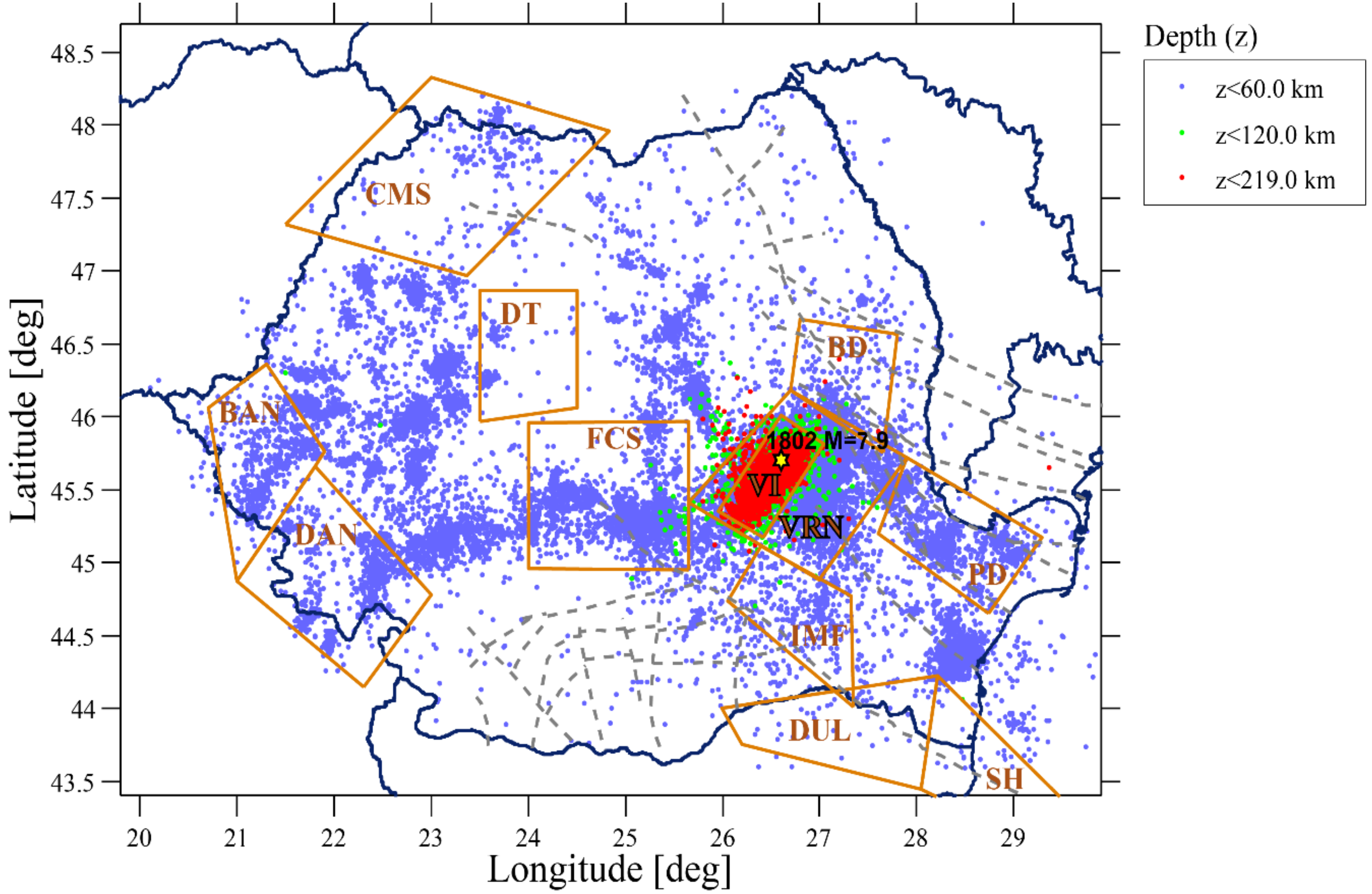
Scientific Report

Analysis and Forecasting of ROmanian Seismicity
AFROS

Cod Project: PN-III-P4-ID-PCE- 2020-1361
Contract: PCE 119/2021

Activitatea A1.1. Forecasting algorithm selection, software description and design

General aspects of seismicity (crustal and subcrustal) of Romania



Map representing the seismicity of Romania (ROMPLUS catalog, 984 – 2022), with the main seismic zones (Moldovan et al., 2017).

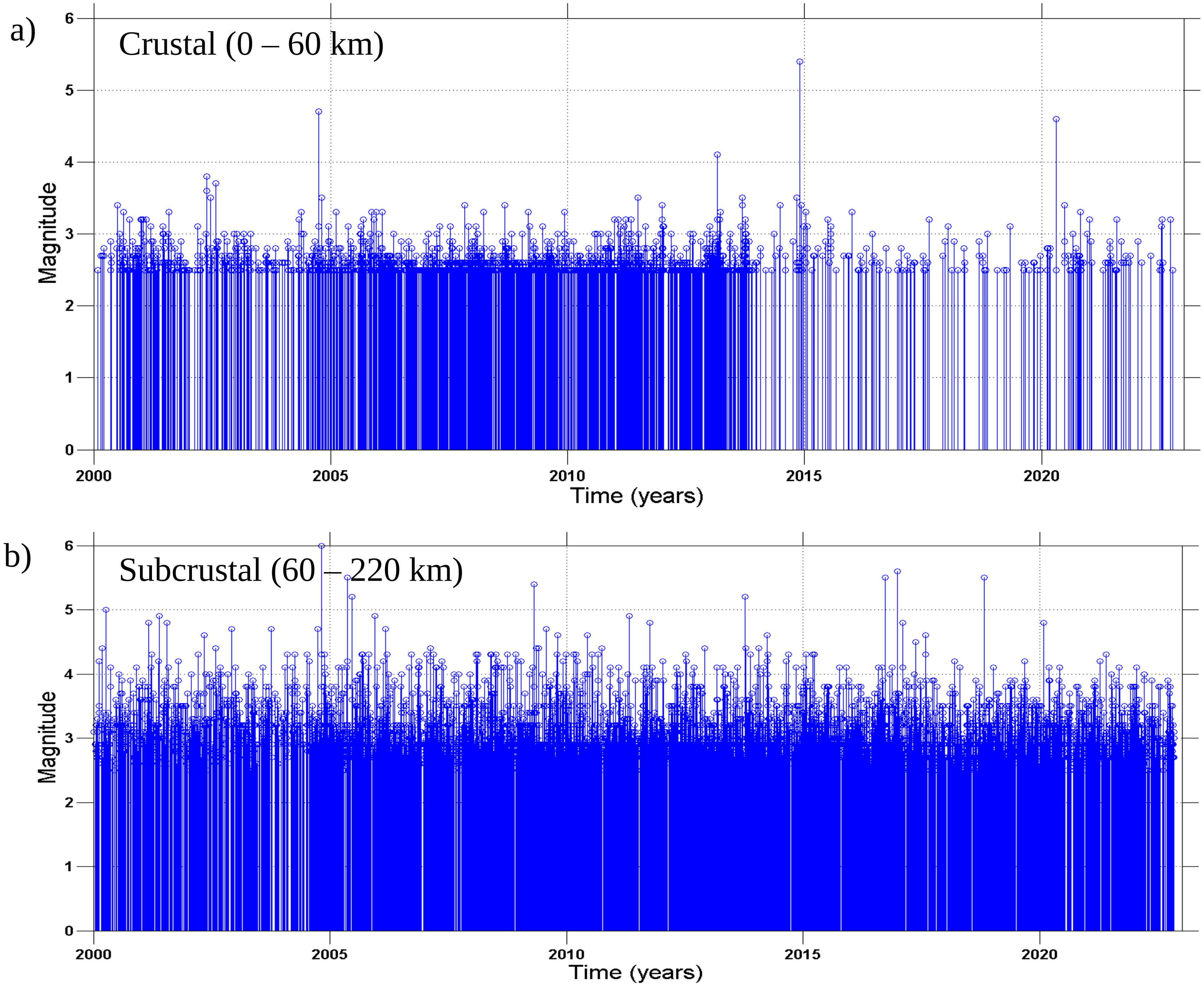
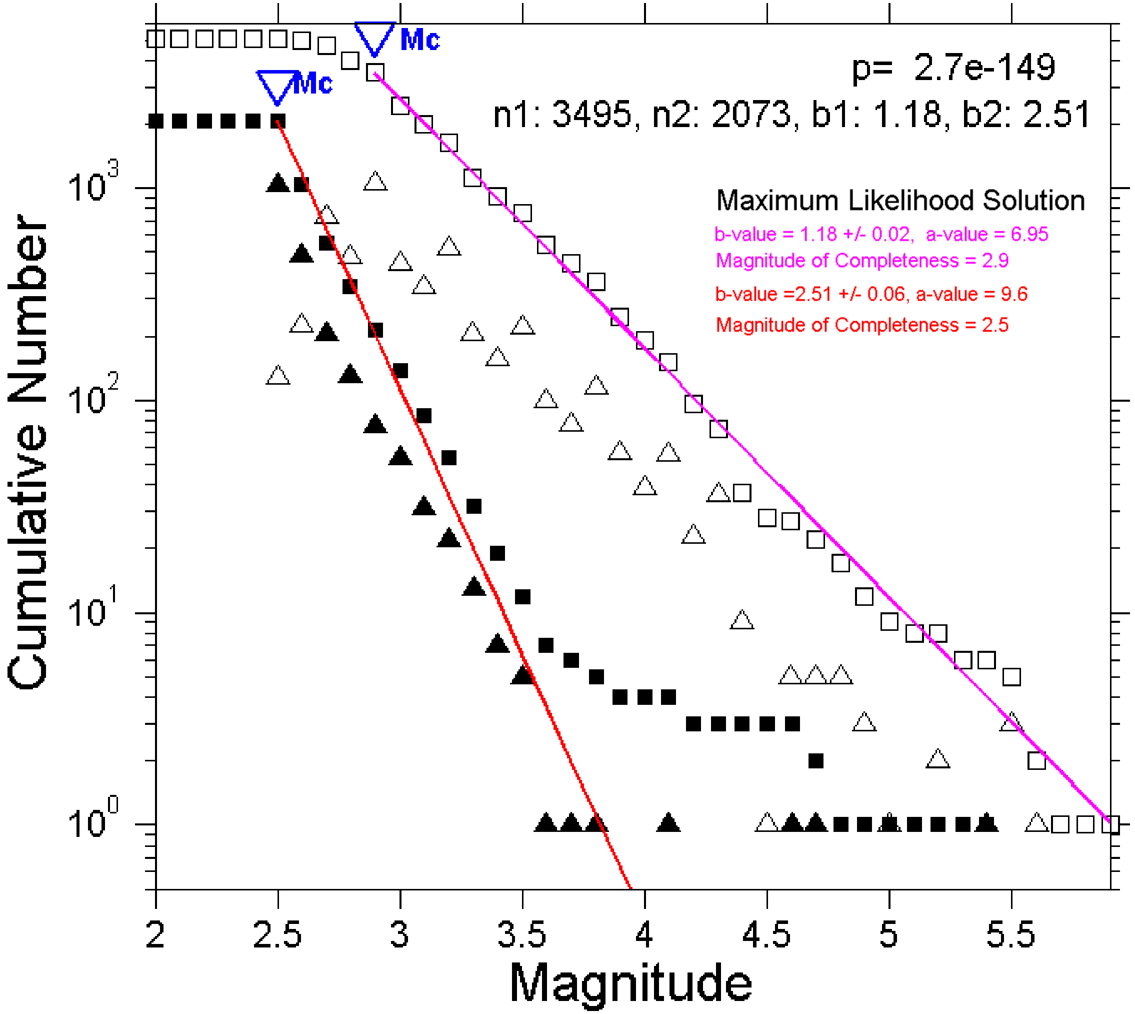


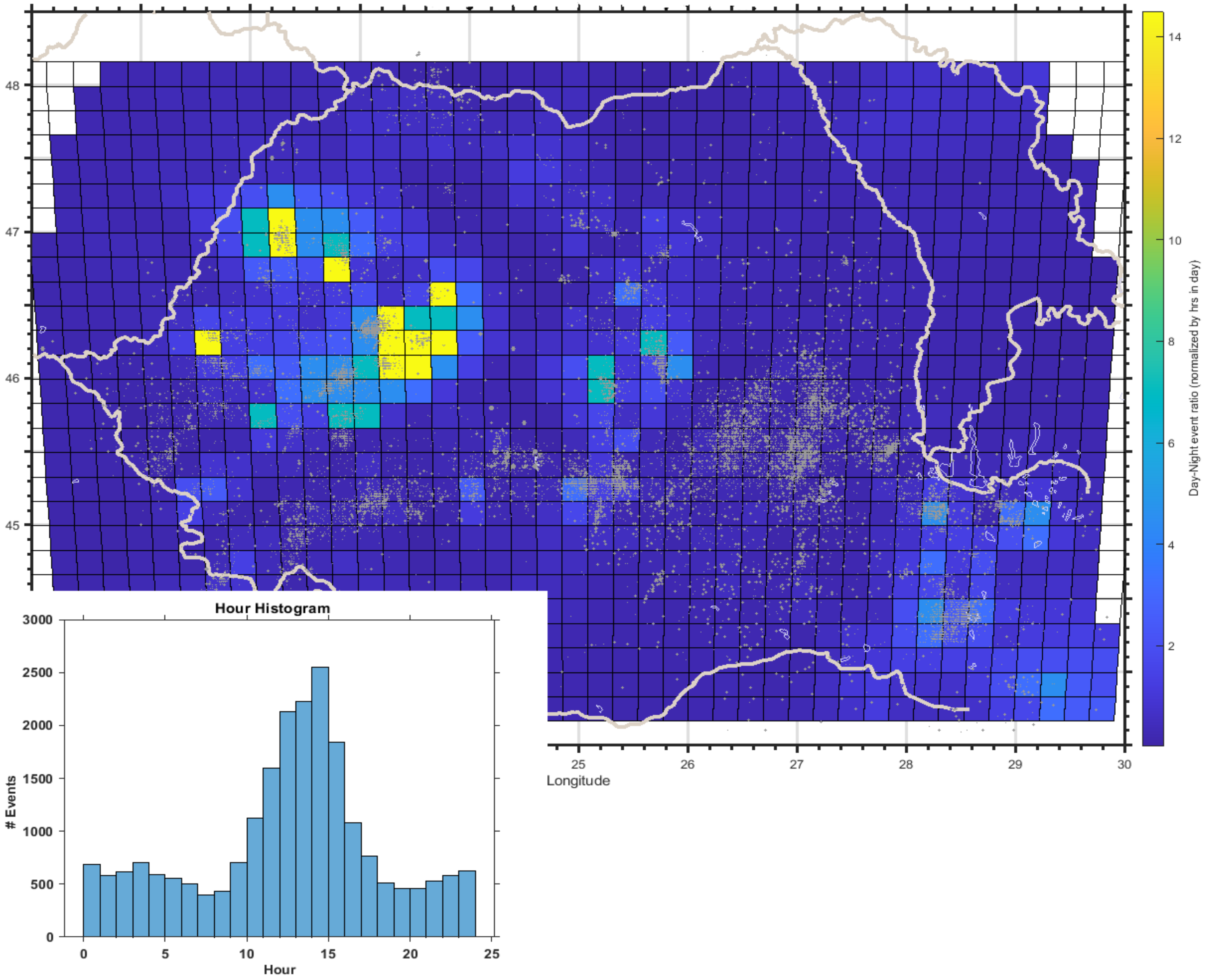
Figure 2. Magnitude-time diagram for (a) crustal (0 – 60 km) and (b) subcrustal (60 – 220 km) earthquakes in Romania, for magnitudes, M ≥ 2.5. Much more sustained activity of subcrustal earthquakes is observed.



Note the large b-value of intermediate-depth earthquakes: scarcity of larger events.

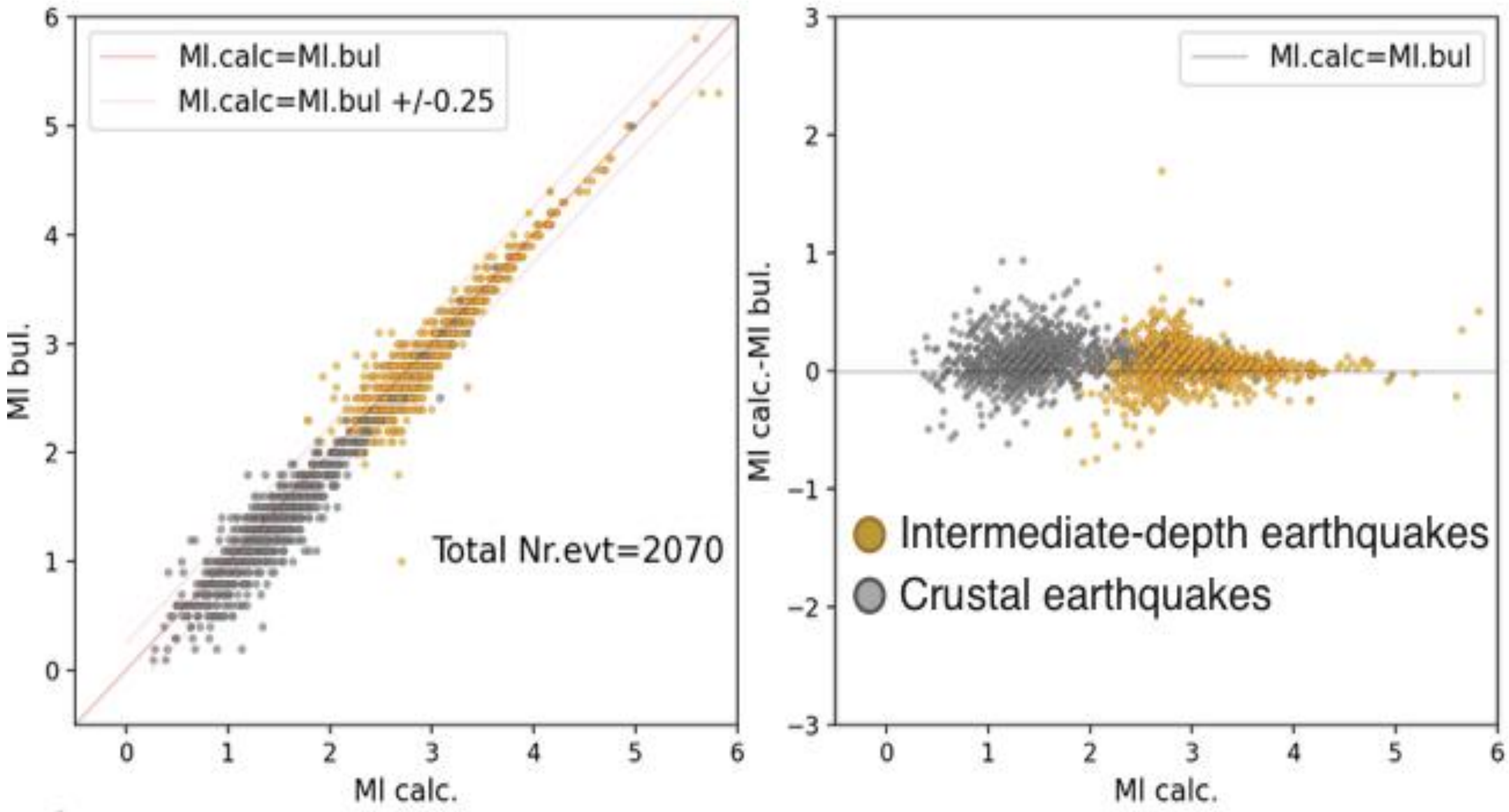
Frequency-magnitude diagram for crustal (0 – 50 km) and subcrustal (60 – 220 km) earthquakes in Romania, for magnitudes M ≥ 2.5, between the years 2000 – 2022. The empty rectangles and triangles represent respectively the cumulative and non-cumulative number of intermediate earthquakes, the full ones represent the same thing for crustal earthquakes. The purple and red lines represent the fitting of the two cumulative distributions (for intermediate and shallow earthquakes respectively) using the "maximum-likelihood" method (Aki, 1965). The figure also indicates the magnitude of completeness (Mc) for the two distributions (determined with the "maximum-curvature" method, Wiemer and Wyss, 2000), as well as the values of parameters a and b of the frequency-magnitude distribution. Earthquakes of intermediate depth are characterized by a coefficient b (slope of the purple line) with a value of 1.2, while crustal ones have a high coefficient b, with a value of 2.5.

Analysis of explosion contamination of the catalog of crustal earthquakes on the territory of Romania and approaches to solving the problem (Armeanu et al., 2022a, b, Varzaru et al., 2022)



Analysis of explosion contamination of the catalog of crustal earthquakes on the territory of Romania and approaches to solving the problem (Armeanu et al., 2022a, b, Varzaru et al., 2022)

Attempts to revise and homogenize the ROMPLUS catalog (material presented by Poiata et al., 2021, 2022; in preparation for publication)



Left: the comparison between the Ml-values (local magnitude) calculated using the ANTELOPE equations and those in the bulletin for the selected period September 2016 – December 2021. Right: the distribution of the magnitude differences between the calculated and reported ones versus the calculated magnitude.

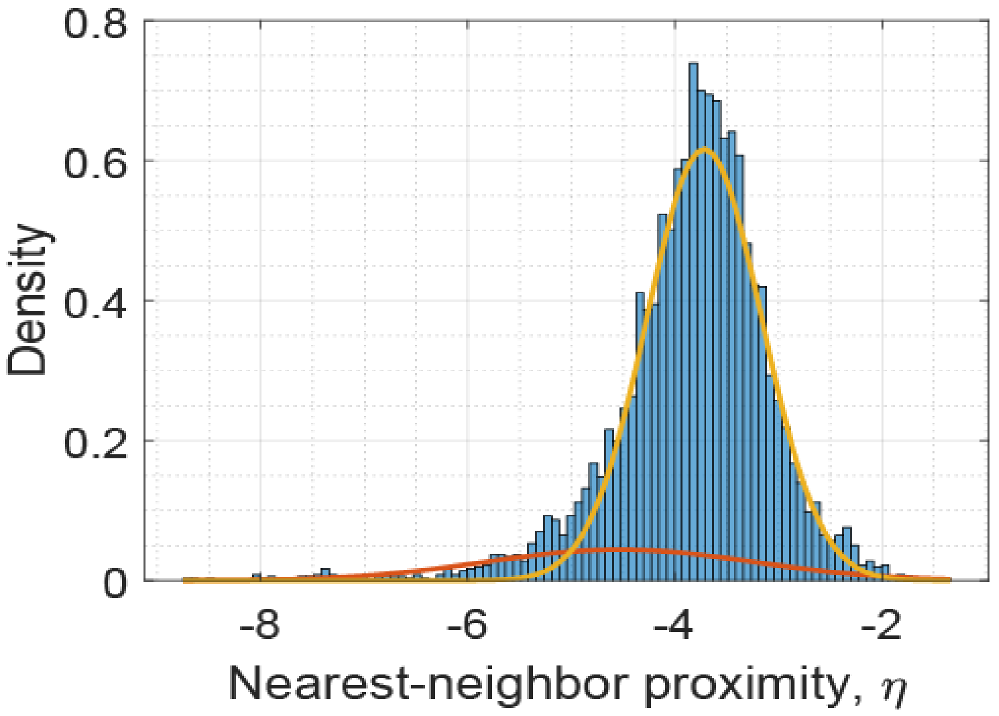
Detailed analysis methods of the earthquake catalog (1)

The method developed by Zaliapin et al. (2013) of separating background seismic activity from cluster type activity (Petrescu and Enescu, 2022, paper in preparation) for crustal and intermediate depth earthquakes in the Vrancea area

Define the nearest-neighbor distance (NND) based on the following relationship

$$\eta_{ij} = t_{ij}(r_j)^{d_f} 10^{-bm_i}, t_{ij} > 0, \qquad \eta_{ij} = \infty, t_{ij} \leq 0$$

where t_{ij} is the time difference between earthquake *i* and earthquake *j*, r_{ij} is the distance between earthquake hypocenters (in km), *b* is the slope of the frequency-magnitude relation and d_f is the fractal dimension of the hypocentral distribution of earthquakes in the area (e.g., Moldovan et al., 2022).



Distribution for Vrancea earthquakes, fitted with a mixed Gaussian distribution. Most earthquakes in the Vrancea zone are background earthquakes (well fitted Gaussian distribution to the right.

Detailed analysis methods of the earthquake catalog (2)

The PI/RI seismicity analysis method applied to the seismicity throughout Romania

PI index

The observed seismic activity rate $\psi_{obs}(x_i,t)$ is the number of earthquakes per unit time, of any size, within the box at x_i at time t. Here the time period is one year, so that $\psi_{obs}(x_i,t)$ is the number of events per year, mean removed. The time-averaged seismicity function $S(x_i,t_0,t)$ over the interval $(t - t_0)$ is:

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

$S(x_i,t_0,t)$ is calculated for N locations and t_0 is a fixed time, such as the start of the catalogue. Denoting spatial averages over the N boxes by <>, the phase function $S'(x_i,t_0,t)$ is defined to be the mean-zero, unit-norm function obtained from $S(x_i,t_0,t)$:

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

Here $|| S(x_i,t_0,t) ||$ is the L2-norm, or the square root of the variance, for all spatial boxes. For a large enough spatial and temporal region, the long-term spatial averages are constant, and the vector $S'(x_i,t_0,t)$ is an effective measure of the local variations in seismicity, given good quality seismic data. Dividing by the constant standard deviation normalizes the regional seismicity by its background and illuminates small, local fluctuations in seismicity. These changes in seismicity are denoted by $\Delta S'(x_i,t_1,t_2) = S'(x_i,t_0,t_2) - S'(x_i,t_0,t_1)$.

Finally, $\Delta S'(x_i,t_1,t_2)$ is averaged over all possible base years, t_0. For any given catalog and time period, the **PI index**, ΔP, is the power associated with $\Delta S'(x_i,t_1,t_2)$, $\Delta P(x_i,t_1,t_2) = \{\Delta S'(x_i,t_1,t_2)\}^2 - \mu_{p.}$, where μ_p is the spatial mean of $\{\Delta S'(x_i,t_1,t_2)\}^2$, or the time-dependent background [*Tiampo et al.,* 2002].

RI index

The RI algorithm is the simplest of smoothed seismicity models and was originally formulated as a binary forecast, although it has been modified in several ways since that time. Initially, the study region is tiled with square boxes. In California, these are typically are 0.1º x 0.1º, so that the forecast locations are small, on the order of the rupture dimension of the smallest forecast magnitude. The number of earthquakes with magnitude $M \geq m_c$, where m_c is the minimum magnitude cutoff, in each box is determined over the time period of the catalogue. The RI score for each box then is computed as the total number of earthquakes in the box in that time period divided by the value having the largest value.

A threshold value in the interval [0, 1] is then selected, and all values above that are expected to have a large event over the forecast period of interest, resulting in a binary forecast. The remaining boxes with RI scores smaller than the threshold represent sites at which large earthquakes are not expected to occur. The result is a map of locations in a seismogenic region where earthquakes are forecast to occur over some future intermediate-term time span. Note that a high threshold reduces the forecast regions but results in more events that are not predicted, while reducing the threshold reduces the failures to predict but increases the false alarms [*Holliday et al.*, 2005].

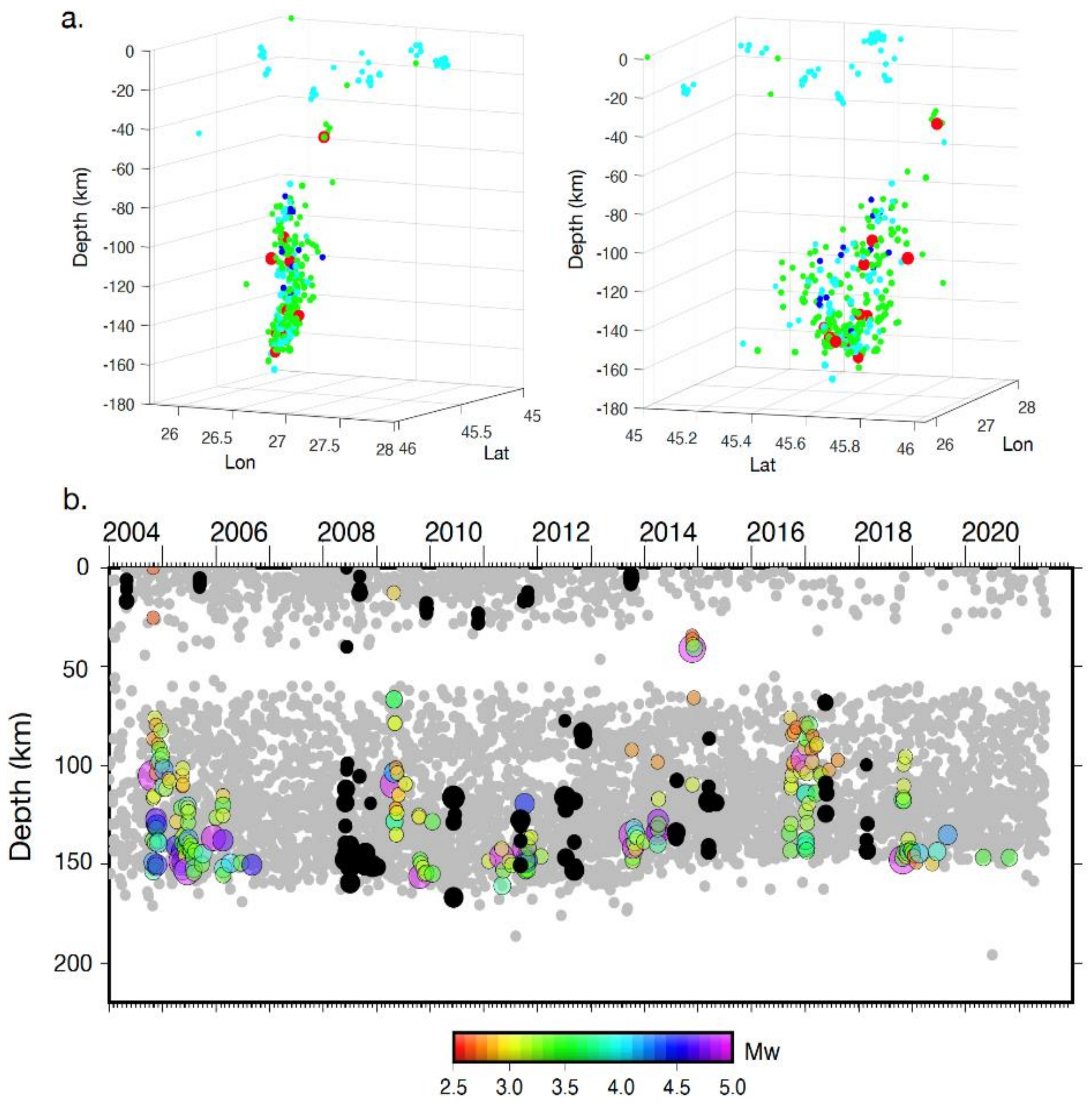
Activitatea A2.2. Application, testing and calibration of forecasting algorithms

The method developed by Zaliapin et al. (2013) of separating background seismic activity from cluster type activity for crustal and intermediate depth earthquakes in the Vrancea area (Petrescu and Enescu, 2022, paper in preparation)

Table 1. Details about the detected clusters (sequences of type foreshocks-mainshock-aftershocks).

Timp cutremur principal	Magnitu-dine cutremur principal	Adâncime cutremur principal (km)	Număr de Preșocuri	Număr de replici	Interval de adâncime (km)	Întindere pe adâncime (km)	Durata (zile)
2004.10.27	6,0	105,4	0	36	25,3-153,5	128,2	129
2005.05.14	5,5	148,5	0	36	101,6-155,5	53,9	2360
2005.12.13	4,9	136,8	0	5	115,5-138,0	22,5	65
2009.04.25	5,4	109,6	0	11	12,7-128,4	115,7	80
2009.10.22	4,6	156,3	3	7	125,6-156,3	30,7	90
2011.05.01	4,9	146,1	0	8	142,3-160,9	18,6	270
2011.10.04	4,8	142,0	0	10	119,5-153,1	33,6	44
2013.10.06	5,2	135,1	0	23	6,2-148,4	142,2	2514
2014.11.22	5,4	40,9	0	7	34,3-109,8	75,4	15
2016.12.27	5.6	96.9	14	28	75.9-143.2	67.3	782
2018.10.28	5.5	147.8	0	22	110.4-149.8	39.4	757

Rather few clusters (just 6% of the total seismicity), 2 sequences have foreshocks



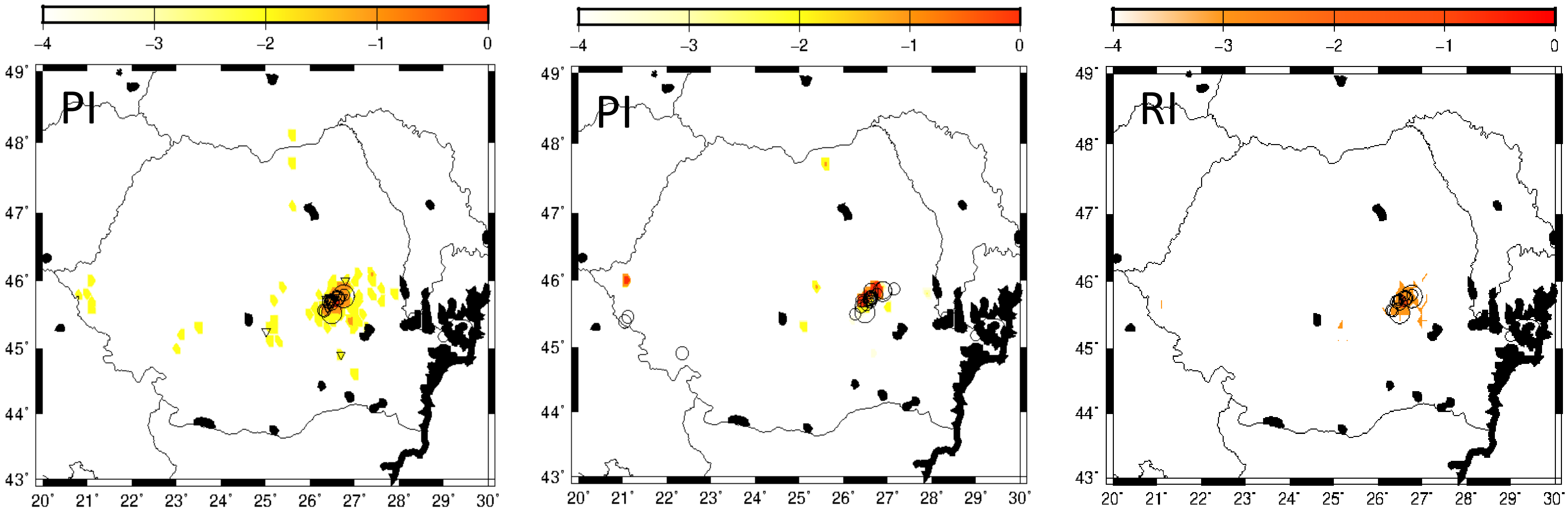
a) Hypocenters of earthquakes in the crustal and subcrustal domains for the Vrancea area, colored as follows: mainshocks (red), aftershocks (green), pre-shocks (blue), seismic swarm events (cyan).

b) Depth-time representation of earthquakes in Vrancea zone, showing pairs of earthquakes with log(η) < − 5.0. Only seismic sequences with at least 3 earthquakes are represented.

Almost no crossing from crustal to intermediate and vice-versa: decoupled or weekly coupled zones.

The PI/RI seismicity analysis method applied to seismicity throughout Romania (Tiampo and Enescu, 2022, paper in preparation)

Results for March 4, 1977, longitude 26.76, latitude 45.77, depth 94.0, M7.4: hot spots



a) PI index, training period 1966-1976, forecast period of 1977-1987. Inverted triangles denote the location of earthquakes that occurred during the forecast period, circles identify the location of earthquakes that occurred during the forecast period. Color scale is logarithmic, white to yellow to red. b) PI index, training period of 1971-1976, forecast period of 1977-1982; symbols and color scale as in (a). c) RI index, thresholded at 0.1, for the training period 1941 through 1976. Circles denote earthquakes that occurred between 1977-1987. Symbols as in (a), color scale is logarithmic, white to red.

Conclusions (1)

The main conclusions of the analyzes carried out during the second year of the project can be summarized as follows:

1) The general analysis of Romania's seismicity between the years 2000 - 2022 (the most recent and most complete time interval from the point of view of recording earthquakes of relatively small magnitude) from the ROMPLUS catalog, a catalog that covers the entire territory of Romania, highlighted an activity much more sustained for subcrustal earthquakes in Vrancea region (7 earthquakes with $M \geq 5.0$, including one earthquake with $M = 6.0$) compared to crustal ones (a single earthquake with $M \geq 5.0$, in the Bârlad Depression).

2) For the same time interval (2000 – 2022), the value of the coefficient *b* from the frequency-magnitude relationship, for crustal earthquakes throughout Romania, has a relatively high value compared to the value of b for the earthquakes of intermediate depth in Vrancea. Therefore, in a certain period of time, we expect a relatively low number of earthquakes with large magnitudes in the case of crustal seismicity in Romania compared to the region of intermediate depths earthquakes in Vrancea.

3) The studies from the first year (2021) of the project highlighted the need to revise the ROMPLUS catalog. Therefore, we performed detailed analyzes regarding, a) the contamination of the catalog of crustal earthquakes with seismic explosions (from quarries, etc...) and b) the homogenization of the ROMPLUS catalog in terms of the magnitude and location of crustal and intermediate depth earthquakes in Vrancea. The contamination of the catalog with explosions was investigated using three different methods, capable of highlighting and discriminating the explosions from natural earthquakes. We appreciate that the objective of improving the ROMPLUS catalog has been achieved to a considerable extent, but it requires further sustained efforts for its effective implementation.

Conclusions (2)

4) We finalized a procedure (and related analysis) that allowed the separation of seismicity in the Vrancea area (crustal and subcrustal earthquakes) into background seismicity and seismic sequences. Seismic sequences can be of the foreshock-mainshock – aftershock type or of the seismic swarm type. This analysis led to three important conclusions: the relatively low number of seismic sequences (compared to the background seismicity), the relatively low number of pre-shocks for the Vrancea earthquakes (both crustal and subcrustal) and the almost total lack of sequences that to penetrate from one area (crustal or subcrustal) to the other. The first two conclusions have direct implications regarding the predictability of earthquakes, especially based on pre-shock activity. However, the current analysis does not exclude the possibility of recording pre-shocks before relatively large earthquakes (which did not occur during the analyzed period, 2000-2021). The third conclusion has implications of a tectonic nature and suggests a probably total decoupling between the crustal and the sub-crustal seismicity segment. We appreciate that this objective was fully achieved.

5) We analyzed the ROMPLUS catalog using PI/RI seismicity indices. We presented in this report only results obtained for a forecast period of 5 years and respectively 10 years, which includes the major Vrancea earthquake of March 4, 1977, magnitude M7.4. Both the PI index and the RI index indicate the existence of a seismicity anomaly in the Vrancea area for the time windows 1977 - 1987 (10 years) and 1977 - 1982 (5 years). We are currently continuing with the calibration of the PI/RI methods and the interpretation of the results. We appreciate that this objective was largely achieved, but the analysis and interpretation of the results will continue in the third year of the project.

Dissemination of results:

For the meeting presentations and scientific papers during the 2 years of the project (2021 and 2022), please check Annex 6.