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A REANALYSIS OF THE SEISMIC ACTIVITY AT THE WESTERN EDGE OF THE EASTERN EUROPEAN PLATFORM

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Abstract. Over the previous decades, seismic activity has sporadically increased along the western edge of the European Platform. Although the Romanian Seismic Network has been continuously enlarged, the growth in the number of events in the Romanian earthquake catalogue, ROMPLUS, in this area does not always follow the number of newly installed stations. To shed light on the patterns of seismic activity in this region, we performed a statistical analysis of events recorded between 2005 and 2021 in the ROMPLUS catalogue and used waveform correlation analysis to investigate the similarity degree and nature of these events. The poorly located events were relocated after the seismic phases were manually examined. We show that a large number of events are clustered around fault systems distributed near several quarries.

Key words: ROMPLUS catalogue, seismic events, statistical analysis, waveforms cross-correlation, earthquakes relocation.

1. INTRODUCTION

The Moldavian Platform, which includes the northeast of Romania, is generally characterized by moderate seismic activity, with minor to moderate-sized crustal earthquakes (Fig. 1). The recent extension and upgrading of the Romanian Seismic Network (RSN) [1] during the last decade have led to significant improvements in detection and location rate of seismic events that occurred in this region, which are also recorded in the updated Romanian earthquake catalogue, ROMPLUS [2, 3]. Efficient distribution of stations lowers the detectability threshold of seismic events and leads to more accurate seismic source parameter determination, offering key insight into seismicity patterns. However, as a result of lowering the magnitude threshold the ROMPLUS catalogue is vulnerable to contamination by man-made events caused by the numerous exploitations in this region [4], affecting the accuracy of various studies (*e.g.*, seismic hazard, microzonation). In order to obtain reliable results and avoid misinterpretation of seismic activity patterns, the earthquake catalogues are periodically reviewed using the latest algorithms, to improve location accuracy or remove anthropogenic events, to provide the most accurate data sets [5–7]. Previous studies have indicated considerable contamination of the ROMPLUS catalogue with non-tectonic events, proposing various methods based on statistics or waveform analysis for the discrimination of seismic events [4, 6, 8]. Furthermore, a considerable number of seismic events listed in the catalogue have depth estimation inquires, as evidenced by large uncertainties or even fixed depths.

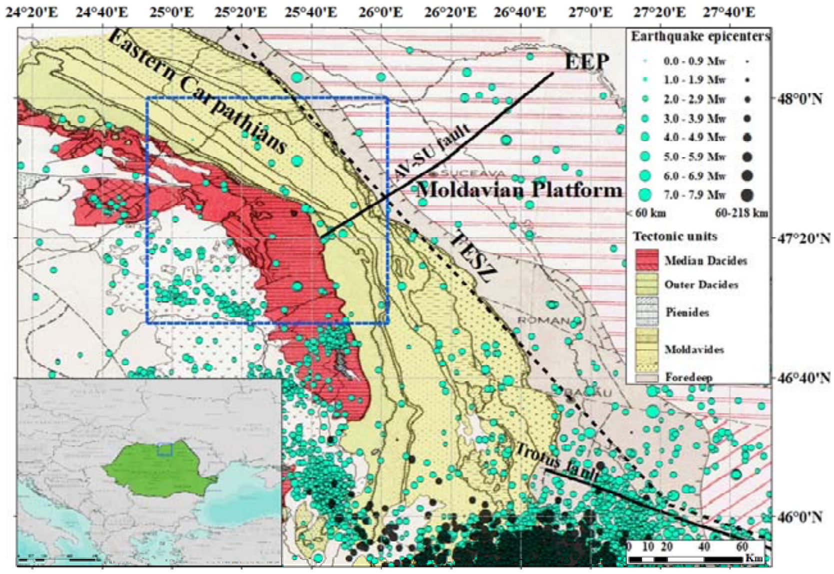

Fig. 1 – Map of the major tectonic and geological features in the study area and adjacent regions modified after [16]. The seismicity (1984–2021) is represented according to the ROMPLUS catalogue and the main fault systems is represented after [17]. The study area is marked by the blue square. The abbreviations are as follows: TESZ – Trans European Suture Zone, EEP – East European Platform, AV-SU – Avramești Suceava. The inset map shows the study region in a regional context.

The purpose of this study is to review the seismic events recorded in the ROMPLUS catalogue between 2005 and 2021 in northeastern Romania (Fig. 1), to distinguish between the tectonic and anthropogenic events, to describe clustered seismicity and to relocate the events with significant errors. This is the first step of a thorough process that aims to get a comprehensive evaluation of the ROMPLUS catalogue. To achieve this purpose, a statistical analysis was performed first on the catalogue data. To increase the reliability of the results, the waveform cross-correlation technique was also applied to the vertical recordings of the BUR31 station, a component of the Bucovina seismic array (BURAR). In addition, to enhance location accuracy, the selected events marked in the ROMPLUS catalogue with fixed depths or the events with great depth errors were manually reviewed and relocated using the LOCSAT algorithm [9] embedded in the Antelope software [10].

2. SEISMOTECTONIC OVERVIEW

The northeastern part of Romania is a very complex and inhomogeneous continental collision area [11] comprising two major tectonic units (Fig. 1): the western side of the Eastern European Platform (EEP) and the Carpathian Orogen, separated by the Trans-European Suture Zone (TESZ), a major geological boundary in Europe spanning from the Baltic Sea to the Black Sea [12]. The study region is characterized by low to moderate crustal seismic activity (Fig. 1) with scattered seismicity possibly associated with marginal fractures of the Moldavian Platform, a fragment of the cratonic area of the EEP. Except for few clustered earthquakes located close to the central segment of the Trotuș Fault (Fig. 1), the epicenters do not appear to outline the orientation of the main faults [13–15]. A probably uplift neotectonic movement, lead to the assumption that the crustal seismicity is driven by flexure that breaks and generates minor normal faults, for which the eastern segment shows an upraise trend, while the western part of the fault is blocked under molasses deposits. This assumption is compatible with the hypothesis that the under-pushing east-west movement of the foreland from the Moldavian Platform is ended under the Carpathians [15].

3. DATA AND METHODS

The methods taken into account combine statistical and seismic waveform analysis. For the events relocation, the P- and S-wave arrival times determined for at least four stations were inverted and the solution accuracies were checked with the modified Wadati diagram [18, 19].

The distinctions between anthropogenic and tectonic events would be as follows: i) the anthropogenic events are in general of low magnitude and occurred during working hours [6]; ii) the time interval of the released energy is different; the explosive is detonated instantly while the release of energy during an earthquake is performed in time [20]); iii) the waveform recorded by a seismic station from an anthropogenic event differs from an earthquake that occurred in the same area, because the energy released after an explosion is sudden, characterized by large P-wave amplitudes, a significant surface waves content and rapid attenuation [20]; as in Fig. 2; iv) P waves generated by explosion always show compression (+) sign at station, the explosion has expansion mechanism and energy is released radially towards the stations in all directions) [20], while for earthquakes that occur at different depths and through different mechanisms, the primary wave may depict compression or dilatation (+ or –) sign as well.

Figure 2 shows two waveforms recorded by the vertical component of the BUR31 broadband station of the BURAR seismic array from a crustal earthquake that occurred in the Bucovina region (01/07/2014, 11:18:51 GMT), respectively a blast event generated in the same area (31/08/2014, 03:00:20 GMT) within the Wide Angle Reflection and Refraction geotraverses of the Romanian Carpathians and Dobrogea – RomSeis 2014 project (WARR) [21], hereinafter referred to as ground truth event.

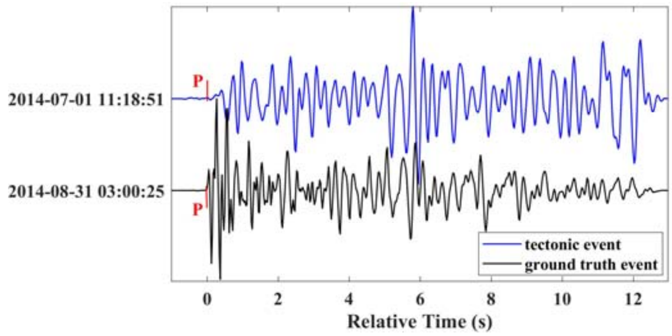

Fig. 2 – Waveforms recorded by the vertical component of the BUR31 station from a crustal earthquake (blue) that occurred in the Bucovina region (01/07/2014, 11:18:51 GMT), respectively a ground truth event (black) generated in the same area (31/08/2014, 03:00:20 GMT).

3.1. STATISTICAL ANALYSIS

We investigated the events that occurred in the study area and recorded in the ROMPLUS catalogue between 2005 and 2021. The selection was performed taking into account the geographic coordinates of the selected area, 46.95°N – 47.90°N and 24.90°E – 25.90°E, resulting in a number of 132 seismic events (Fig. 3b). Despite recent RSN enlargement, the relatively long inter-station distances in this region, along with the low magnitude size of these events, lead many detections to remain unassociated phases because they are not recorded by a sufficient number of stations to be reliably located. Nevertheless, the magnitude threshold of located events has lowered in recent decades, indicating that a high number of low magnitude events have been recorded in the ROMPLUS catalogue, thus increasing the probability of catalog contamination with anthropogenic events.

To better define seismic activity in this region and to bring additional insights into seismicity patterns, the selected events (132) were represented in the following as a function of occurrence time, day of the week, the month of the year and moment-magnitude (M_W).

3.2. WAVEFORM CROSS-CORRELATION TECHNIQUE

3.2.1. BURAR seismic array

The BURAR seismic array, located in the northeastern Romania, in Bucovina region, consists of ten stations distributed over an area of 25 km^2 (Fig. 3c): nine stations (BUR01-BUR09) are equipped with short-period uniaxial sensors (1C-SP), and one station (BUR31) is equipped with a broadband triaxial sensor (3C-BB). Seismic sensors are installed in boreholes at depths ranging from 30 to 60 m [22]. Mining and stone quarrying activities have been observed in this area over time, but without noise sources that could greatly affect seismic recordings [23]. Figure 3 depicts the distribution of seismic stations across Romania, the study area, the location of the BURAR array along with its stations, the distribution of the selected events colored function of depth interval and the existing quarries in the study area, which were taken from previous studies [4, 8].

a)
b)
c)

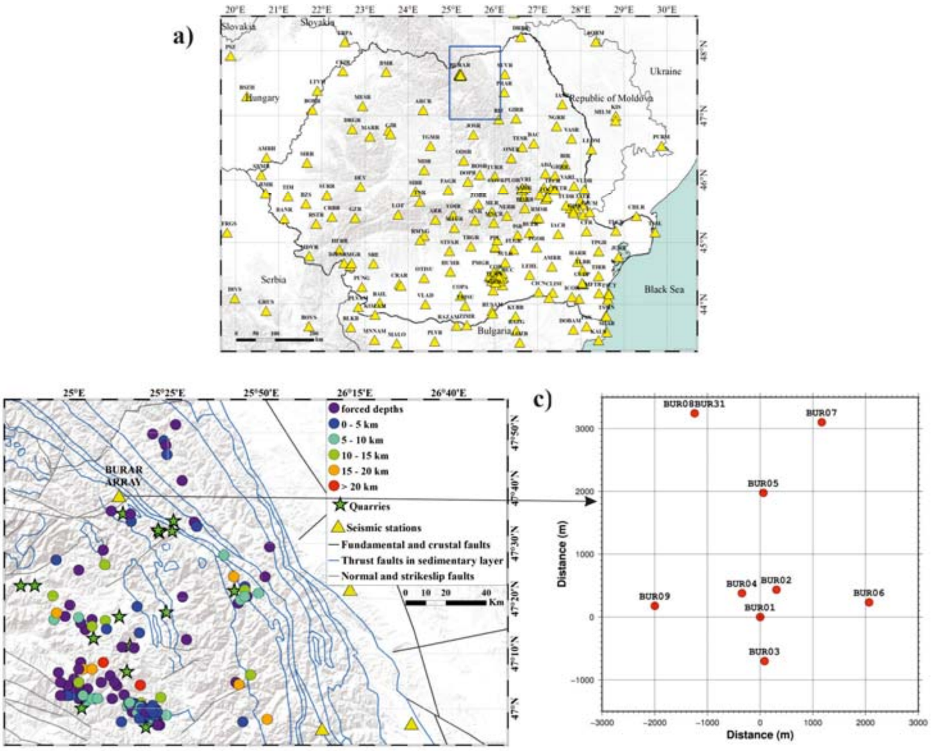

Fig. 3 – a) Map showing distribution of seismic stations in Romania and surrounding areas. The blue rectangle shows the study area; b) distribution of selected events function of depth, known quarries, seismic stations in the study area and the fault system after [17]; c) BURAR seismic array configuration.

3.2.2. Waveforms processing

Figure 4 shows an example of how we determined event similarity by performing the waveform cross-correlation with the selected parameters between two events (recorded by the vertical component of BUR31 station) generated during the 2011 Bucovina seismic sequence [15].

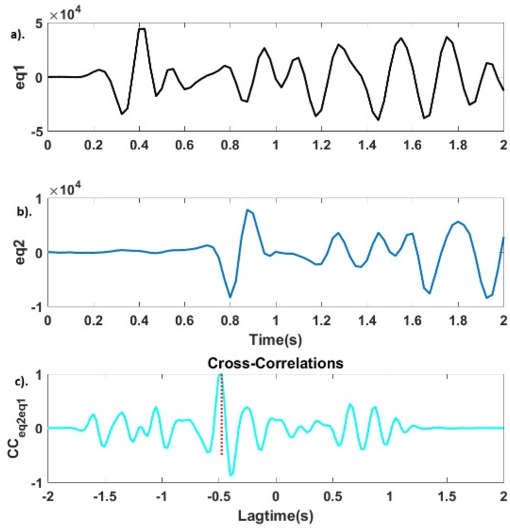

Fig. 4 – Waveform recorded by the BUR31 and filtered using a Butterworth bandpass filter between 2.0 and 4.0 Hz: a) from a seismic event occurred on 24/06/2011 (at 16:18:58 GMT); b) from a seismic event occurred on 30/06/2011 (at 21:21:01 GMT). Both events are closely located in space being generated during the 2011 Bucovina seismic sequence; c) the result obtained from waveforms cross-correlation approach, showing CC and lag time. The dashed vertical line depicts the highest CC.

We apply the waveform cross-correlation technique (WCT) to determine the similarity degree between the selected events. This approach identifies events closely located in space for which the waves have practically the same propagation path [24]. In this stage, we apply WCT to identify groups of seismic events (clusters) generated by repeated sources within the study region in order to establish whether their origins are tectonic or anthropogenic. To achieve this goal, we chose vertical recordings from the BUR31 station (a component of the BURAR seismic array), gathering waveforms from 129 events. The records for three events were not available and have been removed from this analysis.

The waveforms with duration of 120s were extracted from the NIEP database as SAC files [23], and manually analyzed to identify the P-waves arrival times. To determine the correlation coefficients (CC) between the selected events, we applied a Butterworth bandpass filter between 2.0 and 4.0 Hz and selected a time window of 2s around the P-wave arrival (0.2s before and 1.8s after the P-wave). The analysis was performed using the open access GISMO library [25] built under the MATLAB environment. The frequency range and time window for WCT were chosen by multiple trials, as such two events with similar mechanisms generated almost in the same place in the study region [15] to give the highest CC.

Based on the findings highlighted by previous research [4, 5, 8, 16], the recordings of a ground truth event [21] and statistical analysis, we developed a discriminant relying on waveform patterns (previously described, see section 3), their similarity and time of occurrence. If the recorded waveform is comparable to that of the ground truth event, occurs within regular working hours and the polarity of the first P-wave arrival is positive, will be considered with high probability to be generated by an anthropogenic source.

3.2.3. Events relocation

Until 2014, the HYPOPLUS algorithm [2, 26, 27] and a 1-D velocity model determined by [26] for the Romanian territory were routinely applied to locate seismic events that occurred at the crustal level. Since 2014, seismic events have been routinely located with the LOCSAT method [9], an efficient location approach that employs IASP91, the 1-D Earth reference velocity model [26], embedded within the Antelope software. The limited number of seismic stations located in the epicentral region (Fig. 3a) leads to large location errors (Fig. 5), making the depth estimation rather difficult.

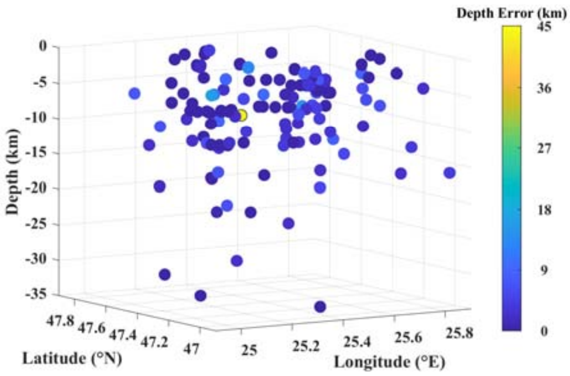

Fig. 5 – 3D hypocenters distribution of the initial 132 events colored function of depth errors.

The accurate assessment of depth plays a crucial role in seismicity and seismic discrimination studies, bringing key information about the depth of the fault or defining the nature of the source. In this context, we expect that anthropogenic events will be concentrated close to the surface, whereas tectonic events will be distributed at different depths.

For 24 of the 132 selected events, we identified significant errors in the depth estimation or fixed depths (Fig. 5) in accordance with the available seismotectonic models [29]. To increase the location accuracy for these events we manually reviewed the onsets of the seismic phases and inspected the waveforms to see if new phases could be identified. Finally, the reviewed data set was relocated with the LOCSAT algorithm. The accuracy of initial and relocated events was evaluated by applying the modified Wadati diagram. This method estimates the linear regression between arrival time differences of S- and P-waves plotted *versus* the P-wave travel time. Subsequently, using equation (1) the seismic velocity ratio could be also determined [30]

$$\frac{T_S - T_P}{T_P} = \frac{V_P}{V_S} - 1\,. \tag{1}$$

T_s and T_p represent the S- and P-wave arrival times and V_p and V_s are P and S-wave velocities.

4. RESULTS

4.1. STATISTICAL ANALYSIS

The magnitude $M_W = 3.0$ is comparable to the energy released by a surface explosion of about one tonne of trinitrotoluene (TNT [20]), hence the probability of producing anthropogenic events of this size or greater in the study region is low. In general, we expect that anthropogenic events that could contaminate the ROMPLUS catalogue would be of small magnitude. Figure 6a shows the distribution of the selected events as a function of magnitude and time of occurrence. We note that the magnitude variation is limited ($1.5 \leq M_W \leq 3.5$) and 80 events (60.6%) are in a magnitude range from 2.2 to 2.6. The relative low number of events with low magnitudes ($M_W \leq 2.0$) may indicate either a limitation in computation of low magnitudes or that not all events detected by the BURAR seismic array could be also located due to the limited number of seismic phases recorded by the nearby stations.

The monthly distribution of events shows two peaks, *i.e.*, one in January and another in June (Fig. 6b), followed by a generally decreasing tendency in the fall and winter months. The unusually high number of events recorded in January is explained by an intense seismic activity, between 03 and 26 of January 2013 when 17 small size seismic events (closely located also in space as can be seen in Fig. 7a) occurred mostly during the nighttime (Fig. 7c). The increase in the number of events in June is explained as well by the occurrence in June 2011 of a seismic sequence of nine events [15]. We identified also a series of six events closely located in time and space in June 2013.

The weekly distribution (Fig. 6b) shows that a large number of seismic events occurred during the working days (Fig. 7b), with a maximum on Thursday. Although we would have expected this increase to be due to the occurrence of anthropogenic events, this large number is associated to the intense seismic activity observed in January 2013, respectively in June 2011 and 2013. A percentage of 53.1% of the events recorded on Thursday is due to the three sequences of earthquakes. The events distribution as a function of origin time (local time, see Fig. 6d) shows that the selected events occurred throughout the day, with a rise of seismic activity during working hours (12–16 pm, local time), suggesting that the earthquakes catalogue may be contaminated by events of anthropic origin (Figs. 6 and 7).

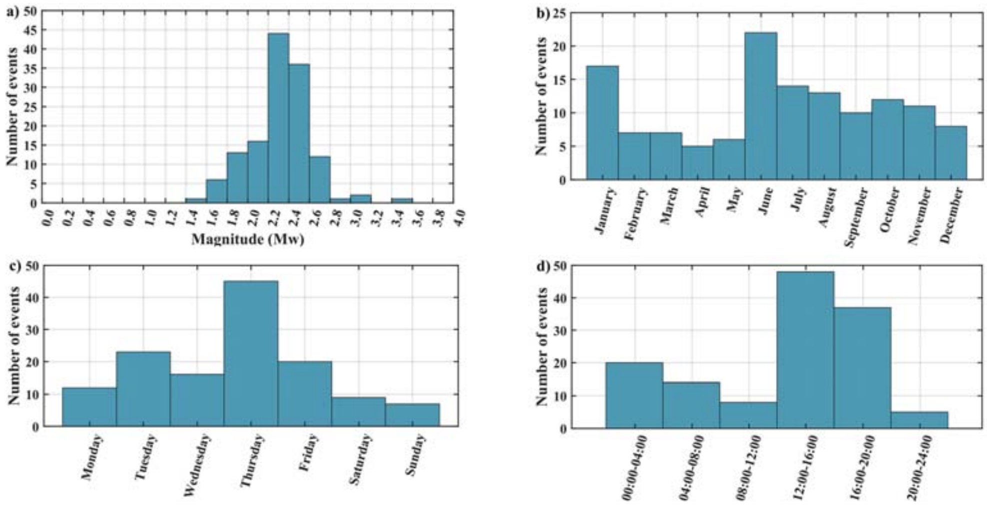

Fig. 6 – Events distribution as function of: a) M_W; b) month of the year; c) day of the week; d) time of occurrence.

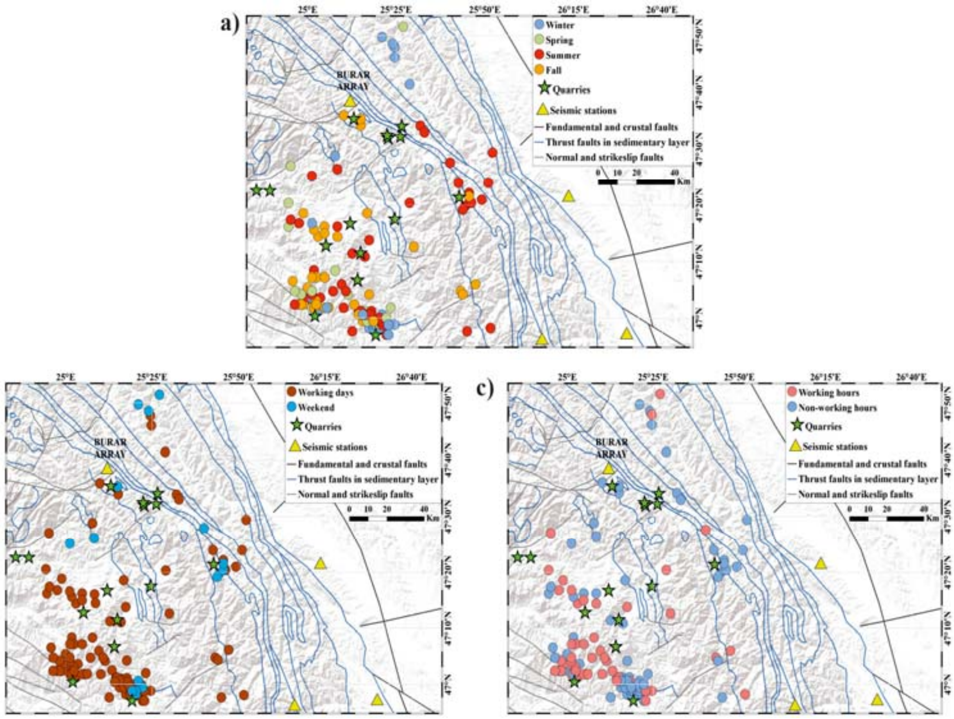

Fig. 7 – Distribution of selected seismic events as function of: a) seasons; b) working and non-working days; c) working and non-working hours. The fault system [17], seismic stations and known quarries are also shown.

In accordance with previous studies [4, 5], we consider as potential anthropic events those generated during working days and hours, representing about 40.2% of the 132 selected events. From this selection, we firstly removed events from the June 2011 seismic sequence [15], as well as those that occurred between January 03 and February 09 respectively from 03 to13 June 2013, all these events being clustered both in time and space, similar to earthquake swarms generated in other areas of the country [3]. The waveforms were separately analysed and the results are shown in the following section.

4.2. WAVEFORM CROSS-CORRELATION ANALYSIS

The determined CC for the analyzed waveforms are represented as a correlation matrix (Fig. 8) to emphasize the similarity degree among the selected events. The warm colors indicate the high similarity between waveforms and the cool colors indicate the opposite. To identify similar events, we used a minimum CC value of 0.7 as a threshold, in agreement with previous research performed in various regions of the world [31, 32].

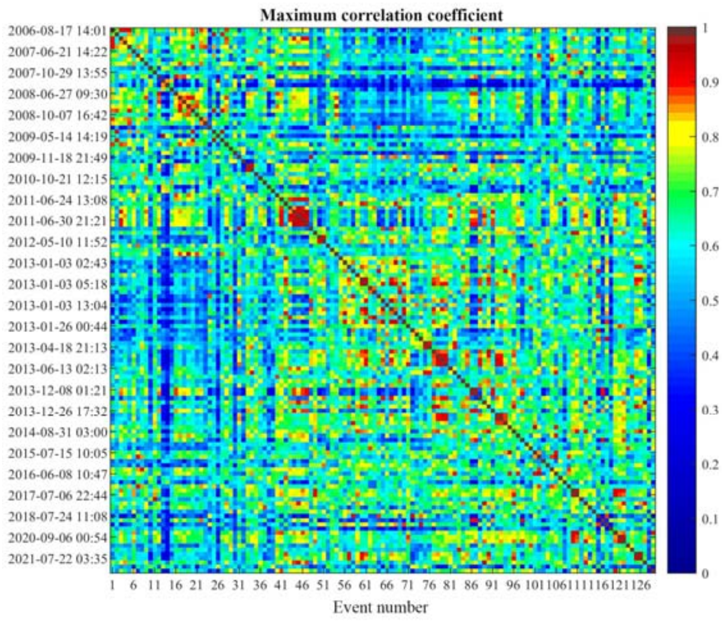

Fig. 8 – The correlation matrix computed based on CC determined for the selected events that occurred in the study region between 2005 and 202.

The correlation matrix, with a few exceptions, displays a high degree of similarity (CC ≥ 0.7) between the selected events, emphasizing clusters of events distributed across different time periods. By analyzing these clusters, we identified the similar events belonging to the June 2011 seismic sequence. The waveforms patterns and previous results [15] certify the tectonic origin of these events, which occurred close to the AV-SU fault (Fig. 1).

In addition to these events, two other clusters with a high waveform similarity were identified in January and June 2013 (Figs. 8, 9, 10). The epicenters of these events are placed close to a quarry located in Toplița city and also near a normal and strike-slip fault systems. Numerous seismic events occurred in this area during the selected time period, however the most of them occurred in 2013 (Fig. 11). The waveforms signatures for these events are close to those of tectonic events, with emergent P-wave onsets and extended seismic signal recordings (Figs. 1, 9). Despite the fact that their magnitudes are rather close ($2.1 \leq M_W \leq 3.1$), there is an event with magnitude larger than 3.0 which considerably diminishes the probability that these events have anthropogenic origins. Moreover, these events occurred at different times intervals during day and night providing another evidence in favour of their tectonic nature.

Figure 9 shows waveform patterns recorded during the June 2011 seismic sequence and both seismic sequences that occurred in 2013 (January and June). It is worth noting the complex signal patterns of these events, as well as the length of the seismic signal and the degree of similarity among the clustered events.

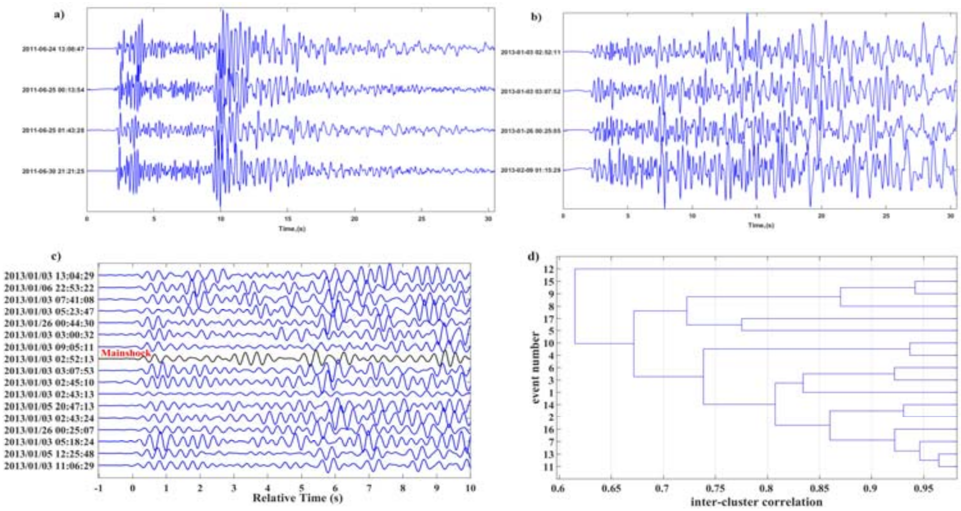

Fig. 9 – Examples of vertical seismograms recorded by the BUR31 station: a) during the June 2011 seismic sequence; b) during the January 2013 seismic sequence; c) Butterworth band pass (2–4 Hz) filtered waveforms recorded by the same station during the June 2013 seismic sequence; d) dendrogram computed based on CC showing the good similarity of these events.

We observed that the events generated in this region are not singular, over time being recorded several events in a very small spatial volume, resulting in clusters. To identify clusters of events with strong waveform similarity, we chose a threshold value of CC ≥ 0.8 and found 13 separate groups of at least two events. The epicenters distribution of these events is represented in Fig. 10, where each cluster is highlighted by a color code.

On the one hand, Fig. 10 emphasizes that a significant number of events occur near quarries, despite the fact that the signature of the waveforms and the time of occurrence assign them to a purely tectonic origin. We do not have information if these quarries were active over the selected time period (2005–2021), we just pointed out periodic increases in seismic activity in areas where the quarries are located near various fault systems.

On the other hand, concerning the location accuracy, it should be noted that in general, the events that form a cluster are closely distributed, highlighting a good location accuracy of the events recorded in the ROMPLUS catalogue, in agreement with the high similar waveforms (CC ≥ 0.8). At the same time, it can be easily observed that the clusters of several events or even several clusters distributed in the southwestern side of the study region are located close or in the extension of a normal and strike slip fault system (Fig. 10).

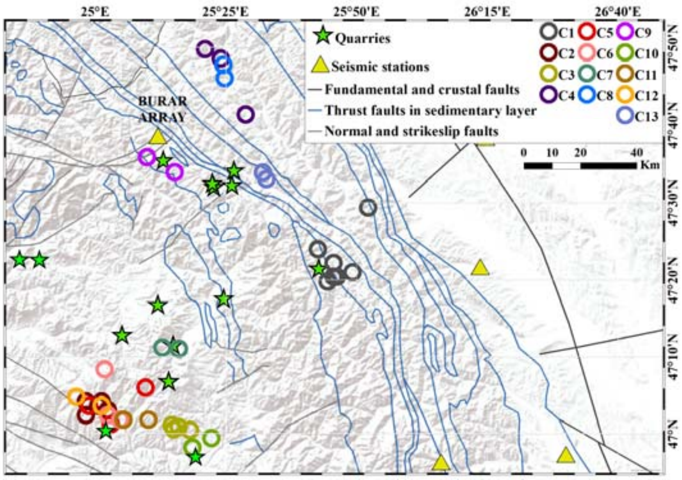

Fig. 10 – Map showing the distribution of clusters with high similar waveforms, the location of nearby seismic stations and quarries positions.

Following the waveform cross-correlation technique and visual analysis of the waveforms for three seismic events, we identified different patterns as compared with those displayed by the tectonic events and more similar to the ground truth event, shown in Fig. 2. Considering that these events occurred during working hours and days, the polarities of the first arrivals are always positive and the seismic signal is quickly attenuated, these events have the highest probability of being generated by anthropogenic activities (Fig. 11a).

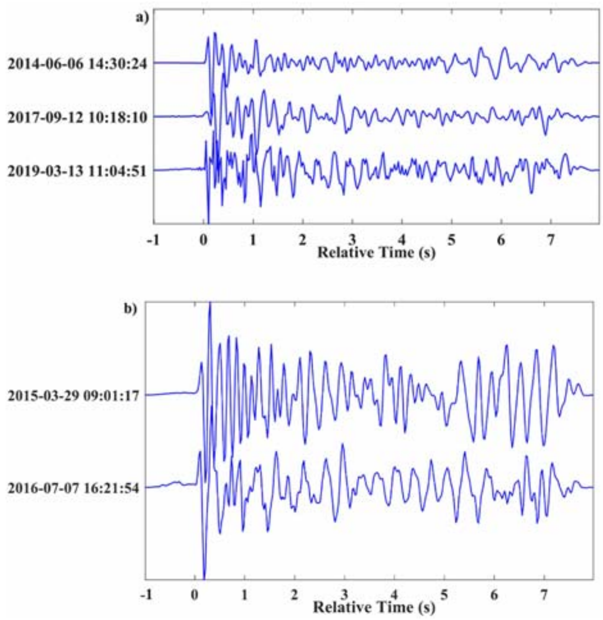

Fig. 11 – Examples of vertical seismograms recorded by the BUR31 and filtered with a Butterworth band pass filter between 2 and 4 Hz from events with potential anthropogenic origins: a) confirmed; b) rejected by statistical analysis.

Apart from these three potential anthropogenic events, another two were identified, presenting similar characteristics of the waveforms, but they occurred outside the usual working time (one during the working days, at 19:20 local time and another on Sunday during lunch time, at 12:01, local time, see Fig. 11b), which would practically reduce the above arguments. However, given the strong similarity between the waveforms patterns generated by these events and the ones generated by the ground truth event, there is a good probability that these events to have also anthropogenic origins.

4.3. EVENTS RELOCATION

The events were relocated with seismic phases manually picked and using the RONDC routine location algorithm (LOCSAT) incorporating 1-D Earth reference velocity model (IASP91), both integrated within the Antelope software. The results tend to be better clustered both horizontally and vertically (Fig. 12). For all initial locations marked with fixed depths, we have been able to determine precise depths as can be seen from low estimation errors (Fig. 13). Most of the relocated hypocenters are spread across the upper limit of the crust.

The accuracy of the initial and the relocated solutions were checked using the modified Wadati diagram and the results are shown in Fig. 14. Notice the smaller deviation from the fitting line for the measurements associated with the relocated events. Moreover, converting P- and S-waves travel time differences in velocity ratios, using equation (1) we estimated a medium V_p/V_s of 1.73 in case of the relocated events, which is similar with the V_p/V_s reference value [30].

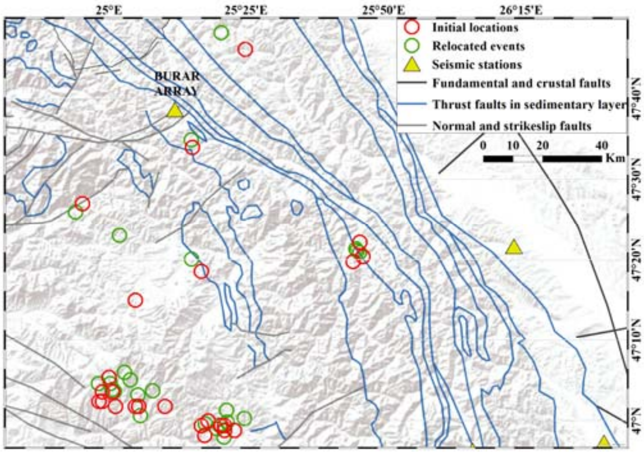

Fig. 12 – Map of the study zone (northeastern Romania), epicenters distribution of seismic events before and after relocation and nearby station distribution.

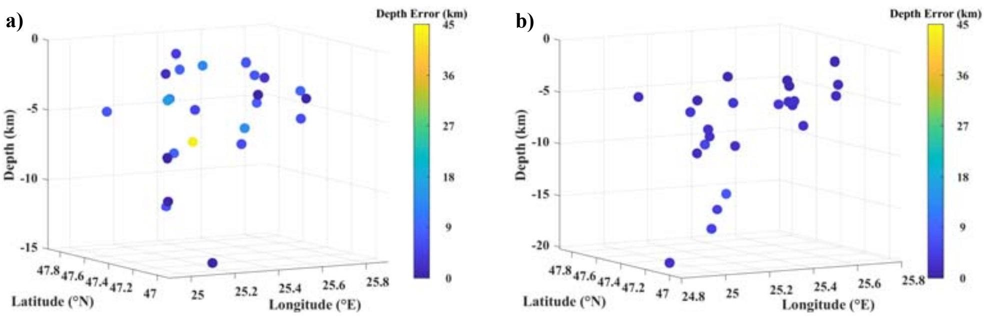

Fig. 13 – 3-D hypocenters distribution represented function of depth errors: a) before relocation; b) after relocation.

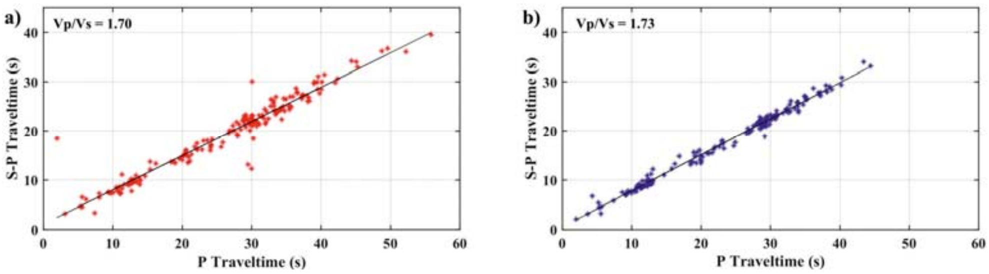

Fig. 14 – Modified Wadati diagrams determined for the events with significant depth errors: a) before; b) after relocation.

5. DISCUSSION

The analysis of the seismic activity in the north-eastern part of Romania reveals several significant patterns. The occurrence of tectonic events in the study region, which seems to be connected to crustal faults distributed around the quarries, is one of the peculiarities highlighted by our study. Our results are consistent with previous studies that analysed the earthquake sequence that occurred in the Bucovina region in June 2011 [15]. The existence of both tectonic and anthropogenic events was highlighted. The man-made events can be linked to various exploitations [4], a number of 16 quarries being identified in this region, based on previous research [4, 8]. However, it is uncertain how many of these quarries are still operational.

The statistical analysis of the 132 selected events from the ROMPLUS catalogue, which occurred between 2005 and 2021, reveals that a significant percentage of events (42.4%) occurred during working hours, and can be considered possible quarry blasts. Furthermore, numerous events have small magnitudes ($M_W < 3.0$), which could be additional evidence in favour of their anthropogenic origins [6]. Despite these arguments, significant increases of seismic activity are highlighted in January and June, which is atypical for events with predominantly anthropic sources. The application of the waveform cross-correlation technique revealed the existence of several seismic events with similar characteristics that are located around quarries and in the proximity of various fault systems (Figs. 10, 15). In connection with the statistical analysis results we identified events in the study area that show comparable patterns to both tectonic and anthropogenic sources. Three events were excluded from the waveform correlation analysis due to a lack of data (Fig. 14).

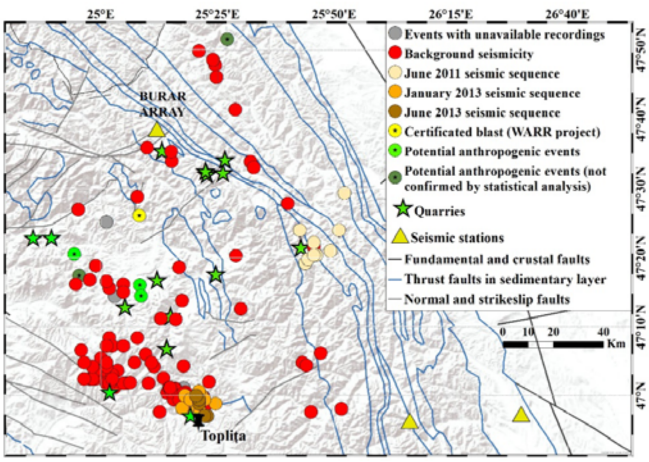

Fig. 15 – Map showing the types of seismic events identified by our results. The distribution of known quarries, seismic stations and the fault system according to [17] are also depicted.

Our results emphasize three events that are most likely to have anthropogenic origins. Another two seismic events that had waveforms similar to the ground truth event were identified, but occurred outside of working hours (Figs. 11, 15). Moreover, our findings highlight two additional seismic sequences, one generated in January and other one in June 2013. Their epicenters distribution shows that many of these events were located close to the Toplița city (Fig. 15). However, this area is characterized by increased seismic activity, which generates clusters of events with a high degree of similarity over time (Figs. 10, 15). It should be noted that the epicenters of these events are placed in the proximity of a quarry and between two normal and strike-slip faults systems, one oriented northwest-southeast and the other northeast-southwest (Fig. 15). The distribution of epicenters seems to be oriented northwest-southeast, which is consistent with the fault system direction. None of these events are large enough to determine a precise focal mechanism solution to correlates the direction of the fault planes with the orientation of the epicenters distribution.

6. CONCLUSIONS

By investigating the 132 events generated in the northeast of Romania between 2005 and 2021 using statistical and waveform cross-correlation analysis we were able to highlight new peculiarities related with the patterns of seismic activity. Our findings indicate that the selected events had primarily tectonic origins. The most intense seismic activity is distributed around Toplița city, where our results reveal clustered events with similar waveforms located at different depths mostly in the upper and middle crust. These were mainly small size events that occurred during 2013 at distinct time periods. Another sequence of earthquakes was identified in June 2011, consistent with previous research, highlighting the reliability of our results. The waveform cross-correlation analysis identifies 13 groups of events with $CC \geq 0.8$. Many of them are distributed in the regions where the seismic sequences were identified, suggesting that the earthquake triggering mechanisms occurred at various depths, but mainly in the upper crust.

The discrimination analysis identifies waveforms with unique properties. We were able to identify five events with comparable features based on their similarity to the waveforms generated by a ground truth event.

Increasing the number of seismic stations in this area will most likely result in a more comprehensive data set and more accurate determinations of seismic source parameters, providing crucial insights into earthquake triggering and tectonic processes along the edge of the Eastern European Platform.

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