AN IMPROVED 1-D SEISMIC VELOCITY MODEL FOR THE ACTIVE TECTONIC DEFORMATION AREA OF THE SOUTH WESTERN CARPATHIAN BEND ZONE (ROMANIA)

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ABSTRACT

Significant advancements in earthquake monitoring were made thanks to the recent developments of the Romanian Seismic Network (RSN). Improved event detection and location have resulted in denser and higher-quality data sets. This gives us the opportunity to develop a new 1-D velocity model for the South-

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Western Carpathian Bend Zone, a region with a high potential for local seismic hazard. The new velocity model and corresponding station corrections are obtained through travel time inversion of P and S-waves using the VELEST algorithm. We started with a modified version of an earlier velocity model and selected a set of high-quality recordings from the 595 crustal earthquakes with at least ten P-wave picks and a maximum azimuthal gap of 180° between stations surrounding the epicenter. The resulting earthquake distribution and station corrections show an excellent correlation with the local geology and vary between – 0.39 s and + 1.16 s. The relocated hypocenters are mostly distributed in the upper crust, revealing at least two clusters of events with potential anthropic origins. Our results also show more accurate locations, with up to 42,5% decrease in RMS location errors.

Keywords: velocity model, seismic activity, South Western Carpathians

INTRODUCTION

Seismic activity in Romania is mainly distributed along the Carpathian Orogen, with the greatest concentration at the bending of the Southeastern Carpathians, in the Vrancea region. In this area, crustal seismicity overlaps the intermediate-depth earthquakes which cause the largest deformations due to the occurrence of 2 to 4 large magnitude events (M > 7) each century, posing the greatest seismic risk in Eastern Europe (Petrescu et al., 2021, Ionescu et al.,2022). Although Vrancea is the most active seismic area in Romania, significant crustal seismic activity also affects the South-Western Carpathian Bend Zone (SWCBZ), a high Earthquake potential region, as previous studies have shown (Oros 2004, Placinta et al., 2016, Oros et al., 2021). In this area, seismic activity (Figure 1) is linked to the active tectonic deformation and is concentrated along pull-apart basins as a result of the dextral movement of the Carpathians Orogen relative to the Moesian Platform (Popa et al., 2018).

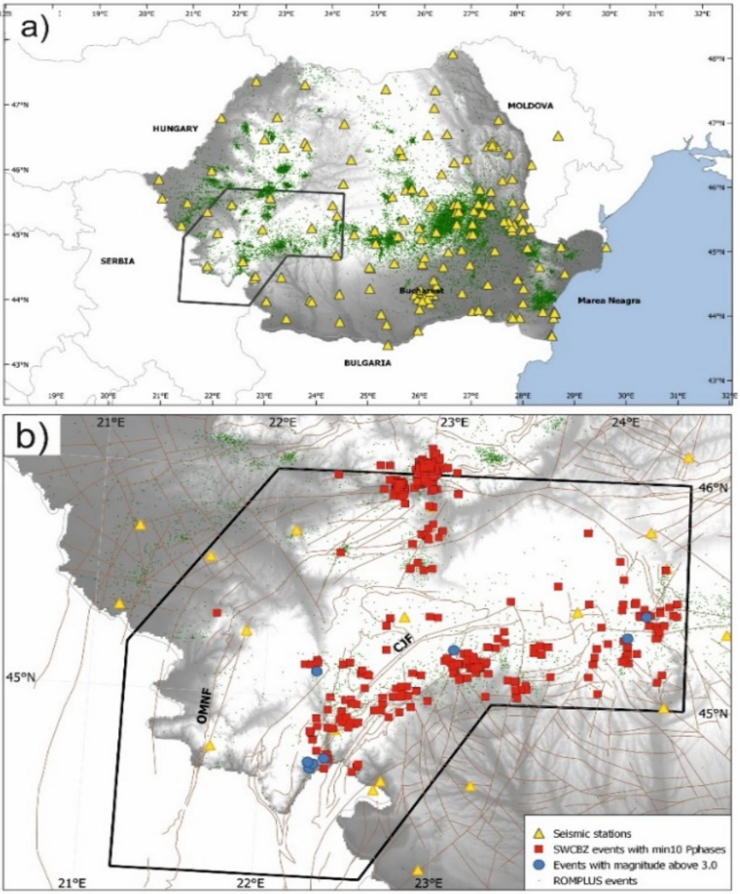

Figure 1 - a) Main tectonic features, crustal and intermediate-depth seismic activity (2015-2021) based on the ROMPLUS catalog and RSN stations distribution (yellow). The black polygon marks the limits of the study area. b) an overview of the study area showing the distribution of seismic stations (yellow triangles) and epicenters (in green - Mw<3 and red - Mw>3 events), as well as the main faults identified in the region. CJF-Cerna Jiu Fault System, OMNF-Oravița-Moldova Nouă Fault System.

Many of the earthquakes generated in the South-Western Carpathian Bend Zone region is distributed on NNE-SSW fault systems dipping to the west, such as the Oravița-Moldova Nouă and Cerna-Jiu (Figure 1), two notable crustal faults that shape the region (Oros 2004, Placinta et al., 2016, Popa et al., 2018, Mitrofan et al., 2020, Oros, 2021).

Previous research that investigated the crustal structure in this region relied on either classical methods, such as seismic refraction or reflection profiles (Enescu et al., 1992, Tesauro et al., 2008), or more modern techniques, such as local body wave or ambient noise seismic tomography (Zaharia et al., 2017, Ren et al., 2012) or joint inversion of dispersion curves and receiver functions (Bala et al., 2019, Petrescu et al., 2019).

Based on the advancement in seismic monitoring in the SWCBZ area as a result of the expansion of the RSN (Marmureanu et al., 2021), 595 well-located local crustal events were extracted from the Romanian earthquake catalogue (ROMPLUS, Oncescu et al., 1999, Popa et al., 2022) to estimate an improved 1-D velocity model. The new model will be used in the routine process of earthquake location, enhancing the image of the seismicity patterns and seismotectonics processes that continuously shape this region.

DATA AND METHODS

To better understand the tectonic processes and crustal properties in such a complex area, we chose 595 small to moderate size ($1 \leq Mw \leq 5$) crustal events ($1 \leq H(km) \leq 20$), generated in the South-Western Carpathian Bend Zone area between 2015 and 2021 (Figures 1, 2). The events were selected based on three criteria to ensure the highest quality velocity model: 1) a minimum of ten P-phases for each individual earthquake; 2) a location RMS of less than one second; and 3) a maximum azimuthal gap of 180 degrees. The events were recorded by a total of 120 short period and broadband permanent seismic stations operated by the RSN. The seismograms were manually picked, resulting in 7365 P and 7440 S-wave arrivals. To determine a high-accuracy 1-D velocity model and estimate station corrections by minimizing the misfit between the arrival times and model predictions, the selected data were inverted using the VELEST algorithm (Kissling, 1988; Kissling et al., 1994; Kisling, 1995) embedded within the SEISAN package (Havskov and Ottemoller, 1999). To run the inversion, we use both P- and S-wave travel time data and employ the following velocity models as input: 1) we started with an earlier velocity model developed for this area 2) the resulting velocity model was then used as an input for the following inversion, completing a total number of five runs. The reference station was chosen, Gura Zlata (GZR) due to its central position. The number of iterations for each run was determined based on previous research (Raffaele et al., 2004) that completed the inversion when the earthquake locations, station corrections, and velocity values did not differ significantly in subsequent iterations. We also assumed that the velocity increases monotonically with depth, to prevent computational bias.

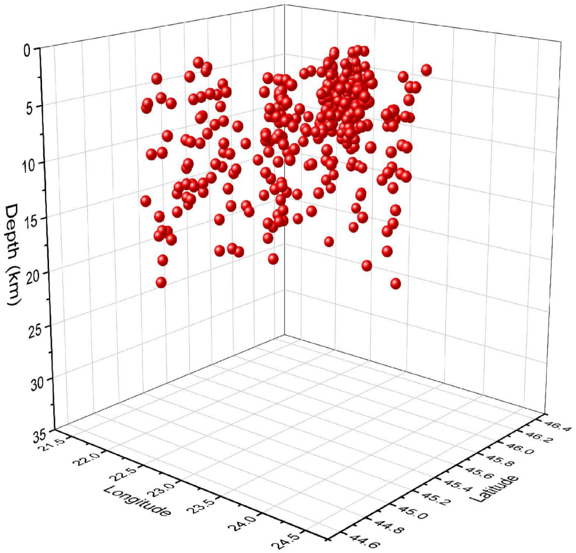

Figure 2 - 3-D hypocenters distribution of selected seismic events

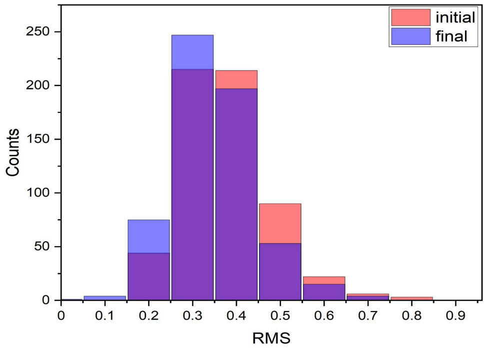

Figure 3 - Comparison of RMS location errors for selected events located using initial (red) and final (blue) velocity models

RESULTS

The VELEST algorithm was run on the selected data and each of the five initial velocity models, generating five new models. We notice a reduction of up to 42,5% in the location RMS for all the resulting velocity models when compared to the average RMS of the initial model (Figure 3).

The resulting models, as well as the RMS values obtained for event relocation, are comparable, indicating that these models have converged, which is in agreement with the results of previous studies based on similar approaches (Kissling, 1995, Popa et al., 2001). The final model was selected based on the lowest RMS misfit and is displayed in Figure 4. The station corrections comprise velocity variations caused by topography and near surface structures (Kissling et al., 1995).

According to earlier studies (Kissling, 1995, Popa et al., 2001), the positive symbols in Figure 5 correspond to the region of low velocities relative to the reference station and negative symbols indicate high velocity regions. The final 1-D velocity model (given in Table 1) and P-wave station corrections are depicted in Figures 4 and 5.

Table 1. The final 1-D velocity model was obtained using the VELEST algorithm

Depth (km)	Vp (km/s)	Vs (km/s)
0	5.82	3.37
12	6.07	3.52
25	6.37	3.94
35	8.01	4.36

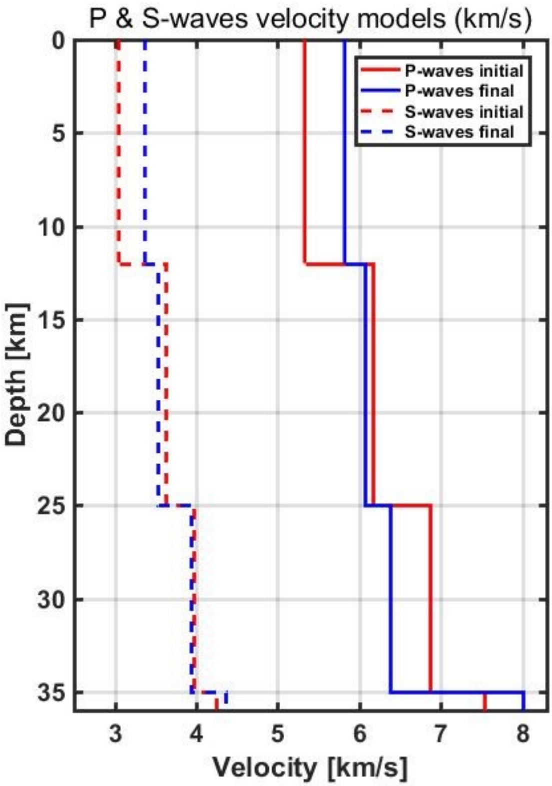

Figure 4 - Starting (red) and computed (blue) P (solid lines) and S (dotted lines)-wave velocity models used as input and resulted after applying the VELEST algorithm

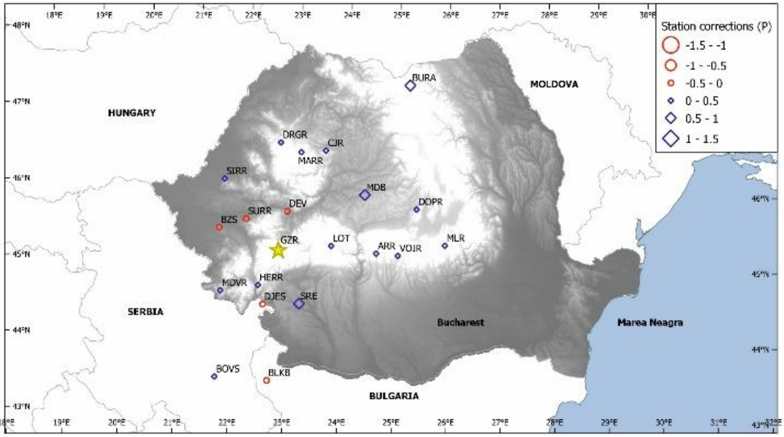

Figure 5 - Map showing P-wave station corrections for the final velocity model determined for the SWCBZ area. The reference station is GZR (yellow star)

Figure 5 shows the P-wave station corrections relative to the reference station (Gura Zlata, GZR) taking into account stations with at least 50 observations. Gura Zlata station was selected as the reference station because it is located in the center of the South-Western Carpathian Bend Zone area and has the largest number of observations in comparison to the surrounding stations.

DISCUSSION AND CONCLUSIONS

Compared to the initial velocity model, our results indicate lower P wave velocities in the upper and middle crust (Figures 2 and 4). The resulting P-wave velocities for deeper depths are higher than those predicted by the starting velocity model. However, because the hypocenters are distributed up to the middle crust, for the higher depths, the resolution of the new velocity model is considerably reduced. It is worth noting that, the resulted corrections (relative to GZR station, Figure 5) show in general low amplitudes (values smaller than 1s), except Bucovina (BURAR), Medias (MDB) and Strehaia (SRE) stations which all show high positive values (>1s). The sign and the amplitude of the station correction are mainly related to geological structure. The large positive amplitude corrections highlighted by the above stations can be explained by the fact that they are located in regions with complex geology at the contact between major tectonic units (Figure 1). Our results are consistent with previous studies (Popa et al., 2001). They estimated a 1-D velocity model for the Vrancea region (Figure 1), highlighting positive corrections for the stations along the Carpathian Orogen and negative corrections for stations in the platform areas.

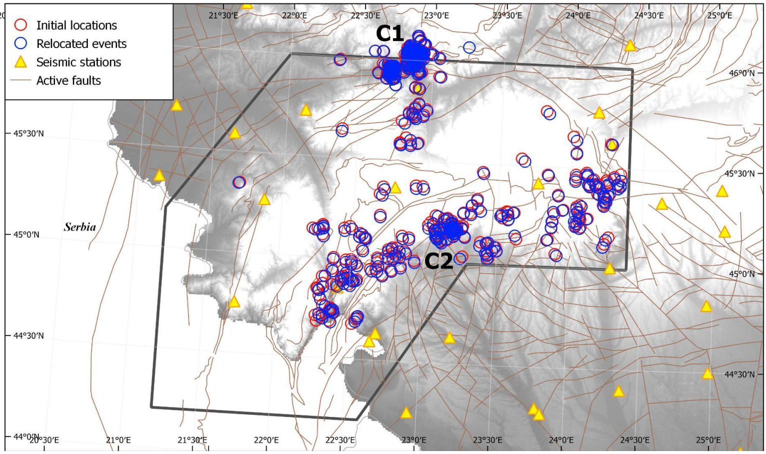

Figure 6 - Seismic stations, epicenters and faults distribution in the SWCBZ area. The distribution of epicenters is shown before and after relocation using the determined 1-D velocity model

Using the new 1-D velocity model (Figure 4 and Table 1) and the obtained station corrections, we relocated the selected events using Joint Hypocenter Determination (JHD) algorithm (Kissling et al., 1994). A comparison of the seismic event locations obtained using the initial and new velocity model resulted from the inversion is shown in Figure 6. It is worth noting that the relocated events are better grouped in the horizontal plane, highlighting at least two clusters of events (C1 and C2 in Figure 6).

The depth variation for the events of the two clusters is limited (between 0 and 2 km) since a part of the events is shifted toward the surface (Figure 7). This is consistent with earlier studies that suggested that the ROMPLUS catalog may be contaminated with events of anthropic origin (Dinescu et al., 2021).

The comparison of the depth distributions of these events seems to also support this hypothesis (Figure 7). We note that a part of the relocated events based on the new velocity model are moved close to the surface (H<2km). On the other hand, the events that were originally located in the 2–7 km depth range appear to have been shifted to greater depths (4–12 km), in good agreement with the thickness of the sedimentary layer, highlighted in the study region (Ioane and Ion, 2005)

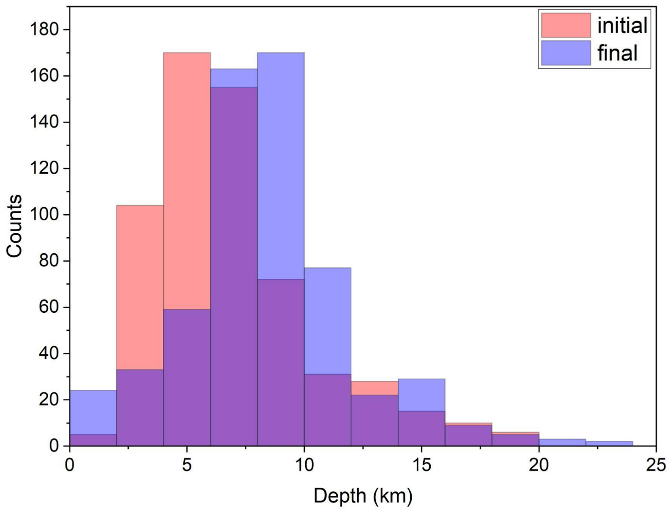

Figure 7 -Histograms showing depth differences resulting from the location of selected events using initial and computed velocity models

Based on the new data provided by the RSN and ROMPLUS catalog, we developed an improved 1-D velocity model to be used for routine earthquake locations within the South-Western Carpathian Bend Zone area and as a reference model for future research. The model has the highest resolution in the upper crust and correlates well with local geology. The relocated events based on the newly determined velocity model emphasize at least two clusters of events with potential anthropic origins (Figure 6). The distribution of relocated events, except for the two clusters (C1 and C2 in Figure 6), generally follows the orientation of the major fault systems. Our results also show an improvement in earthquake locations by decreasing RMS location errors by up to 42,5%.

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