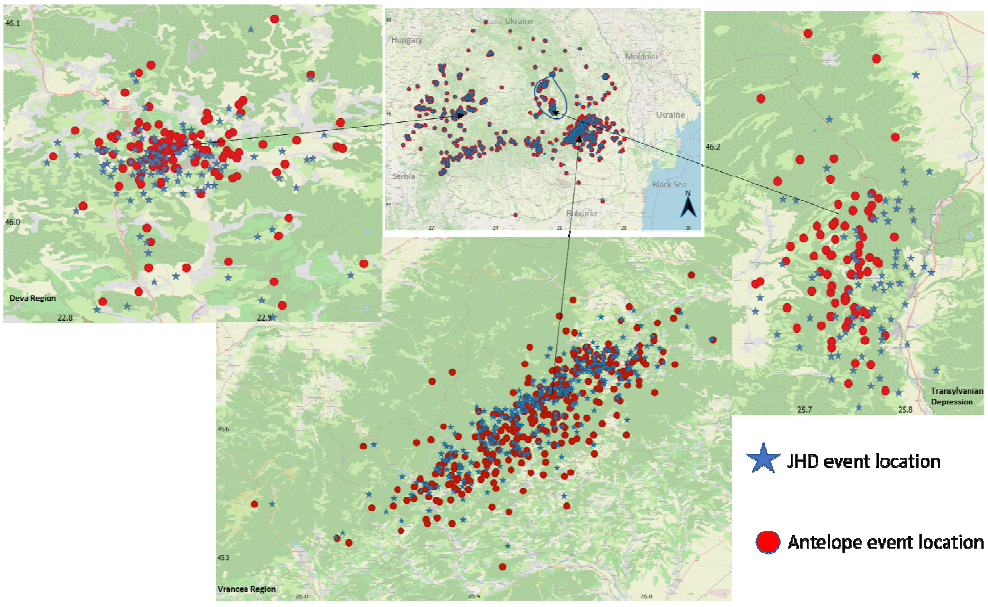

Fig. [5] - Epicentral distribution of Antelope/JHD compared locations. Highlights: Deva area (left), Harghita region (right), Vrancea (center).

3.3. STATION CORRECTIONS

The station corrections represent the average difference between observed and computed travel times at each station. If statistically (for a significant number of events) they are distributed around 0, that means the 1-D structure model is close to the real model. If systematic deviations are obtained for one station or the other, that means the real structure presents significant lateral variations against the reference model: positive deviation - if less consolidated structures, such as sedimentary basins, are located on the source - station path; negative deviation - if hard rock structures, such as outcrops, are present along the source - station path.
We plot in the Fig. [6] the station corrections obtained after applying inversion for the Vrancea intermediate-depth earthquakes only. Note the clear separation between the positive and negative anomalies for the inner (Transylvania) and outer (Moesia Platform) Carpathians areas. The anomalies are systematically positive in the Modova Platform as well. This configuration is noticeably distinguished from the configuration obtained for crustal events.
Whereas for shallow events the propagation anomalies outlines local effects, such as positive anomalies for sedimentary basins and negative anomalies for the

stations on hard rock, the anomalies obtained when the seismic waves propagate from deep Vrancea hypocentres are mainly determined by the lateral inhomogeneities in the deeper structure. Thus, we ascribe the positive anomalies in the Transylvanian and Panonnian basins to the lithosphere structure with lower velocities beneath these areas, while the negative anomalies for the Moesia platform are ascribed to the higher velocities characterizing the lithosphere beneath platform regions. It is surprising, however, to obtain positive anomalies in the Moldovian platform, which is known to have a cratonic structure underneath (East European platform).

We consider these results as preliminary, given the relatively small amount of data used (the number of residuals, respectively, which is statistically not sufficient for many stations to assure a high degree of reliability). Given the preliminary nature of these results, it remains to investigate in a future study, the corrections at the stations, separately for deep and surface events, for statistically consistent data sets, to constrain these corrections as accurately as possible.

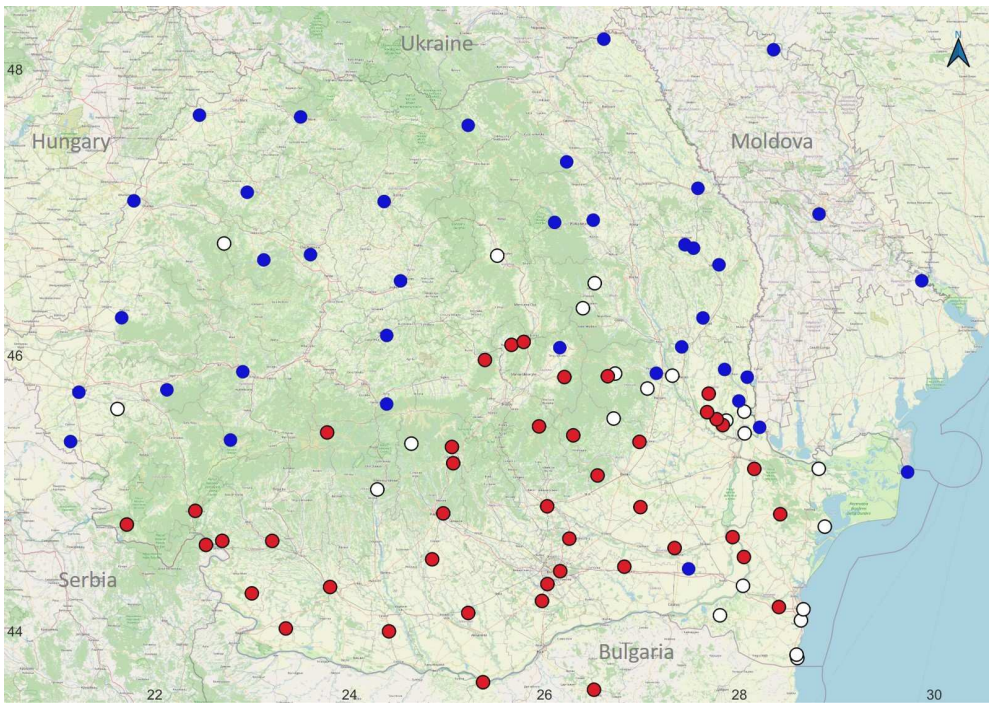

Fig. [6] - Station corrections as obtained for Vrancea intermediate-depth earthquakes. The coloured circles represent station corrections: red circles for negative values, blue for positive values, and white for values close to or equal to zero.

3.4. TEST OF STATISTICAL SIGNIFICANCE

The root mean square of the residuals at stations averaged for each event represents a statistical measure of the location accuracy. As shown in Fig. [7], the RMS values are acceptable since most of them are below 1.5 s. In order to test the efficiency of the multiple location technique and the velocity model obtained, we applied the JHD method and the new velocity model on two datasets of different size. Thus, the first set contains about 470 locations and the second set 1200 locations (the first one is a subset of the second one) We can see from the resulting histograms that the RMS values are similar for the larger and smaller datasets. This similarity suggests that applying the inversion to a data set of about 400 events leads to acceptable location errors.

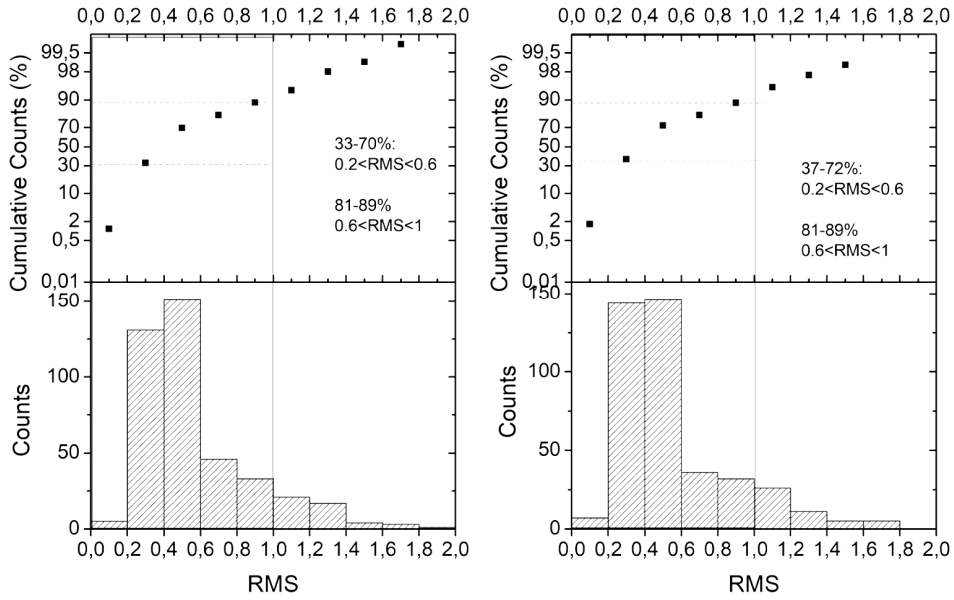

Fig. [7] - RMS histograms, left histogram represent the RMS values obtained for a data set of about 500 local earthquakes, the right histogram represents the RMS values obtained for a data set of about 1200 local events.

4. CONCLUSIONS

The main purpose of this study was to compute a new 1-D velocity model at the scale of Romania territory. The model is optimizing the P-wave and S-wave arrival times recorded for a selected set of events produced in Romania during 2020-2021. To achieve this goal, we applied the VELEST software, based on the JHD inversion method, on the selected dataset. The new model reproduces well the

IASPEI model used routinely in the Romanian catalogue (ROMPLUS) for the crustal depth (0 - 60 km), but differs significantly at higher depths. The velocity increase in the upper mantle fits well the presence of a high-velocity lithospheric body beneath the Vrancea region, where intermediate-depth earthquakes are continuously generated.

The relocation of the events on the basis of the new velocity model keeps the space configuration as for the location with ROMPLUS catalogue parameters. The relocated coordinates show a better grouping of events, especially for deep Vrancea ones. Location changes for the events in the crust are generally small, because the structure beneath the crust is almost not influencing the wave propagation above. In some cases, the new locations are shifted with a certain amount relative to the locations in ROMPLUS.

An important measure of the degree of location accuracy is the root mean square (RMS). For the selected dataset, RMS values are mostly below 1.5 s, which is an acceptable value for routine locations. The tests performed by reducing the number of events to about one-third (from 1200 events to 470 events) showed that location accuracy remains virtually unchanged.

In addition to the optimized reconfiguration of the structure model, the JHD algorithm determines the corrections associated with the seismic stations. The tests carried out so far indicate that the statistics used are not sufficient to stabilize the station corrections, especially for the crustal events. As an interesting preliminary result, we obtained a striking delimitation between the positive and negative corrections for the Vrancea intermediate-depth earthquakes, which apparently can be related to the lateral inhomogeneities of the structure in the area of the upper mantle. The borders that separate these areas of different anomalies fit well with the delimitations between the different tectonic blocks existing on the territory of the country (East European toward north-east, Moesian in south, Intra-Alpin toward west). Considering the importance of evaluating the corrections as correctly as possible, this will be a subject of analysis in future works. What we have been able to show convincingly in this paper is the importance of separating corrections when analysing surface earthquakes and deep ones.

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