Final Scientific Report of the Project

PN-III-P4-ID-PCE-2020-1361

(Analysis and Forecasting of ROmanian Seismicity)

AFROS

2021 – 2023

Competition:	**Exploratory research projects (PCE 2020)**
Contract no.:	PCE 119/2021
Project code:	PN-III-P4-ID-PCE-2020-1361
Research domain:	Earth Sciences
Title:	Analysis and Forecasting of ROmanian Seismicity
Acronym:	AFROS
Project start date:	04/01/2021
Project end date:	31/12/2023
Duration (month):	36
Total budged:	1.198.032,00
Source 1 State budget:	1.198.032,00
Source 2 Other sources attracted:	0 lei
Project website:	http://afros.infp.ro/
Coordinating institution:	National Institute for Earth Physics (INCDFP RA), Măgurele, Romania
Project manager:	Enescu Bogdan Dumitru

Project implementation plan

Record type	Phase name / Activity name	Act. type	Results	Reporting date
Phase 1	**Design and implementation of the algorithm for the investigation of intermediate depth seismicity in the Vrancea area**	-	● Increased expertise in seismicity analysis (including mastering ML techniques) of the 2 PhD students - training report; ● Web page creation	31/12/2021
Act 1.1	Forecast algorithm selection, description and software design	A1	● Subcrustal seismicity modelling and forecasting algorithms - research report;	31/12/2021
Act 1.2	Application, testing and calibration of forecasting algorithms	A1	● Estimation and forecasting of intermediate depth seismicity parameters - research report;	31/12/2021
Phase 2	**Design and implementation of the algorithm for the investigation of shallow, crustal seismicity in Romania**	-	● Increasing expertise in seismicity analysis of 2 PhD students - training report; ● 2 ISI papers and 2 conference presentations ● Website update	31/12/2022
Act 2.1	Forecast algorithm selection, description and software design	A1	● Subcrustal seismicity modelling and forecasting algorithms - research report;	31/12/2021
Act 2.2	Application, testing and calibration of forecasting algorithms	A1	● Estimation and forecasting of shallow, crustal seismicity parameters - research report;	31/12/2022
Phase 3	**Integration and implementation of the general forecasting algorithm**	-	● 2 ISI papers and 2 conference presentations; ● Explanatory flyers; web page updated	31/12/2023
Act 3.1	Integration of geophysical data into the forecasting system	A1	●Correlations between geophysical observations and seismicity - part of the final research report;	31/12/2023
Act 3.2	Building the virtual application architecture and aggregating seismic and geophysical data into the platform	A1	●Platform design for data visualisation and anomaly detection - part of the final research report;	31/12/2023
Act 3.3	Platform implementation		●Platform implementation - part of the final research report.	31/12/2023

*A1 – Fundamental research

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Note: A brief summary of the project for the public can be found on the project webpage in English and Romanian (links below), as well as in Appendix 11 and 12.

Romanian:
http://afros.infp.ro/proiect.php

English:
http://afros.infp.ro/proiect_en.php

1. Overview of the achievement of the project objectives, highlighting the results and degree of achievement of the objectives

The overall objective of the AFROS project was to analyse the seismicity of Romania, both for subcrustal, intermediate - depth (60 - 180 km) earthquakes from the Vrancea area, and for crustal, shallow depth (0 - 60 km) earthquakes throughout Romania, and to develop and implement algorithms for forecasting seismic activity for both types of seismicity. The first year of the project (Phase 1) focused on intermediate seismicity in the Vrancea area, while in the second year (Phase 2), efforts focused on crustal seismicity. In the third year of the project (Phase 3), the main objective was to integrate geophysical data into the forecasting system and to implement a virtual platform for seismicity forecasting.

As we will detail in the presentation of the scientific results for Phase 1, the main result of the first year was the implementation of statistical parameters for the analysis and forecasting of intermediate seismicity: the Z parameter (Z-value), the PI/RI parameters and the application of a new algorithm for separating background seismicity from aftershocks and preshocks. The Z-parameter has been calibrated so that it can be applied to detect possible precursor anomalies.

In Phase 2 of the project, the focus was on characterisation/prediction of crustal seismicity. On the one hand, PI/RI forecasting algorithms were developed and implemented for crustal earthquakes. On the other hand, the earthquake sequence in the Gorj region was analysed and a new algorithm for seismic aftershock forecasting was successfully implemented.

The activities in Phase 3 were the implementation of a monitoring system for various geophysical and seismic parameters and the definition of threshold values for the specification of a seismic alert. The project's virtual platform, which can be accessed from the project's web page, implements various analysis and forecasting algorithms, based both on real-time data and on the ROMPLUS earthquake catalogue, which is the definitive version of the list of earthquakes produced on the Romanian territory from 984 to date.

During the implementation of Phases 1 and 2 of the project, some difficulties were encountered with the quality of the ROMPLUS catalogue. In particular, some changes in the location of deep earthquakes and subtle changes in the magnitude scale were detected, which partly originated from changes in some location algorithms that occurred in 2014. This finding has launched an extensive effort to create a homogeneous earthquake catalogue, which is ongoing.

From the brief review above, we appreciate that the project has achieved all its major objectives, although the "road" has not been without its difficulties. In addition to the research outputs, we mention the training of PhD students (Phase 1 and 2), as well as the organising of numerous seminars with the invitation of researchers in the field to give presentations and trainings. A total of 13 ISI papers (journals registered in Web of Science, WoS) were published as part of the project. Members of the project have often been interviewed in national and international media, especially regarding seismic activity in Gorj. Activities started and carried out during the project will continue in the future, for example the application of machine-learning (ML) techniques for seismicity analysis.

2. Phase 1: Design and implementation of the algorithm for the investigation of intermediate depth seismicity in the Vrancea area

The first phase of the project was dedicated to the analysis and modelling of intermediate depth seismicity in Vrancea, as well as the development, calibration and application of forecasting algorithms. In the first phase several forecasting algorithms were tested (Act 1.1 activity), the algorithms that seem to give the best results were selected and the codes for subcrustal seismicity modelling were developed. The algorithms selected for the analysis and forecasting of subcrustal seismicity are Mc (magnitude completeness characterization of the data), as well as, for effective forecasting, the b-parameter (b-value from the earthquake frequency-magnitude relation), the Z-statistic test (Z-value), the Beta statistical test (□-value) and the PI, RI statistical tests. Extensive application and testing as well as calibration of the selected forecasting algorithms was done in the Act 2.2 activity.

First we briefly present the Z-value methodology, which is one of the methodologies tested for seismicity forecasting and a recent result (which can also be viewed on the project's Virtual Platform).

The Z parameter is a statistical parameter, which can be used to indicate a relative increase or decrease in the seismicity rate between two time periods; it is defined mathematically as follows:

$$Z = \frac{m_1 - m_2}{\sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}} \tag{1}$$

were,

- m_1 and m_2 represent the average earthquake rate for the two periods (W1 and W2) we want to compare;
- n_1, n_2 and s_1, s_2 are respectively the earthquake numbers and standard deviations for the 2 time periods.

The presentation of the variation of the Z parameter is shown on a depth section oriented SW - NE, through the Vrancea area. We present results only for the depth range of intermediate (sub-crustal) earthquakes. The aim is to detect depth ranges, which for certain time periods show anomalous activity that may be precursory activity.

The calculation algorithm to produce the "Z-value" depth sections is:

1. On a SW-NE section, all intermediate depth earthquakes in the Vrancea area (h ≥ 60 km) are projected, with M ≥ 3.0.
2. On the plane defined in (1), a grid is formed that has a distance between nodes of 5km x 5km, which covers most of the earthquakes in the section (see Figure 12 in the 2021 project report). (2021 report: http://afros.infp.ro/documente/raport_AFROS_2021_RO.pdf).

3. For each network node, the nearest 100 earthquakes are selected for the calculation of the Z parameter.
4. The Z parameter is calculated, for each node, using the above formula.
5. The Z parameter values are interpolated to create the figure showing the distribution of the parameter along the section, by depth (Figure 13 in the 2021 report).

A positive value of the Z parameter (warm colours on the map) represents a relatively low seismicity in the W2 window compared to W1, while a negative value (cold colours on the map) represents an activation of seismicity in the W2 window compared to W1. The W1 window is variable and will be defined here from the year 2004 until the time the W2 window starts. Ideally, a longer W1 window gives a better approximation of the background seismicity, but other variants (e.g., fixed length W1 window can also be considered). The W2 window extends from the time for which the Z parameter is determined and has a defined length of 1.5 years. We call the W1 window the background seismicity window, and the W2 window the monitoring window. The values of the Z parameter have the same interpretation in terms of statistical significance as the number of standard deviations from the mean value for a normal distribution. The displayed cross-sections have been calculated every three months since 2020.

Based on previous studies and our own investigations, values of the Z-parameter in absolute values greater than 5.0 are considered anomalous. In particular, large, positive values have been associated with precursor seismic gaps (e.g., Enescu et al., 2001).

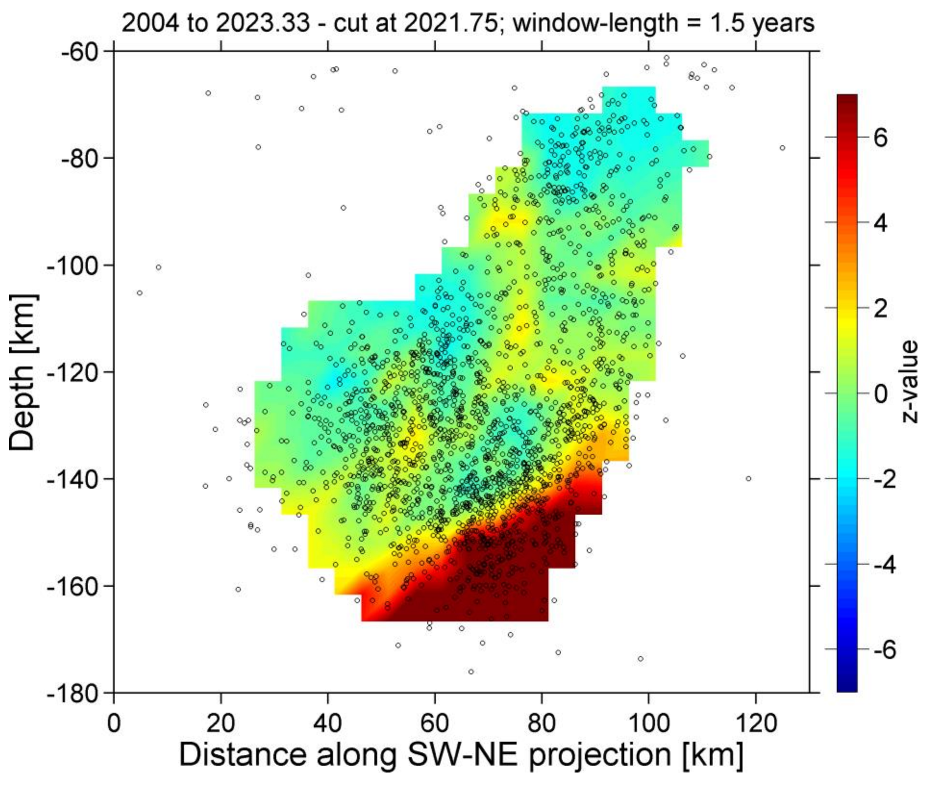

Figure 1. Vertical section through the Vrancea area, showing the variation of the Z parameter, for subcrustal seismicity (H < 60 km). For explanation, please see the text above, as well as the virtual platform documentation. The W2 window extends from October 2021 to March 2023.

As an important note, the high values (Z > 5.0) (red color on section) observed at depths below ~140 km are related to some changes in the earthquake location method that took place in 2014 (see 2021 project report).

Based on such sections, maps or graphs, we can state that we are currently not in an anomalous (medium-term) seismic period.

Un al doilea rezultat, este legat de variația unui alt parametru statistic, beta-value (β-value), pe care deasemenea l-am investigat ca posibil parametru care poate detecta activările si lacunele de seismicitate (prezentate in lucrarea Enescu et al., 2023), pentru seismicitatea subcrustala din Vrancea.
A second result is related to the variation of another statistical parameter, beta-value (β-value), which we also investigated as a possible parameter that can detect seismicity activations and gaps (presented in Enescu et al., 2023), for subcrustal seismicity in Vrancea.

The quantification of seismicity rate changes based on the beta-value statistic is sensitive to the difference in average seismicity rates over two time periods and is defined as follows:

$$\beta = \frac{N_a - NT_a/T}{\sqrt{N(\frac{T_a}{T})\,(1 - \frac{T_a}{T})}} \quad (2)$$

where N is the number of earthquakes in the seismic background window, T, and Na is the number of events in a time period of interest, Ta. The background window, T, covers the entire period of the analyzed dataset except Ta; the window Ta, chosen here as 1.5 years, is shifted over the entire period with a 14-day step. The choice of Ta = 1.5 years is somewhat arbitrary; we avoided choosing long windows that would not be sensitive to relatively short but significant increases or decreases in the seismicity rate, as well as windows that are too short and may reveal only very local fluctuations in seismicity. To estimate the statistical significance of the beta values obtained, we simulate 10,000 random sets of earthquakes, with the same time intervals and number of events as the real data, and estimate the beta values in the same way as for the real data set. The beta values obtained for the random earthquake catalogues follow a normal distribution. The statistical significance of the beta values obtained for the real data is interpreted in terms of deviations from the mean of the normal distribution.

Figure 2 shows the variation of the beta parameter as a function of time for the period 1960 to 2000. Parameter values are plotted at the end of the 1.5 year window. It can be seen that the most prominent negative beta value, indicating a relative decrease in seismicity, started around 1970 (with a minimum value of -3.1 reached in early February 1971) and continued until the time of the M7.4 Vrancea earthquake in 1977, when the parameter started to increase sharply. The highest positive beta value (of +6.81), was recorded in January 1988, in a window (of 1.5 years) including the M7.1 Vrancea earthquake of 30 August 1986. The negative value is interpreted as a precursor anomaly to the 1977 earthquake, and the positive value is due to aftershock activity after the 1986 earthquake.

The statistical significance of relative seismicity decreases and increases was evaluated using random earthquake simulations, as explained in the previous paragraph. The results are shown in Figure 3. Seismicity decreases marked Q1 and Q2 precede the occurrence of the March 4, 1977

Vrancea earthquake (M7.4) and are significant at the 95% confidence level (with some parts being significant at even higher confidence levels). The seismic activities marked A1 and A2 in the same figure correspond to aftershock periods that occurred after August 30, 1986 and May 30, 1990, when two large earthquakes occurred in the Vrancea area.

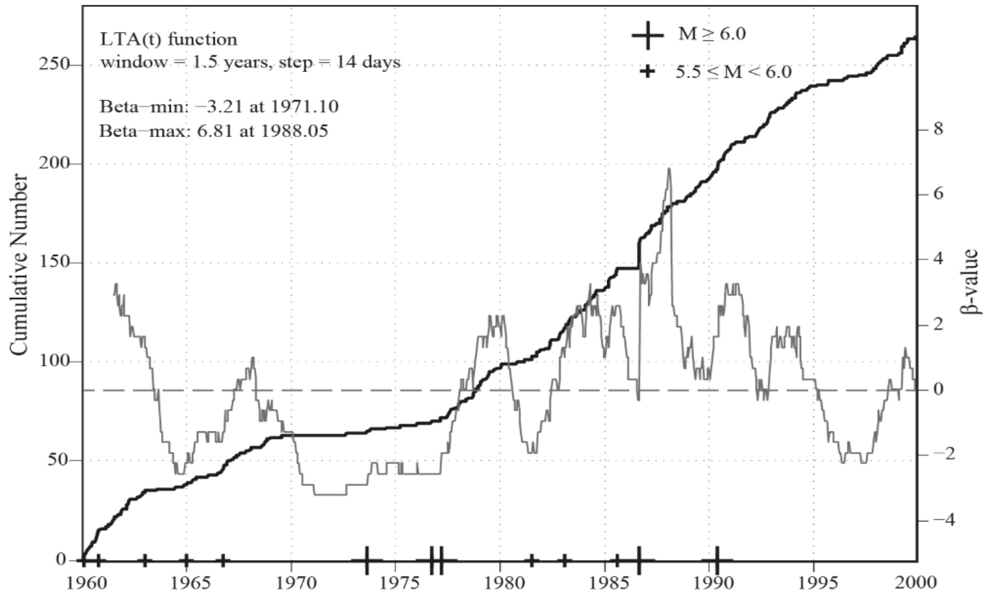

Figure 2. Cumulative number of earthquakes (black line) and beta value variation (LTA(t) function, grey line) for intermediate depth earthquakes in Vrancea ($M \geq 4.0$), as a function of time (range 1960 - 2000). Large and small crosses on the time axis indicate events with magnitudes $M \geq 6.0$ and $5.5 \leq M < 6.0$, respectively.

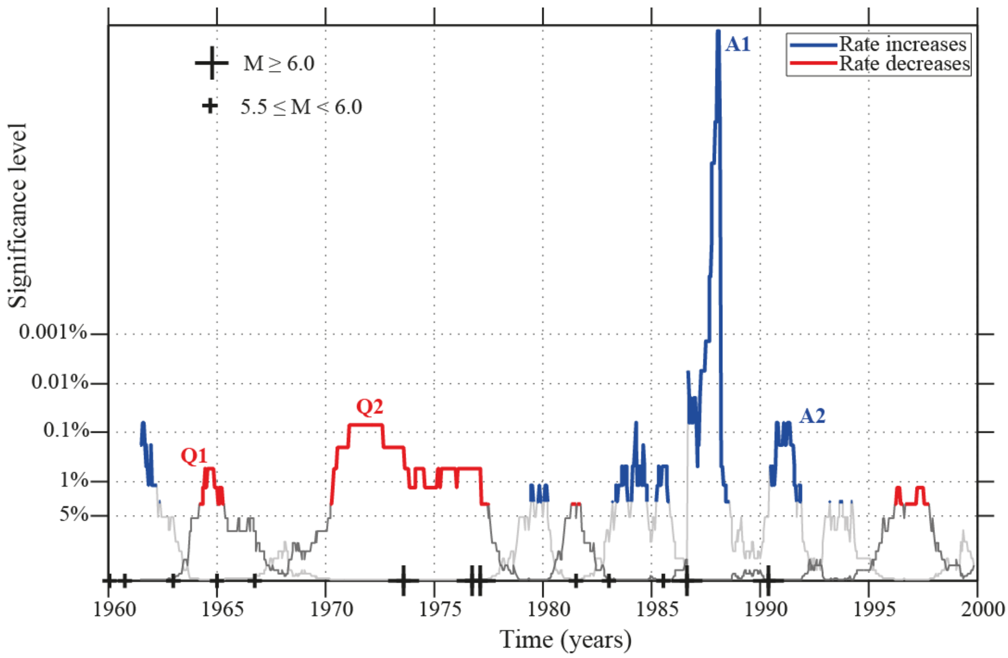

Figure 3. Significance of seismicity rate that increases and decreases for intermediate depth earthquakes in Vrancea ($M \geq 4.0$, 1960 – 2000). The blue and red colours indicate windows of increasing and decreasing seismicity rates, respectively, which have significance levels below 5% (confidence levels above 95%).

The beta parameter, presented above and applied in the recently published paper, Enescu et al. (2023), is also considered for monitoring, both as a function of time and space.

Among the results with relevance for this stage we include the dynamic triggering (due to the stress caused by the passage of seismic waves) of an earthquake of magnitude $M_L3.1$ in the Vrancea area (Appendix 1; Petrescu et al., 2023). These studies were carried out during Phase 3, after the earthquake generated in Turkey on 5 February 2023 triggered the earthquake in the Vrancea area. Monitoring induced earthquakes is also important for seismic hazard and forecasting.

3. Phase 2: Design and implementation of the algorithm for the investigation of shallow, crustal seismicity in Romania

Similar to Phase 1, in the first activity (Act 2.1) of Phase 2 several forecasting algorithms were tested, the algorithms that seem to give the best results were selected and codes for subcrustal seismicity modelling were produced. The algorithms selected for the analysis and forecasting of subcrustal seismicity are Mc (magnitude completeness characterization of the data), as well as, for effective forecasting, the b-parameter (b-value from the earthquake frequency-magnitude relationship), the PI statistical tests, RI, the ETAS model and another algorithm for seismic aftershock forecasting.

We mention here in detail two results that we consider notable for Phase 2. These are the implementation of the PI algorithm (PI index) for seismicity anomaly detection (Tiampo, Klein and Enescu, 2023; Tiampo and Enescu, 2023, paper in preparation) and another algorithm, for seismic aftershock forecasting (Ghita et al., 2023, Appendix 2), which was recently implemented on one of the most important seismic sequences in Romania, the Gorj 2023 sequence.

The **PI index** is calculated in seismic active areas for magnitudes greater than the completeness magnitude. The area of interest is divided using a gridding technique (similar to the calculation of the spatial variation of the statistical parameter Z) into several rectangular boxes (sub-areas). The method defines the seismicity rate, $\psi_{obs}(x_i,t)$, as the number of earthquakes per unit time (one year in our case) in a box with location x_i, at time t. The average seismicity represented by the function $S(x_i,t_0,t)$ over the interval $(t - t_0)$ is given by the relation:

$$S(x_i, t_0, t) = \frac{1}{(t - t_0)} \int_{t_0}^{t} \psi_{obs}(x_i, t)\,dt \,. \tag{3}$$

$S(x_i,t_0,t)$ is computed for N locations and t_0 is a fixed time, such as the beginning of the catalog. Noting the spatial averages for N boxex cu <>, the phase function $S'(x_i,t_0,t)$ is defined as the zero-mean unit norm function obtained from $S(x_i,t_0,t)$:

$$S'(x_i, t_0, t) = \frac{S(x_i, t_0, t) - < S(x_i, t_0, t) >}{\| S(x_i, t_0, t) \|} \,, \tag{4}$$

where || S(xi,t0,t) || is the square root of the variance for all boxes. The function defined above can be used to calculate the temporal and spatial changes in seismicity, between 2 time points, t_1 and t_2: $\Delta S'(x_i,t_1,t_2) = S'(x_i,t_0,t_2) - S'(x_i,t_0,t_1)$. The average of the values of $\Delta S'(x_i,t_1,t_2)$ for all possible values of the base year, t_0, is obtained. Finally, the PI index, ΔP, is obtained as: $\Delta P(x_i,t_1,t_2) = \{\Delta S'(x_i,t_1,t_2)\}^2 - \mu_p$, where μ_p is the spatial average $\{\Delta S'(x_i,t_1,t_2)\}^2$.

Figure 4 exemplifies the application of the PI algorithm for a relatively long term period of 5 years (the periods tested were 5 and 10 years) throughout Romania, including the Vrancea area, over the full depth range. The learning period extends over the period 1981-1985 and the forecasting period over the period 1986-1990. The earthquakes considered were those with magnitudes greater than 4.0. From the figure we can see anomalies (red colours, values between -0.5 and 0) associated with the Vrancea area. Indeed in the period 1986 - 1990 two strong earthquakes of magnitudes M7.1 and M6.9 occurred in the Vrancea area. From the figure it can be seen that although some anomalies (yellow colours) in the crustal domain are present, they have relatively low intensities. Indeed, during the period in question, no earthquake of significant magnitude occurred on the Romanian territory, in the crustal depth zone.

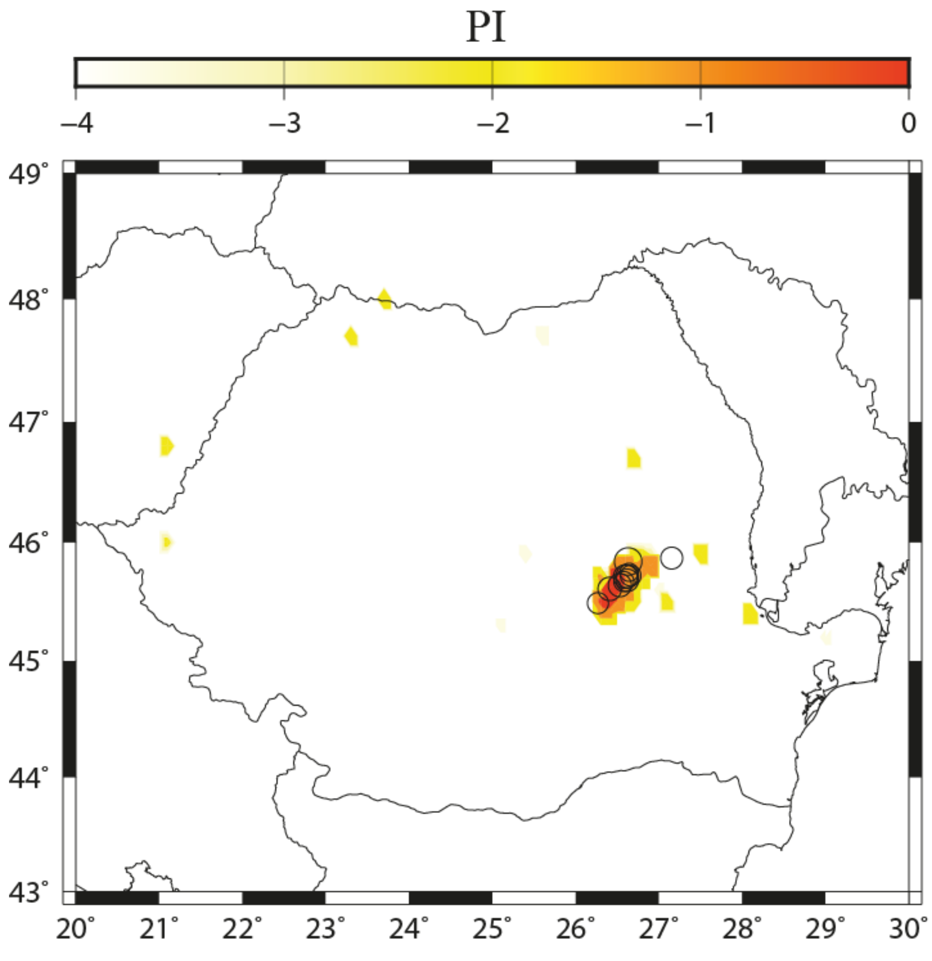

Figure 4. Variation of the PI parameter over Romania in the forecast period 1986-1990 (learning period 1981-1985). The circles represent earthquakes with magnitude greater than 4.0 produced in the period 1986 - 1990.

A few comments are necessary:

1) The anomalies in the subcrustal zone are significant and define a relatively large area compared to crustal anomalies, which are much less intense and local.

2) The earthquakes generated in subcrustal regions generally have smaller magnitudes and considerably longer recovery times than those from Vrancea. Therefore, for crustal earthquakes, one can only make long-term (5, 10 years) forecasts based on seismic data.
3) It is expected that geophysical data (Phase 3) will bring improvements in terms of the forecast window, in other words to make medium- and short-term forecasting possible.
4) For the moment, no significant crustal and subcrustal anomalies have been detected over Romania.

Seismic aftershocks are a considerable hazard and, as the sequence in Gorj county showed, can create anxiety, discomfort, even panic, among the population. Therefore, an integral component of the project aimed to develop a methodology for seismic aftershock forecasting.

In the present study (Ghita et al., 2023, paper submitted for publication; Appendix 2) we analysed crustal earthquake sequences in Gorj county from 2023 and in the Vrancea-Mărășești area from 2014 (Figure 5). In both cases, the main shock had a moment magnitude, Mw, of 5.4 (local magnitude, M_L, of 5.7).

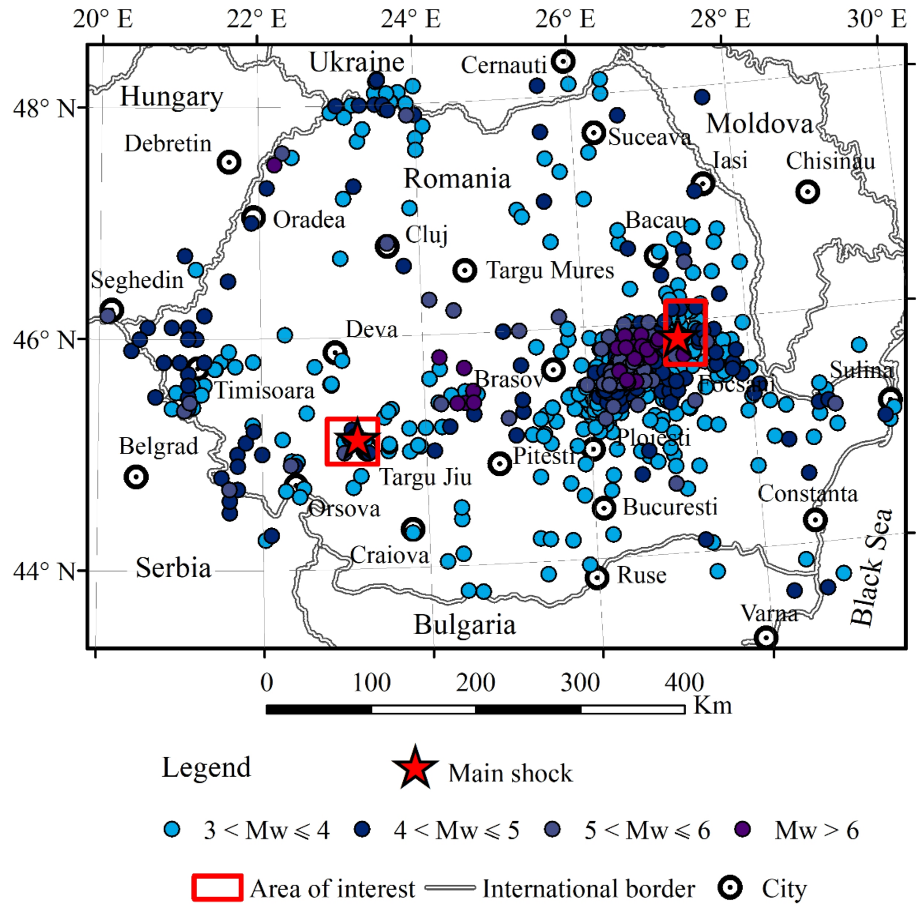

Figure 5. Seismicity of Romania (period 1000 - 2023), with Mw > 3.0. The rectangles mark Vrancea-Mărășești (east) and Gorj (south-west) areas. The catalogue period is 12.05.1022 - 26.10.2023. In this report we discuss only the Gorj sequence (both sequences are discussed in Appendix 2).

The data processing consisted in the estimation the parameters of Omori-Utsu law and of the aftershock probabilities. The methods used are briefly described below.

The Omori-Utsu law (e.g., Utsu et al., 1995) is an empirical relationship that describes the decrease in the aftershock rate following a mainshock, as expressed by the formula:

$$N(t) = \frac{K}{(t+c)^p} \tag{5}$$

where N(t) is the aftershock rate function of time t (in days) after the main shock, while K, c and p are earthquake sequence dependent parameters.

The above formula can be used to calculate the rate of aftershocks of a certain magnitude:

$$\lambda(t, M) = \frac{K}{(t+c)^p}\beta e^{-\beta(M-M_0)} \tag{6}$$

where the parameter M_0 is the magnitude of the mainshock and the value β is related to the value of the parameter "b" in the earthquake frequency-magnitude distribution (Gutenberg şi Richter, 1944). The probability of seismic aftershocks (and thus their forecast) is calculated by a Bayesian method (Omi et al., 2019), based on the Omori-Utsu models and earthquake frequency - magnitude. We present below our estimates for the Gorj county sequence. Figure 6 shows the seismic sequence in the Gorj area.

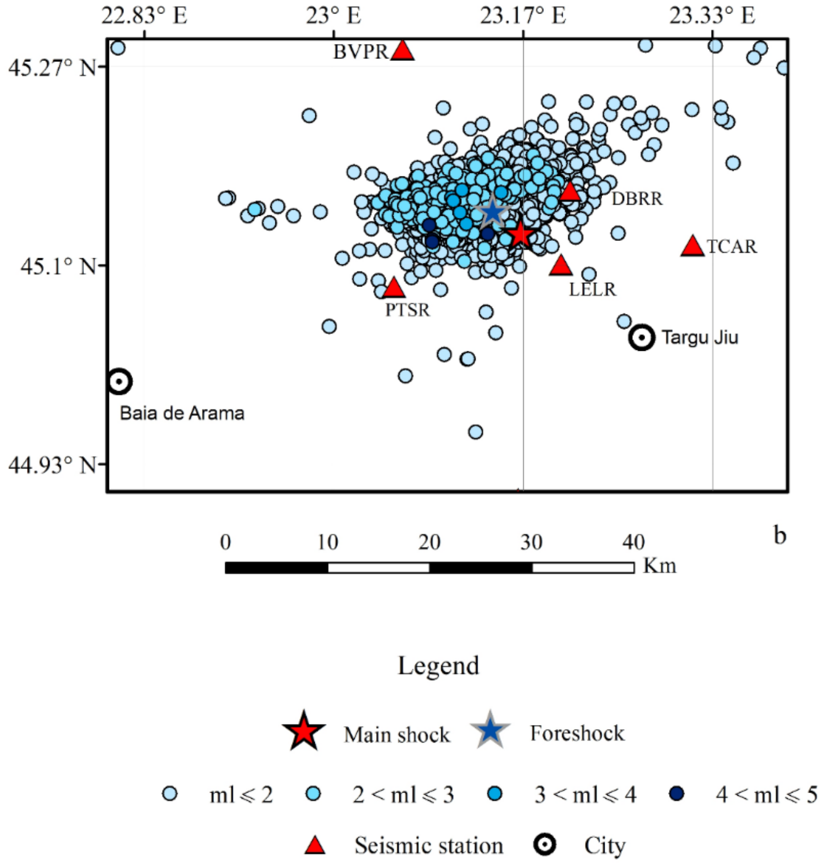

Figure 6. Seismic sequence in Gorj county, recorded in February 2023 (main shock, Mw 5.4).

We present in Figure 7a the evolution of the cumulative number of aftershocks of the sequence as well as the seismic forecast. Figure 7b shows the frequency-magnitude relationship forecast and the actual observed data.

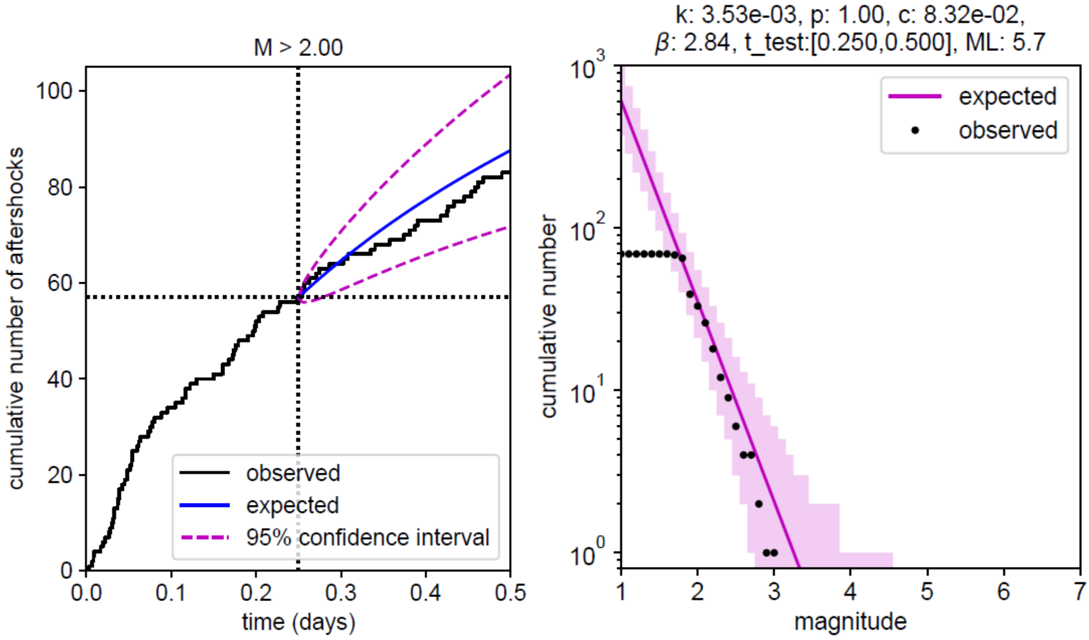

Figure 7. a) Cumulative aftershock forecasts for the Gorj area: expected values (blue) versus observed values (black) for the forecast period [6h, 12h], with learning period [0, 6h] after the main shock. Dotted pink lines indicate the confidence interval; b) Frequency-magnitude relation for the Gorj sequence. The values of the Omori-Utsu law parameters and the estimated β-value during learning are specified above the plot.

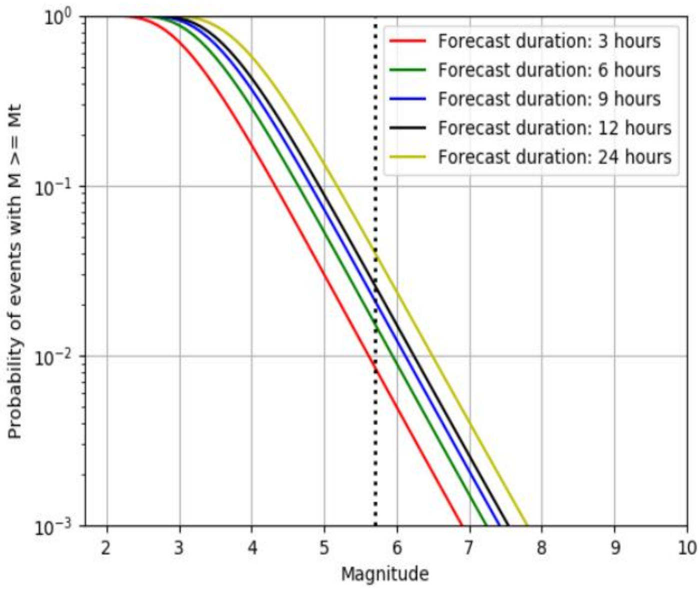

Figure 8. Probabilistic predictions of aftershocks as functions of magnitude for the Gorj sequence with a learning period of 6 hours after the mainshock. Forecast periods vary from 3 to 24 hours after the learning period. The vertical dashed line represents the magnitude of the mainshock, while Mt represents the magnitude value.

Figure 8 shows the probabilities of seismic aftershocks as a function of magnitude for different prediction intervals. Such graphs can be used to make specific forecasts: for example, the probability of an earthquake with a magnitude equal to or greater than that of the main shock (Mw 5.4), between 6 and 9 hours after the main shock (red curve in Figure 8), is about 1%, so extremely low. On the other hand, the occurrence of an earthquake with magnitude greater than or equal to 4.0, between 6 and 9 hours, is about 20%.

Another approach to the Gorj earthquake sequence, using the ETAS seismicity model, is presented in Appendix 3 (Ghiță et al., 2023, work in preparation).

The sequence of earthquakes in the Gorj region is also the subject of Appendix 4 (Radulian et al.), in which the significant intensification during 2023 of seismic activity in the crustal part of the Southern Carpathians (contact zone with the Getic Plateau) and in Banat (in the northern part, the Zarand Depression) is analysed. As the authors show, this increase in seismic activity in the western part of Romania can be traced as starting after 2010. As the authors conclude, "the intraplate seismicity recorded in recent years in different areas in the western part of Romania has drawn our attention to the potential of moderate to large earthquake generation in these areas, as also predicted in previous works (Radulian et al., 2019; Bala et al., 2020; Oros et al., 2021). Therefore, it is necessary to reconsider the definition of seismogenic zones and associated characteristic parameters in this part of the country and to adjust the regional seismic hazard according to the new recorded data."

Also relevant to crustal earthquakes is the study carried out by Borleanu and collaborators (Appendix 5), in which the explosion contamination of the Romanian crustal earthquake catalogue is analysed and discrimination techniques for explosions and earthquakes are proposed to improve the quality of the ROMPLUS catalogue.

Finally, Poiata and collaborators (Appendix 6) propose techniques to revise the ROMPLUS catalogue, in particular an extended flow testing methodology for M_L magnitude estimation, using an extended dataset of Vrancea earthquakes and the first days of the Gorj county earthquake sequence. The technique for data homogenization, proposed by Zheng, Enescu, Zhuang and Yu (2021), is currently being tested as an alternative homogenization possibility for the ROMPLUS catalogue.

4. Phase 3: Integration and implementation of the general forecasting algorithm

In this section, we present the results related to the variation of some geophysical fields in relation to the seismic activity on the Romanian territory, the integration of the various data into a general forecasting algorithm (Act 3.1 activity), as well as the construction and implementation of the forecasting algorithm in the virtual platform (3.1 and 3.2 activities*). Note that the results of Phase 3 are not presented in a separate report (as this is not required in the final phase), but as an integral part of this final report, as well as in the mentioned appendix.* We first present results related to **magnetic field variation** as a potential precursor of earthquakes (these results are presented in detail in Appendix 7 and in the paper Mihai et al., 2023).

Geomagnetic precursors refer to variations in the Earth's magnetic field that are anomalous in nature, which occur before an earthquake and have no other known cause (e.g. a magnetic storm).

Although the relationship between geomagnetic anomalies and earthquakes is not yet fully understood, some studies suggest that certain geomagnetic field disturbances are associated with the run-up to an earthquake and may serve as precursors to seismic activity. Among the anomalies that have been reported to have a premonitory character, we mention emissions in the ULF (ultra-low frequency) and VLF (very low frequency) frequency bands.

Correlations between magnetic field variations and seismicity were made on seismic data from intermediate depth earthquakes in the Vrancea area between 2014 and 2023. Geomagnetic data were recorded at Muntele Roșu as the primary station and at Surlari National Geomagnetic Observatory (USA) as the reference station unaffected by moderate earthquake preparation processes. We assumed that the area of effective manifestation of precursor deformations is a circle with radius taken from the equation of Dobrovolsky, 1979. Geomagnetic indices were retrieved from NOAA (USA) and GFZ (Germany) and were used to separate global magnetic variation, such as magnetic storms associated with solar activity, from possible local seismo-electromagnetic anomalies that might occur in the preparation zone of an earthquake generated in Vrancea.

In addition to the geomagnetic field, geomagnetic indices and seismicity, the temporal variation of seismic velocities was also studied using MLR station records. We used the Phenomenal platform (https://ph.infp.ro/seismicity/data) to download the data (more information in Placinta et al, 2022), and the seismic energy released during the anomalies observed on the By. Seismic energy release in the Vrancea area was calculated only for medium depth earthquakes with Mw>3. As methods for the analysis of magnetic data we highlight the polarization method, the diurnal variation method and the direct visualization method. We present below, in Figure 9, results obtained by the direct visualization method. From this figure it can be seen that:

(i) all earthquakes occurred during periods of minimum solar activity, (ii) all magnetic storms have significant signatures on all three records, (iii) on the EV component (By) we have a common anomaly at MLR, except that this type of anomaly does not occur consistently before earthquakes, (iv) the NS Bx horizontal component and the Bz vertical component were perturbed by -200nT and -400nT respectively compared to the monthly average on 16 August, in a period with minimum Kp, 45 days before the first earthquake. Since the time to the earthquake is too long compared to that specified in the literature, we tend to associate this anomaly with one due to human intervention or to a deficient digitizer operation due to a electrical spike.

From all these representations (Figure 9 and Appendix 7) we can conclude that the direct visualization method did not identify any anomalous signals that could be related to the three earthquakes. However, it remains open the possibility that there were signals at other frequencies higher than 0.01Hz, namely at 0.1Hz, or even at 1Hz (one recording per second). Unfortunately, the digitizers used in the past did not allow us to record data more often than once per minute. Today we have high-performance equipment that allows us to record more often and to continue studies in different frequency bands.

Figure 9. From top to bottom: visualization of magnetic data Bx, By and Bz and index Kp from June 26, 2016 to February 28, 2017. The stars show the three Vrancea earthquakes produced during this period.

We also investigated the magnetic field variation with the seismic energy released daily by earthquakes in Vrancea, calculated using the formulas in Appendix 7. Figure 10 shows the results.

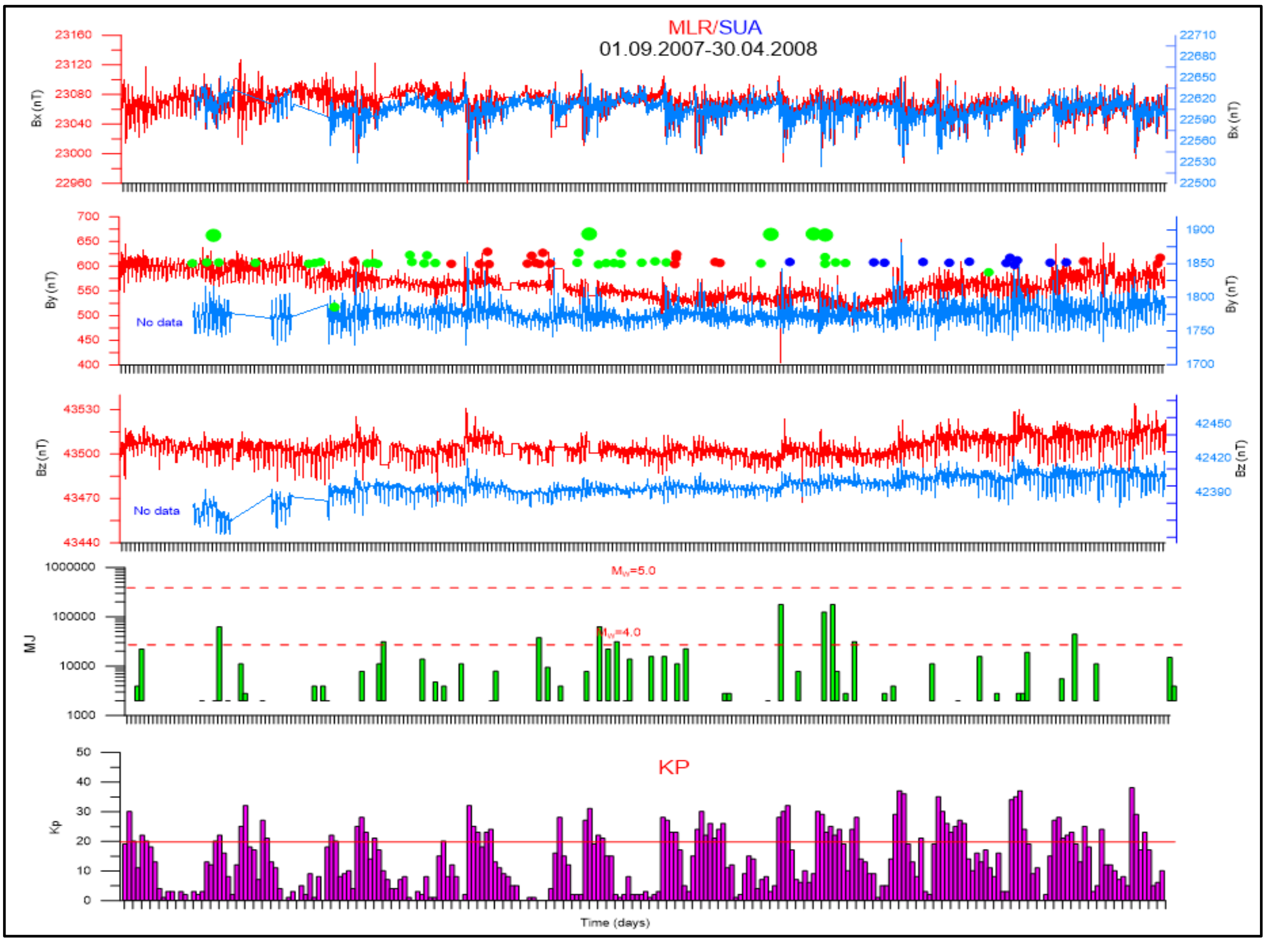

Figure 10. Representation of the three geomagnetic field components (Bx, By, and Bz) measured at Muntele Roșu (MLR, with red) and Surlari (USA, with blue). The green histogram represents the daily released seismic energy, and the purple histogram represents the sum of the Kp indices.

It has been observed that the magnitude of geomagnetic anomalies varies from year to year, as does the seismicity. The variability measured on the By component was revealed by calculating the standard deviation for each anomaly recorded on the horizontal By component of the geomagnetic field. Solar activity, in particular solar flares and coronal mass ejections (CMEs), can have a significant impact on the Earth's geomagnetic field. An efficient way to quantify these variations in the By component is to calculate the standard deviation on the geomagnetic data sets. This method has been applied to the MLR station (Muntele Roșu), but also to the US station (Surlari), which is used as a reference station. As shown in Figure 11, there is no clear relationship between the measured standard deviation values on the By component at Muntele Roșu and the seismic energy released over the whole anomaly period. Indeed, the maximum and minimum standard deviation values coincide with the minimum and maximum energy, but there is no proportionality between them. Normally the standard deviation values obtained at Muntele Roșu (MLR) and Surlari (USA) should be similar, being influenced by solar activity, with high values for periods of high solar activity and low values for periods of low solar activity. However, as shown in Figure 11, these values do not coincide, indicating the possible presence of a seismotectonic factor. However, we cannot rule out the possibility that the seasonal anomalies recorded at Muntele Roșu are caused by a "thermal drift" or have an anthropogenic cause.

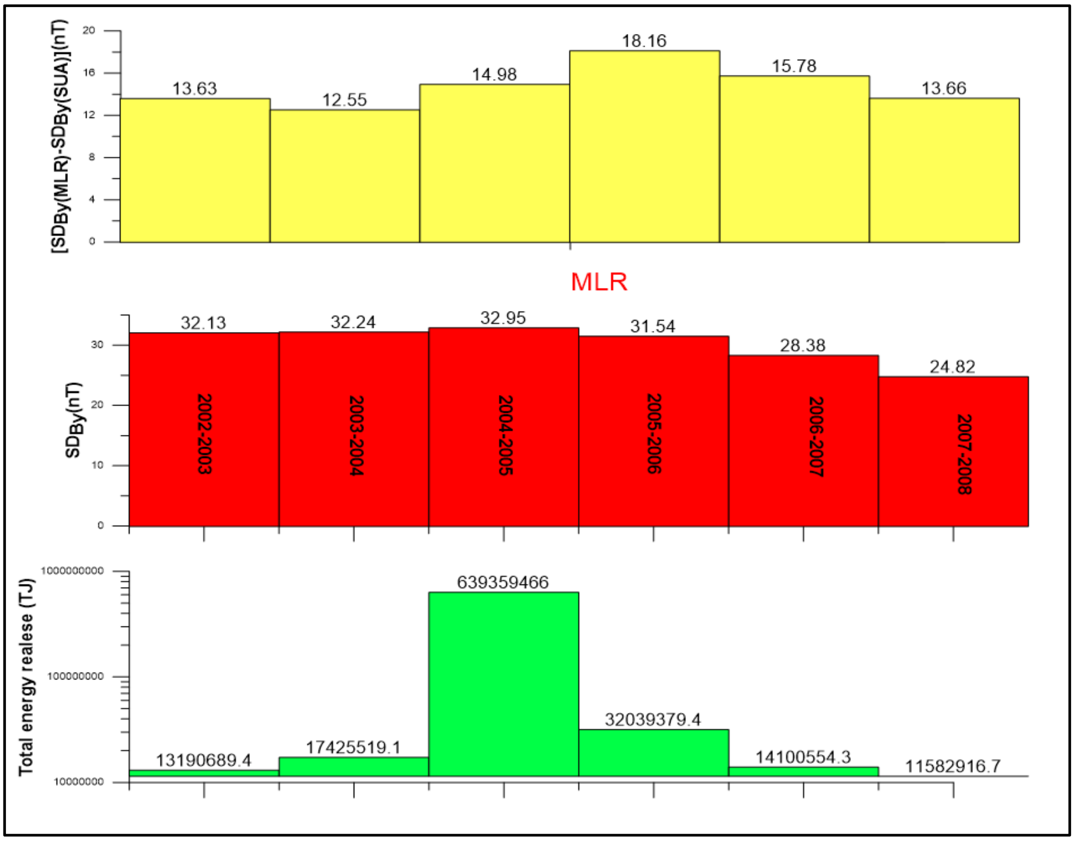

Figure. 11. Standard deviation measured on the By component at MLR (red) and USA (yellow) and cumulative seismic energy for each recorded anomaly (green).

The results clearly indicate a higher variability on the By component measured at Muntele Roșu, but to identify the cause of this variability, geomagnetic data must be correlated in a multidisciplinary way with weather data to eliminate possible thermal variation of the instrument. In the future, this method will be applied on a consistent data set (20 years) and Pearson correlation indices between the released seismic energy and the magnitude of the standard deviation values measured on the By component of the magnetic field will be calculated. These indices will also be calculated for the weather factors: external tunnel temperature, internal tunnel temperature and MLR tunnel humidity.

Below, we present results obtained from the correlation of some **geophysical parameters characterizing gas emissions with the production of earthquakes** (for more details, see Appendix 8 and Toader et al., (2021, 2023)).

INCDFP has developed an Operational Earthquake Forecasting (OEF) application (Toader et al., 2021) in which geophysical parameters are correlated with short-term changes in seismicity using an amplitude-frequency relationship. Mainly the results indicate gas emission (radon and CO2) as seismic precursors. For the seismicity the evolution of parameters a and b of the Gutenberg-Richter law (GR a-b) was considered. We observed that a decrease over a period longer than 18 days of the parameter 'b' of the Gutenberg-Richter law (GR_b) is followed by earthquakes with magnitude greater than 5R (magnitude on the Richter scale) for the Vrancea area (Toader et al., 2023).

Data analysis involves integrating the signals and applying a STA/LTA (Short-Term-Averages/Long-Term Averages) algorithm to the result. An example for the 5.3R earthquake of 2022/11/03, 04:50:25 UTC (Gura Teghii area) is shown in Figure 12, where we have the time series of radon and CO_2 at 3 stations located in the epicentral area.

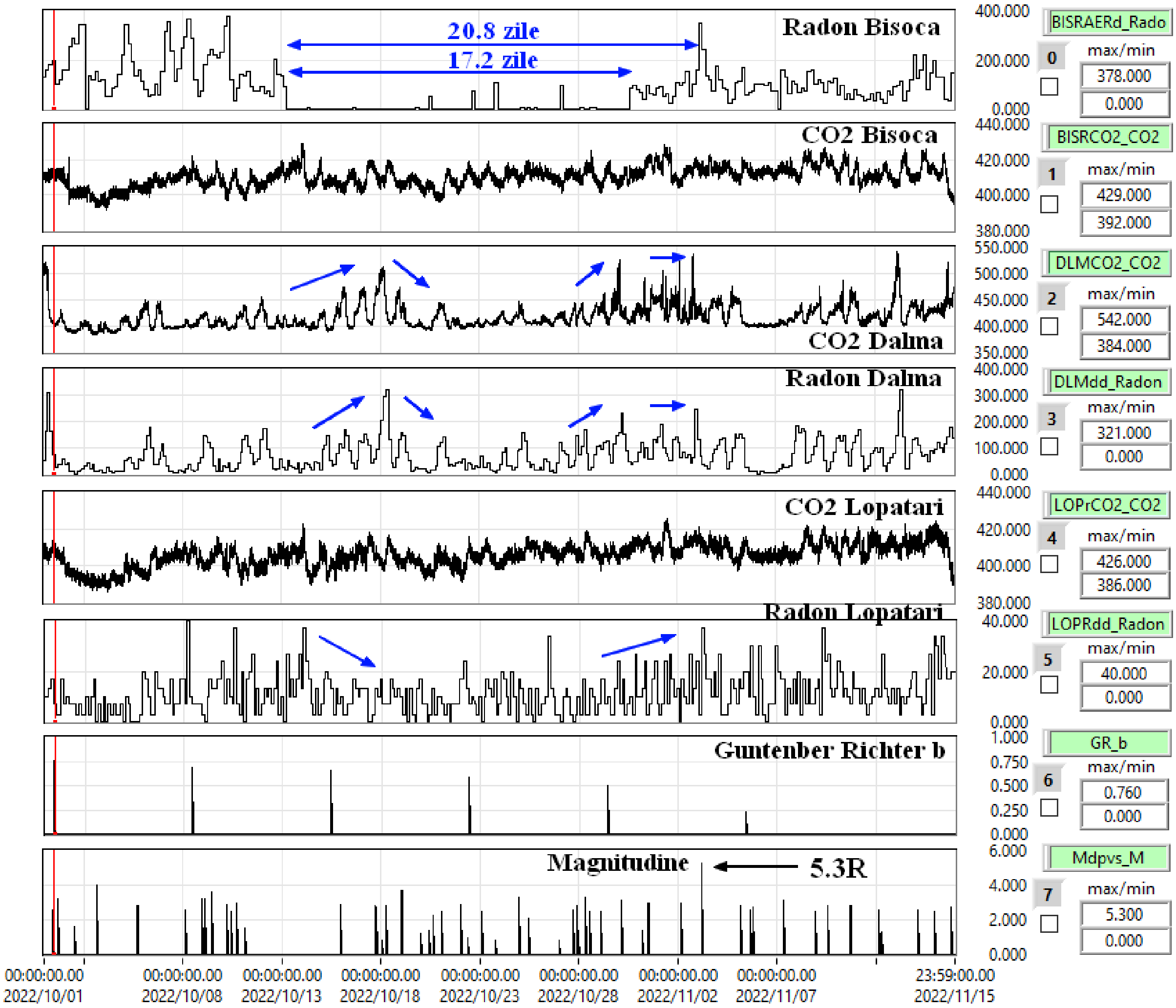

Figure 12. Vrancea earthquake, magnitude 5.3R (Richter scale), time series seismic precursors: radon, CO_2, GR-b, plotted with magnitude as a function of time.

A particular feature is the decrease in radon levels over a period of about 20 days, in Bisoca area. This happens rarely and can be explained by deformation of the ground in the area, which closes the pores through which the gas is emitted. In the same period of time we have disturbances in Dâlma (DLM) but less evident in Lopătari (LOPr) which was closest to the epicentre. The GR_b parameter decreases before the earthquake but a longer time window is needed to determine it.

By integrating the radon and CO2 time series we obtain Figure 13. And in this case the time interval between the peak of radon in Bisoca (BISRAER) and the occurrence of the earthquake is about 20 days. Application of an STA/LTA detection algorithm (Figure 3.1.3, Appendix 8) indicates an interval of about 12 days.

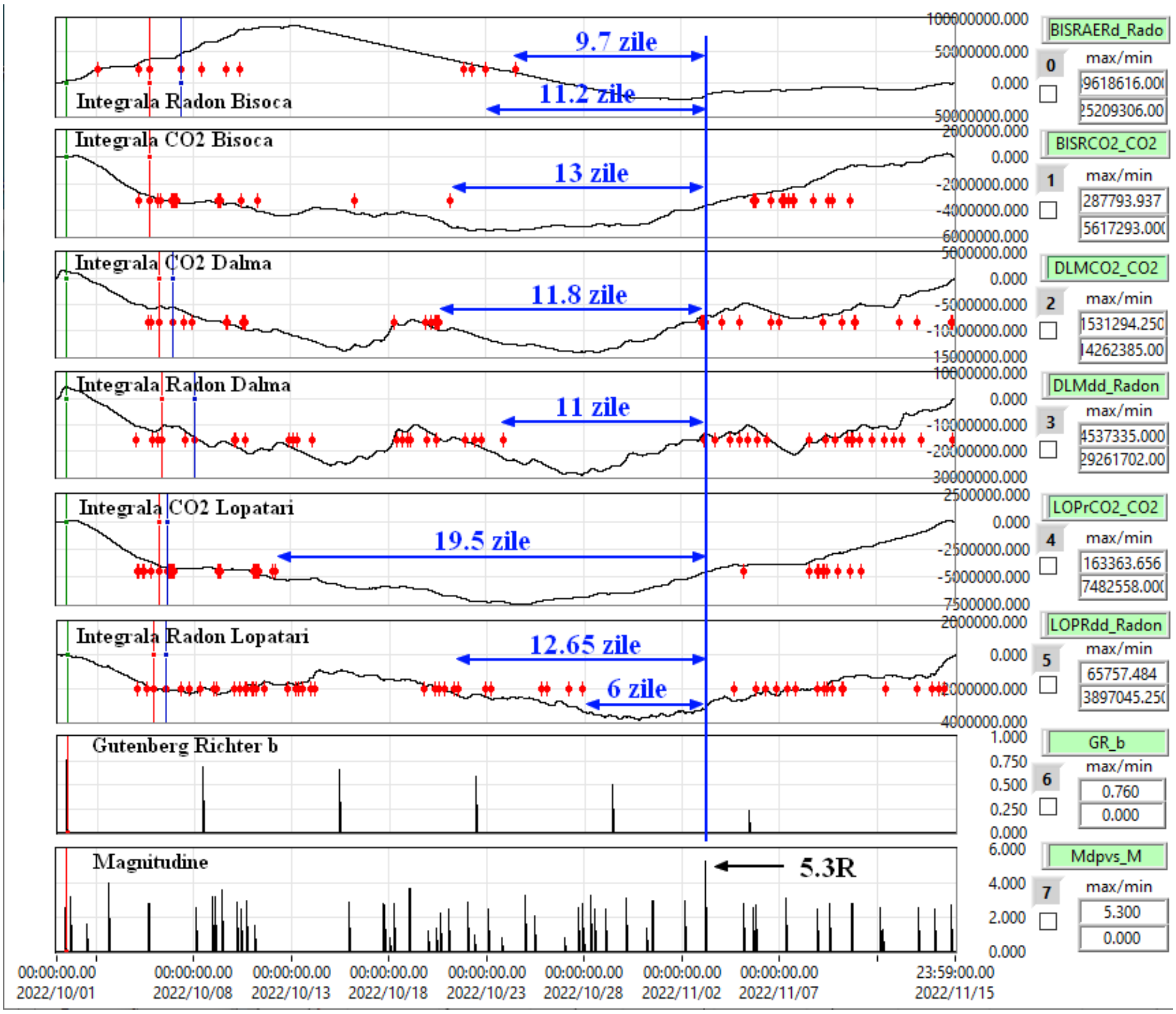

Figure 13. Vrancea 5.3R earthquake, integrated signals: radon, CO2, STA/LTA trigger (red dots).

Appendix 8 shows more details, as well as a similar study of the crustal earthquake zone in the Galati area.

In conclusion, gas emission monitoring can provide short-term (on the order of days) forecasts of significant earthquakes, either in the Vrancea subcrustal zone or in other areas of crustal seismicity. We present below the procedures underlying the construction and implementation of the forecasting algorithm in the virtual platform (3.1 and 3.2 activities). The diagram from Figure 14 shows the general idea behind the construction of this platform. Other parameters for forecasting will be added.

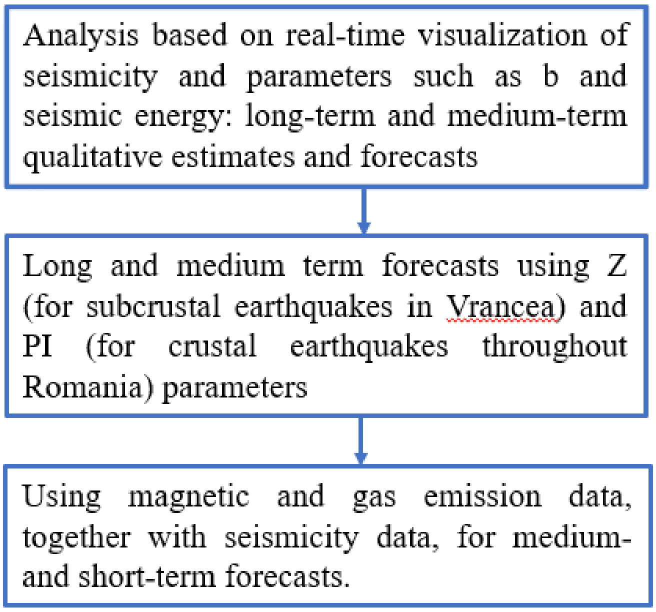

Figure 14. The design of the general forecasting algorithm of the vertical platform.

The implementation of the platform followed the steps briefly outlined in Figure 14. Please note that detailed explanations on how to use the virtual platform can be found on the platform's web page, either accompanying the graphics or in the dedicated web documentation (PDF file). The virtual platform can be accessed from the platform's web page by clicking on the "Virtual Platform" button or directly from the page: http://afros.infp.ro/AFROS.php.

The first part of the virtual platform ("**Seismicity**" button) displays the time and space evolution of the seismicity, the b-value for the seismicity of the geographical perimeter and the selected magnitude range and time interval (the selection is interactive) and the seismic energy as a function of time. These graphs made with real-time data provide both a qualitative and quantitative picture of the seismic activity in a given area. The b parameter (b-value) can be used as a predictive indicator of seismic activity, as this parameter is often reported to decrease before large earthquakes occur due to the increase/accumulation of tectonic stress (for more details, see Enescu et al., 2001, 2023).

The Z-parameter (Z-value) for investigating changes in the seismicity rate of intermediate depth, subcrustal earthquakes in the Vrancea area as a function of time and space is presented by pressing the "**Z-value maps**" button. Z-values are displayed in SW-NE vertical sections through the Vrancea area for different time periods. The Z-parameter can indicate periods of seismic activation or seismic gaps, which can be precursors (e.g., Enescu et al., 2001). The forecast window is medium term (1.5 years).

The PI parameter for investigating seismicity anomalies for shallow, crustal earthquakes in Romania is presented by pressing the "**PI RI maps**" button. PI parameter values are displayed for Romania, indicating the seismicity forecast for the next 5 years (long term period).

Real-time display of geophysical parameters, which characterize magnetic field variations and gas emissions (radon and carbon dioxide) is done by pressing the "**Geophysical Data**" button. This page also displays thresholds for declaring seismic "alarms", as explained in detail in the platform documentation.

The virtual platform also contains a button, "**Miscellaneous**", which displays a page that currently contains some information related to the earthquake sequence in Gorj.

5. The degree of achievement of the estimated results and the impact of the obtained results, emphasizing the most significant result obtained.

All the objectives of the project were achieved during the three stages, through the activities proposed in the implementation plan, the results obtained being in accordance with the planned ones.

The objectives of **Stage 1, Designing and implementing the algorithm for the investigation of intermediate depth seismicity in the Vrancea area**, were fully achieved, both by carrying out the two proposed activities and by achieving the expected results.
The objectives of **Stage 2, Designing and implementing the algorithm for the investigation of superficial, crustal seismicity in Romania**, were fully achieved, both by carrying out the two proposed activities and by achieving the expected results.
The objectives of **Stage 3, Integration and implementation of the general forecasting algorithm**, were fully achieved, both by carrying out the three proposed activities and by achieving the expected results.

Regarding the *impact of the project*, the results of the project studies, published in prestigious journals in Romania and abroad and presented at international meetings, have reinvigorated the seismicity analysis efforts on the Romanian territory and represent the first systematic efforts to forecast intermediate depth (Vrancea area) and shallow seismicity on the Romanian territory. Romania thus joins countries such as the United States and Japan in the study and development of seismic forecasting techniques. This project has also highlighted the particularities of the Vrancea seismic zone, in the context of global seismicity, and has created new methods of seismicity characterization.

We consider that *the most important result* achieved is the creation of the virtual platform, which represents the culmination of the research efforts of all the members of the project during the three years of activity. This platform will contribute to the correct information of the public about seismic forecasting in Romania. It also creates the conditions for the advancement of research in the field of seismic forecasting by incorporating new, improved and performing techniques in the years to come.

6. Exploitation and dissemination of project results. Future plans.

The results of the project have been published in numerous national and international journals and presented at numerous international conferences (Annex 9). Also, during the earthquake sequence in Gorj county, in February 2023, the project director, Dr. Bogdan Enescu, as well as other members of the project, including the Director General of INFP, Dr. Ionescu Constantin, Dr. Mircea Radulian and Dr. Iren-Adelina Moldovan had appearances in the media and other social media (e.g., Facebook, X/Twitter) where they explained the sequence to the public and provided statistical forecasts of the seismic aftershock sequence as part of the AFROS project efforts.

Figure 15. Online televised intervention during the **Euronews Romania Conferences**, with the Gorj earthquakes as a topic of debate. (On the conference screen, Dr. Bogdan Enescu, AFROS Project Director).

As future plans, we will continue with the implementation of new algorithms for seismicity analysis and forecasting. On 24 November 2023 a virtual meeting was held between project members to discuss future work strategies, including the application of ML techniques for seismicity detection and study.

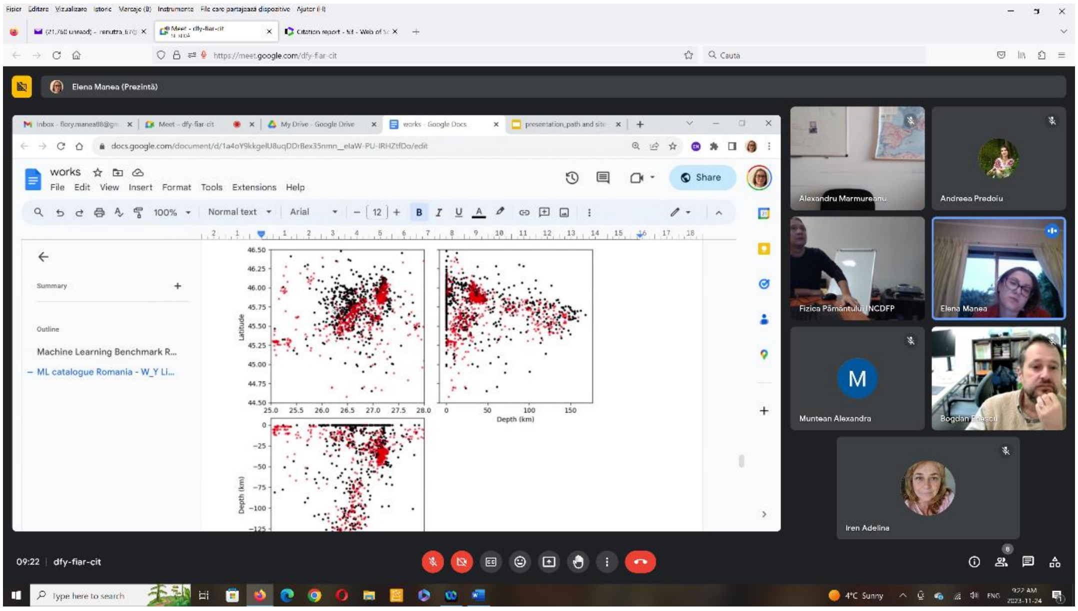

Figure 16. Project members meeting, 24 November 2023.

7. Presentation of deliverables/indicators obtained at the end of the project compared to those proposed.

In the project implementation plan 3 Stages were foreseen, each stage with a number of outputs, and indicators, as follows:

Stage 1. Design and implementation of the algorithm for the investigation of intermediate depth seismicity in the Vrancea area

Results: „Subcrustal seismicity modelling and forecasting algorithms” and „Estimation and forecasting of intermediate depth seismicity parameters” were delivered in full in the form of forecasting algorithms and forecasting parameter estimates as specified in the implementation plan.

Indicators: „Increased expertise in seismicity analysis (including the acquisition of ML techniques) of the 2 PhD students" and „Web page creation" - fully achieved. The two PhD students, Alina Coman and Andrei Mihai, benefited from the organization of 5 online seminars, with the participation of specialists in the field of Seismology and Machine Learning (ML) (details are included in the Stage 1 report). Alina Coman, as well as other members of the project, also participated in a ML course organised by the company "Features Analytics" (Belgium), their participation being co-financed by the AFROS project. The project had 4 papers published ISI and 2 under review in journals indexed in international databases. There were 8 conference participations.

Phase 2: Design and implementation of the algorithm for the investigation of shallow, crustal seismicity in Romania

Results: „Subcrustal seismicity modelling and forecasting algorithms” and „Estimation and forecasting of shallow, crustal seismicity parameters” were delivered in full in the form of forecasting algorithms and forecast parameter estimates, as specified in the implementation plan.

Indicators: „Increase expertise in seismicity analysis of 2 PhD students", „2 ISI papers and 2 conference presentations" and „Update web page" - fully achieved. During the second year of the project we organised 4 online seminars aimed at training the 2 PhD students and young researchers in general (details are included in the Stage 2 report). The project had 2 ISI papers published, with 2 others being accepted, 3 under review and 8 book chapters. There were 16 conference presentations.

Step 3: Integration and implementation of the general forecasting algorithm

Results: „Correlations between geophysical observations and seismicity", „Platform design for data visualization and possible anomaly detection" and „Platform implementation" have been fully delivered.

Indicators: „2 ISI papers and 2 conference presentations"; „explanatory leaflets", „website updated" - fully achieved. The project has 10 ISI papers published, with a further 6 papers and a book chapter under evaluation. Also 4 articles were published in journals indexed in international databases. There were 22 conference participations. We also produced explanatory leaflets/flyers. We would like to point out that the virtual platform, which can be found on the project page, has been tested by users, as can be seen in Annex 10.

In the tables at the end of Annex 9 the indicators for all three phases of the project (36 months) are presented in an organised way.

From the above and from the tables in Annex 9 with the project result indicators, it can be seen that all the proposed values have been achieved and even exceeded by far. Note that more than half of the published articles are published in ISI journals in Q1 and Q2 (after IF and/or AIS).

Regarding the two PhD researchers, we would like to clarify a few details.

The first of them, Alina Coman, enrolled at the PhD at the University of Bucharest, Faculty of Physics, with the title of her PhD thesis „Development of seismic velocity models for the Romanian territory", is at an advanced stage of her studies, and is presenting her thesis in the department. It is expected that by the end of the year the public defence of the thesis will be planned.

The second PhD student, Andrei Mihai, enrolled at the University of Bucharest, Faculty of Physics, with the PhD thesis title „Research on the correlation of local magnetic field behaviour with seismicity in the Vrancea area", is also at an advanced stage, having defended all his exams and dissertations in the department and having published the required number of articles. He is currently working on the final version of his thesis. **Both PhD students have carried out their PhD activities in the framework of the AFROS project, with the coordination and supervision of AFROS staff.**

Data
December 6, 2023

Project Manager
Enescu Bogdan Dumitru