Analysis and Forecasting of Romanian Seismicity (AFROS) Project: Aim and Preliminary Results

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Introduction

The AFROS project (2021 – 2023) aims analyzing the seismicity on the territory of Romania, with a special emphasis on Vrancea intermediate-depth events and finding elements with possible forecasting character that can be used to develop appropriate forecasting techniques for the Romanian territory. An indirect purpose of this project is to build an earthquake database, which is necessary for the analysis and forecasting of Romania's earthquakes. Here we will present the studies carried out in the first year of the project regarding the intermediate-depth seismicity in the Vrancea region.

The Vrancea seismic zone is located beneath the Eastern Carpathians, in Romania, and characterized by persistent and well-defined seismicity. The epicenters of the Vrancea earthquakes are located inside a rectangle of latitudes between 44.90 - 46.50 and longitudes between 25.50 - 28.00. The hypocentral depth of the events varies from 0 to 220 km, but the main seismic activity takes place at intermediate depths (60 - 180 km) (e.g., Oncescu et al., 1999).

Numerous studies have explored Vrancea's seismicity. Some of them have been dedicated to the statistical analysis of the recurrence patterns of major intermediate-depth earthquakes ($Mw \geq 6.5$) (e.g., Enescu et al., 1974; Enescu and Enescu, 1996; Hurukawa et al., 2008). Other studies have searched for potential precursory models of seismicity for strong earthquakes in Vrancea (e.g., Mârza, 1979; Radulian and Trifu, 1991; Enescu and Ito, 1999; Hurukawa and Imoto, 2010).

The largest known earthquake of intermediate depth in Vrancea took place on October 26, 1802, and had an estimated moment magnitude, $Mw = 7.9$ (Georgescu, 2004). Crustal seismic activity in the Vrancea region is relatively low, with maximum magnitudes in the range of 5.0 - 5.5 (Radu, 1979; Moldovan et al., 2008).

Methods (1)

(1) Clustering algorithms

We apply two clustering algorithms to understand the distribution of Vrancea EQs:

(1) K-means is an unsupervised machine-learning data partitioning algorithm that iteratively separates convex clusters by minimizing the average square distance between cluster points. The algorithm operates based on a set of pre-defined parameters such as a maximum number of clusters and or a maximum number of data points in each cluster (Lloyd, 1982; Arthur and Vassilvitskii, 2006).

(2) DBSCAN which stands for Density-Based Spatial Clustering of Applications with Noise (Ester et al., 1996; Schubert et al., 2017) finds data points in the densest data regions and expands clusters from them. It is generally fit for data comprising similarly dense clusters.

Methods (2)

(2) Analysis of the frequency-magnitude distribution of earthquakes

$$\log N = a - bM \quad (1)$$

a, b – constants (parameters to be determined by fitting the data distribution);
N – cumulative (or non-cumulative) number of earthquakes, with magnitudes larger or equal to M.

In order to determine the parameters a and b, the earthquake data is fitted using the maximum likelihood method (Aki, 1965), which provides stable estimates of the parameters (i.e., not affected significantly by data outliers). The fit is done for magnitudes equal or above the magnitude of completeness (Mc) of the data, determined using the maximum curvature method (Wiemer and Wyss, 2000).

Methods (3)

(3) The z-value statistical parameter for the analysis of seismicity rate changes is given by the following formula (Habermann, 1983):

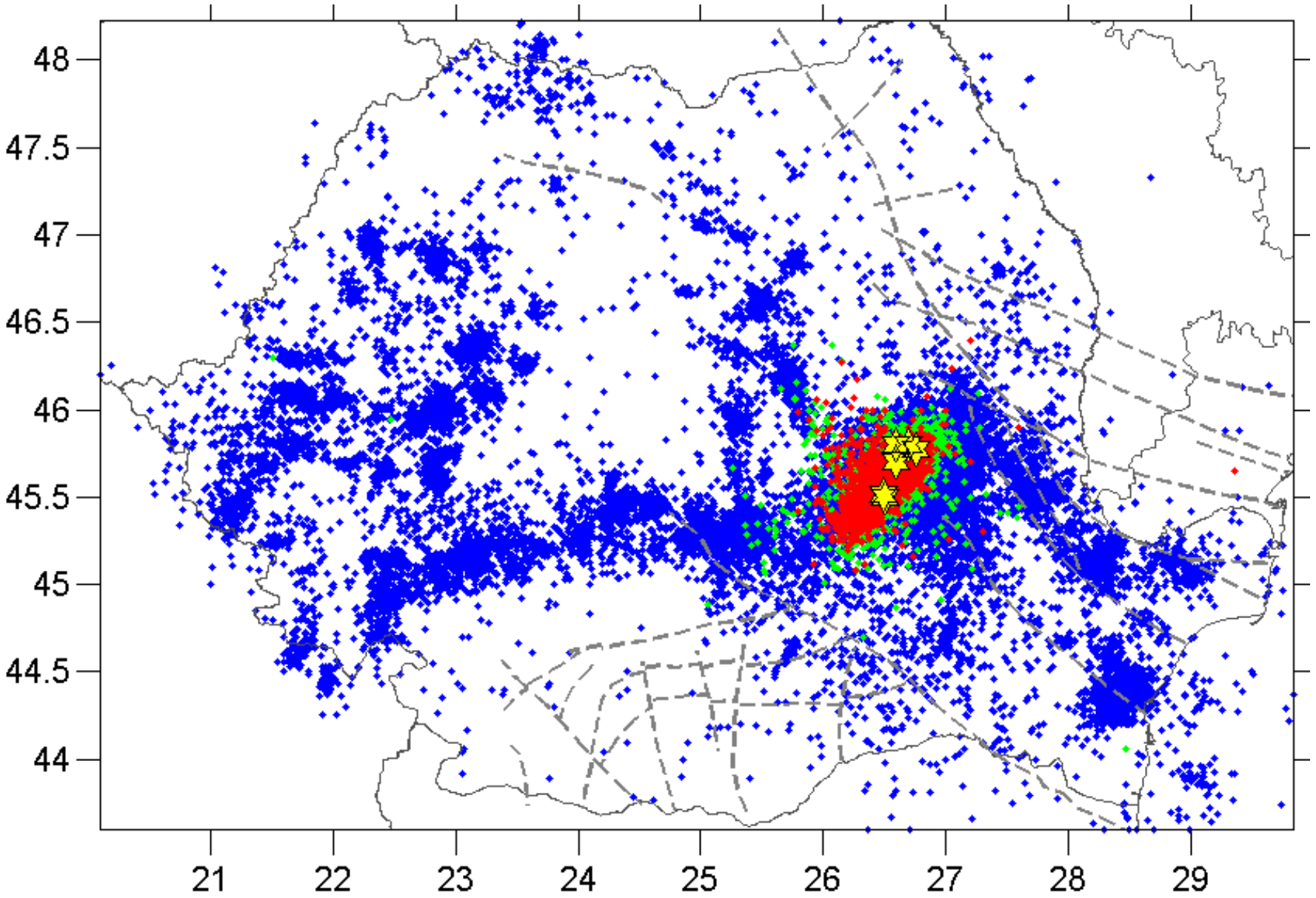
$$Z = \frac{m_1 - m_2}{\sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}} \qquad (2)$$

where,

- m_1 and m_2 are average earthquake rates for 2 periods (W_1 and W_2) that we wish to compare;
- n_1, n_2 and σ_1, σ_2 are numbers of events and standard deviations, respectively, for the 2 time periods.

The resulting z-value has the same interpretation in terms of significance as the number of standard deviations from the mean of a normal distribution, but some authors (e.g., Katsumata, 2017) recommend using higher thresholds.

Seismicity of Romania (984 – 2021; all earthquakes of ROMPLUS catalog)



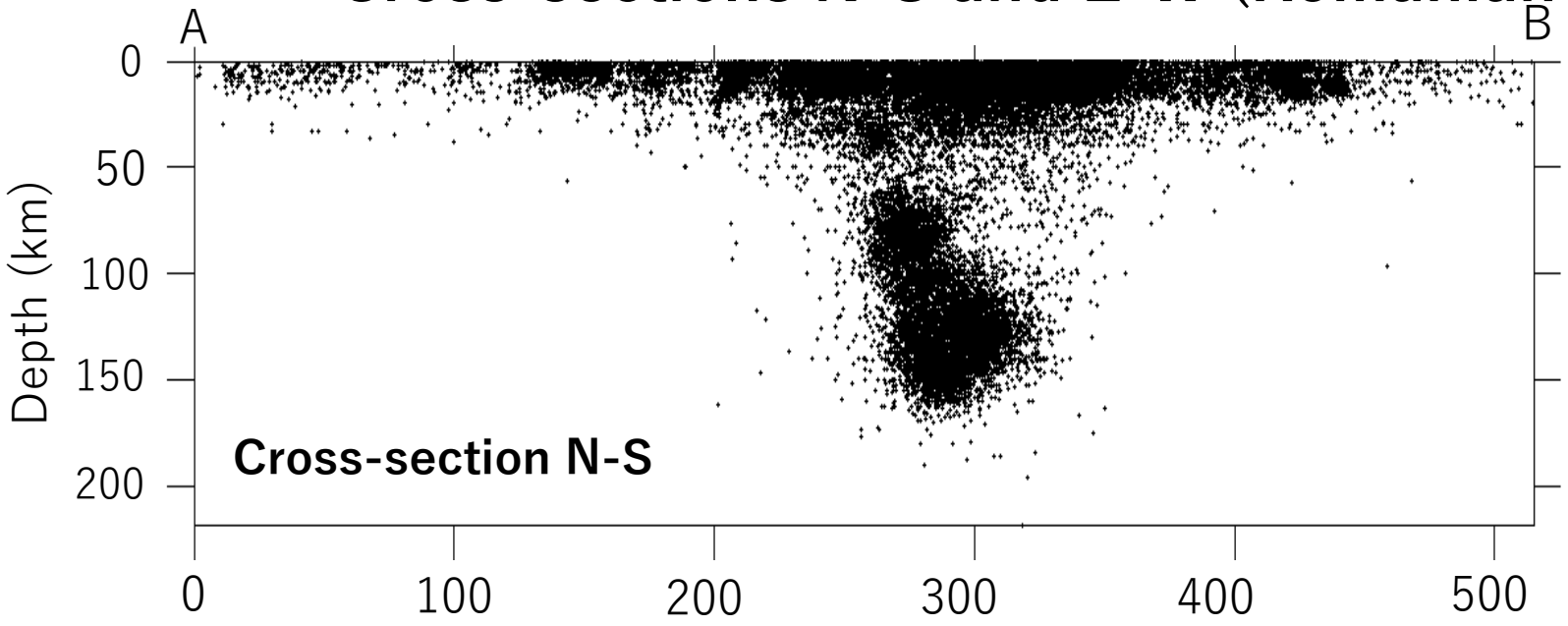
Depth scale

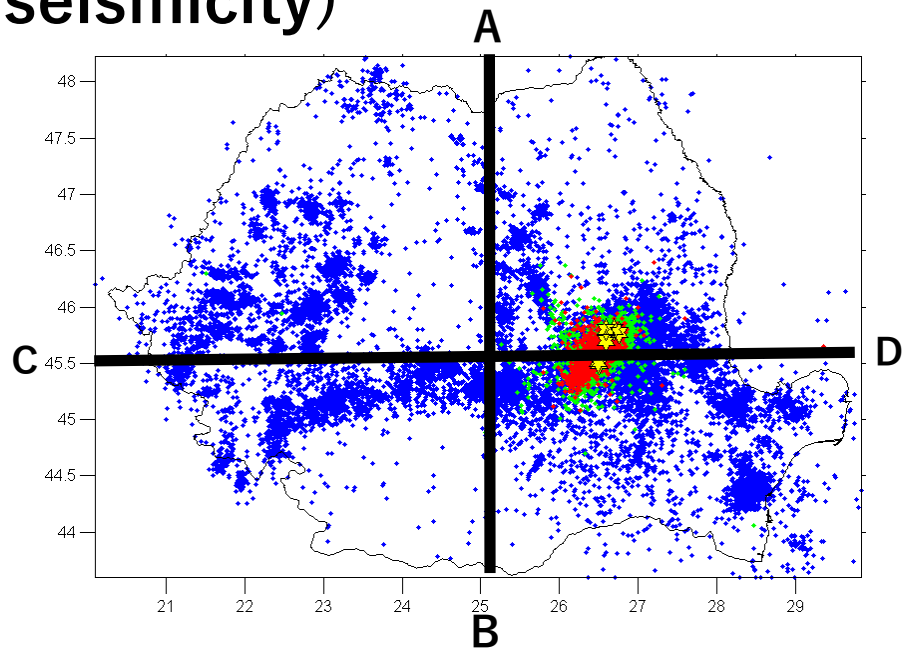
- z<60.0 km
- z<120.0 km
- z<218.4 km

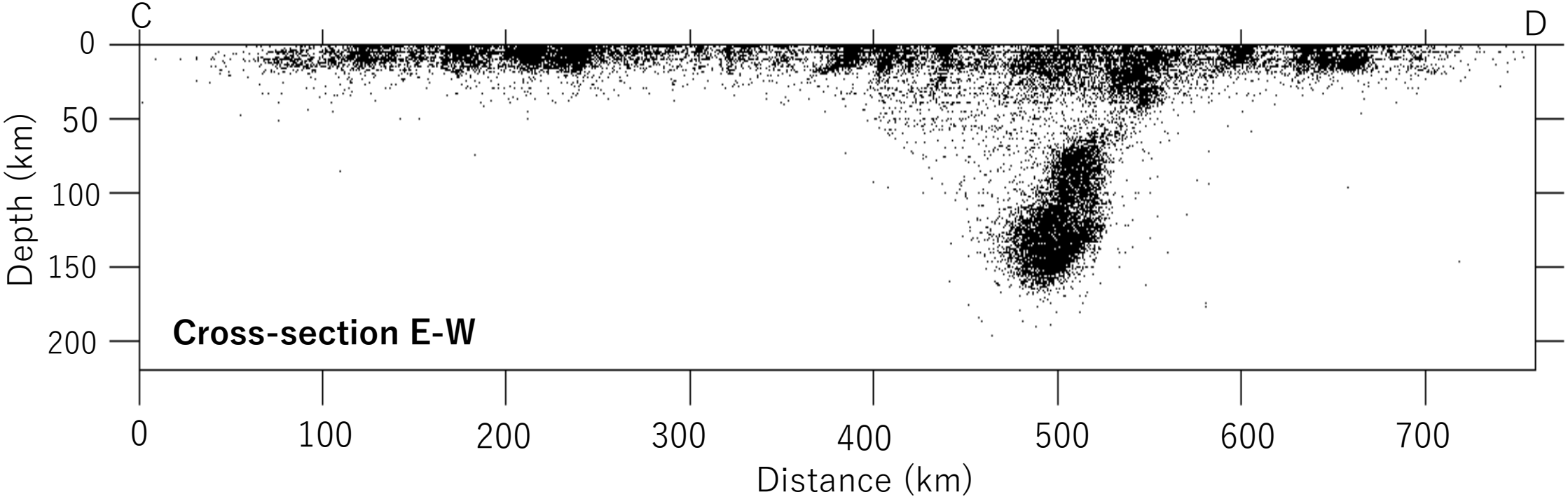
Yellow stars:
M >= 7.0

Earthquakes deeper than 60 km indicate Vrancea subcrustal events

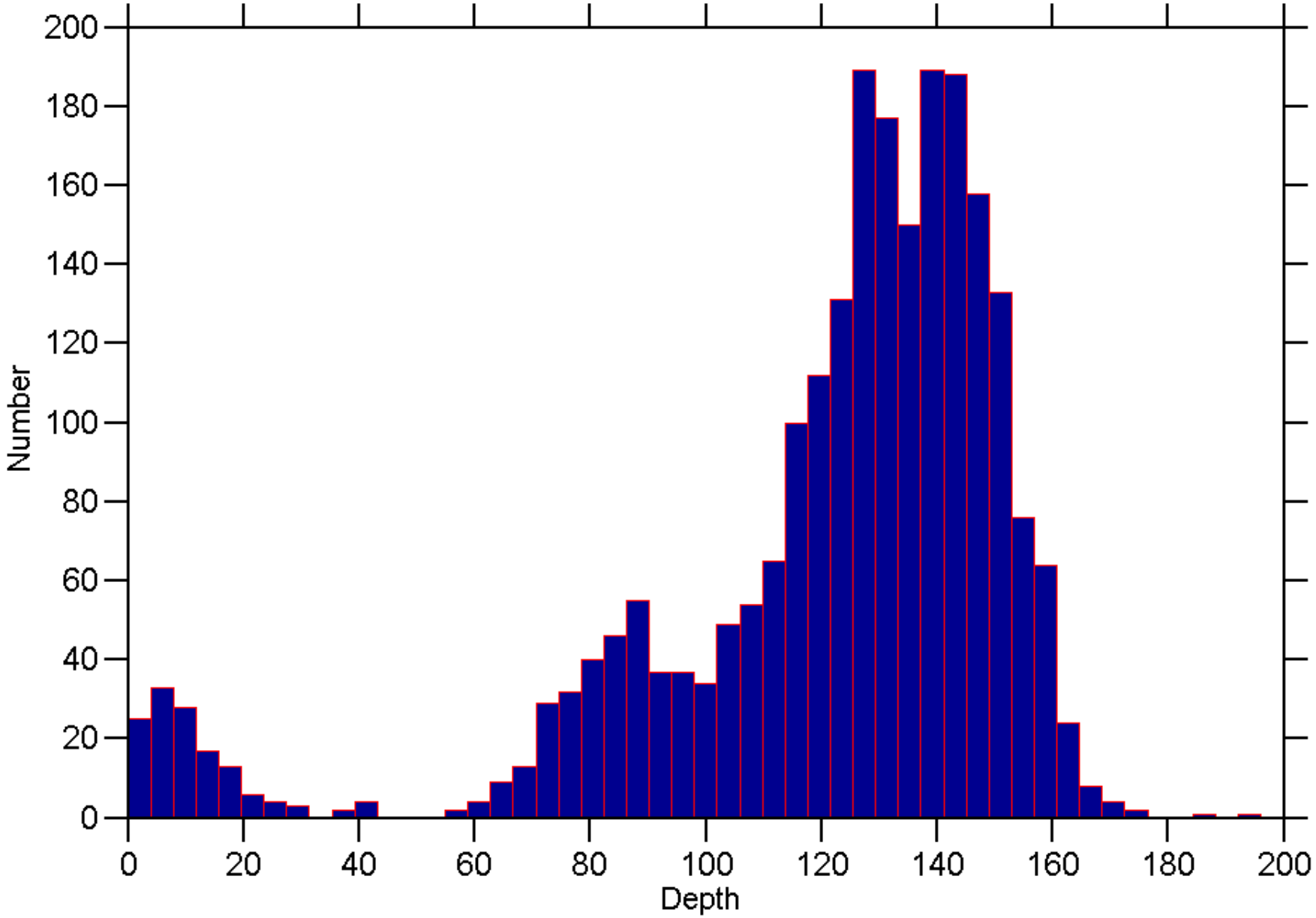
Cross-sections N-S and E-W (Romanian seismicity)







Depth histogram for all Romanian seismicity (M ≥ 3.0; 2000 – 2021)

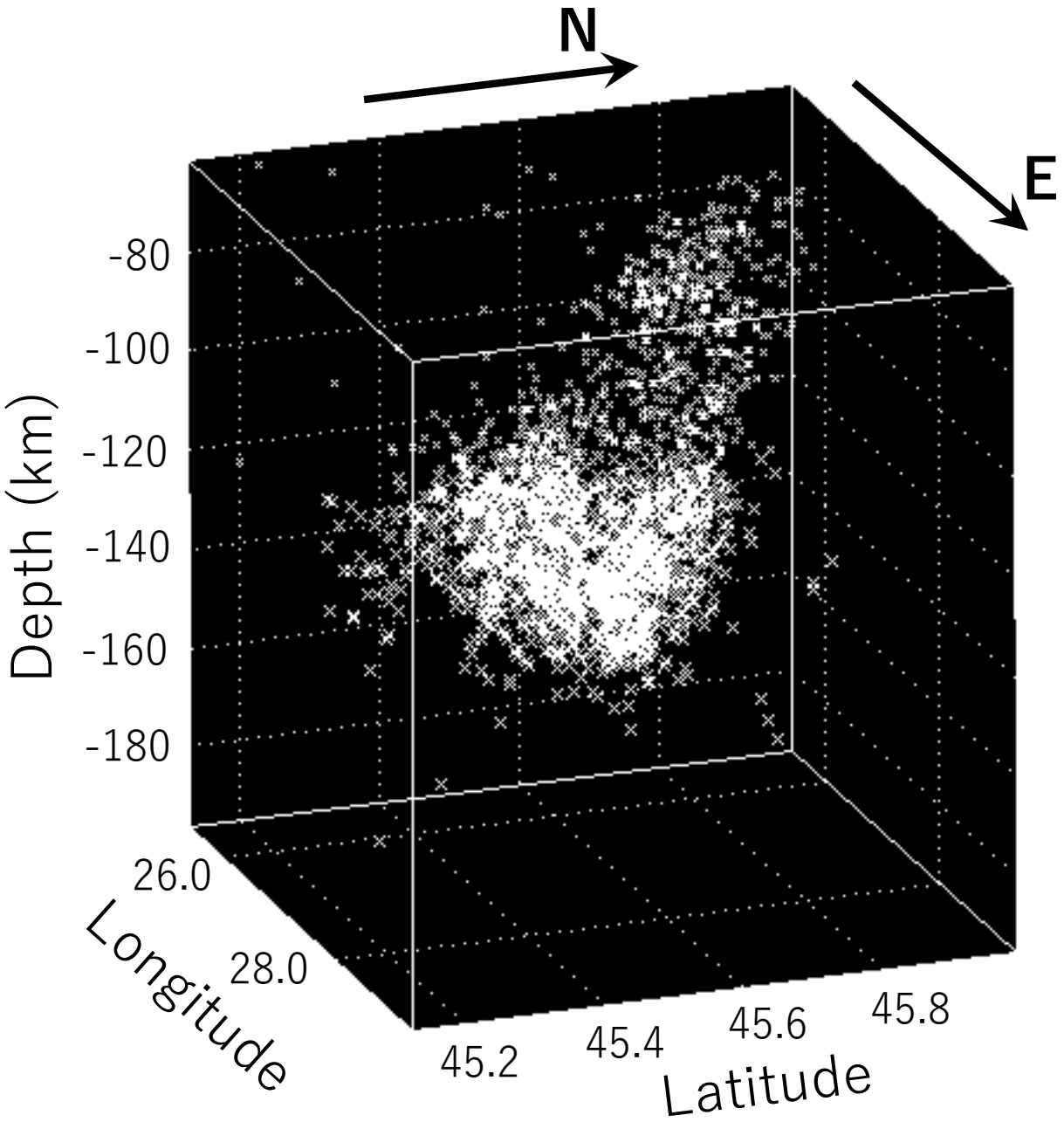


Note the shallow (crustal) seismicity and the intermediate-depth earthquakes of Vrancea region (depth below 60 km)

The deeper seismicity has an upper cluster (60 – 100 km) and a deeper one (100 – 180 km) depth.

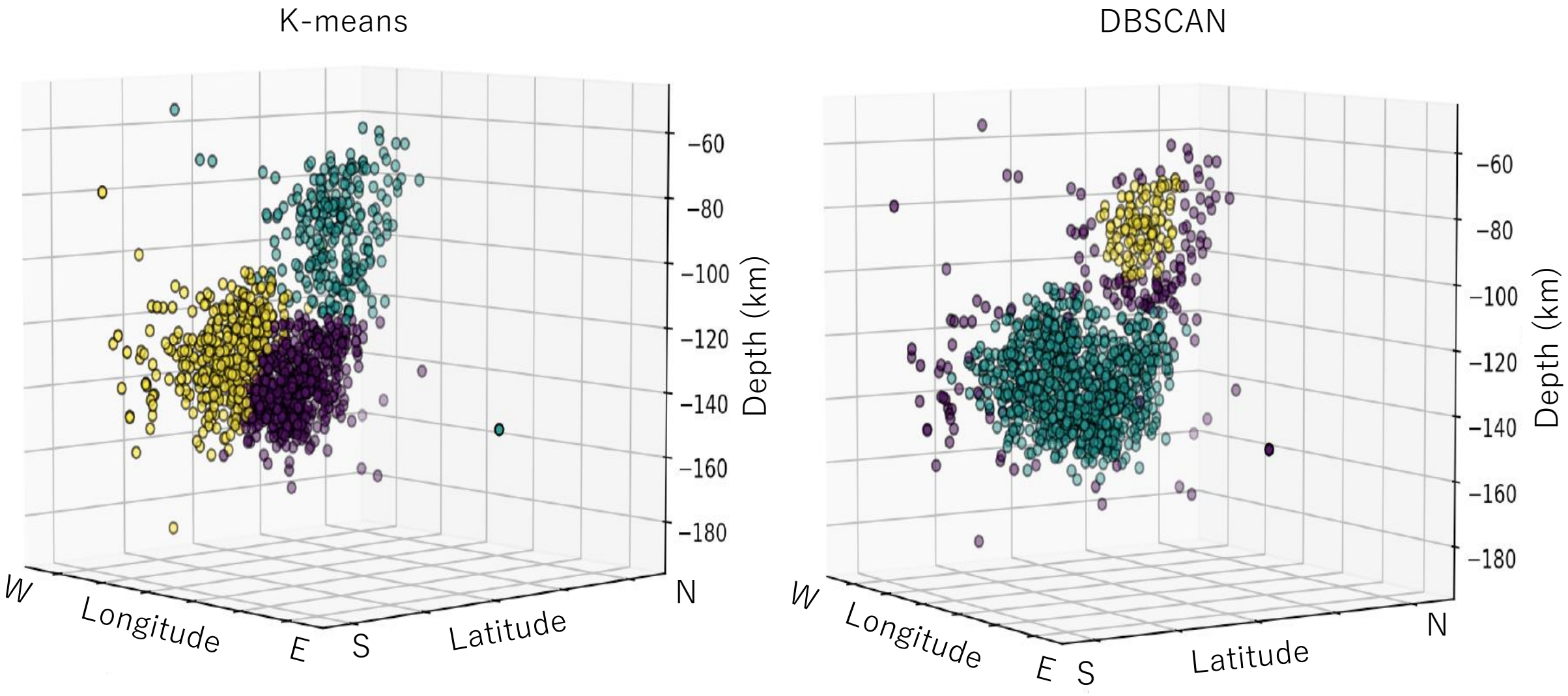
Note the seismic gap between ~40 – 60 km depth (specific for the Vrancea region).

3D plot of Vrancea subcrustal seismicity (M ≥ 3.0)

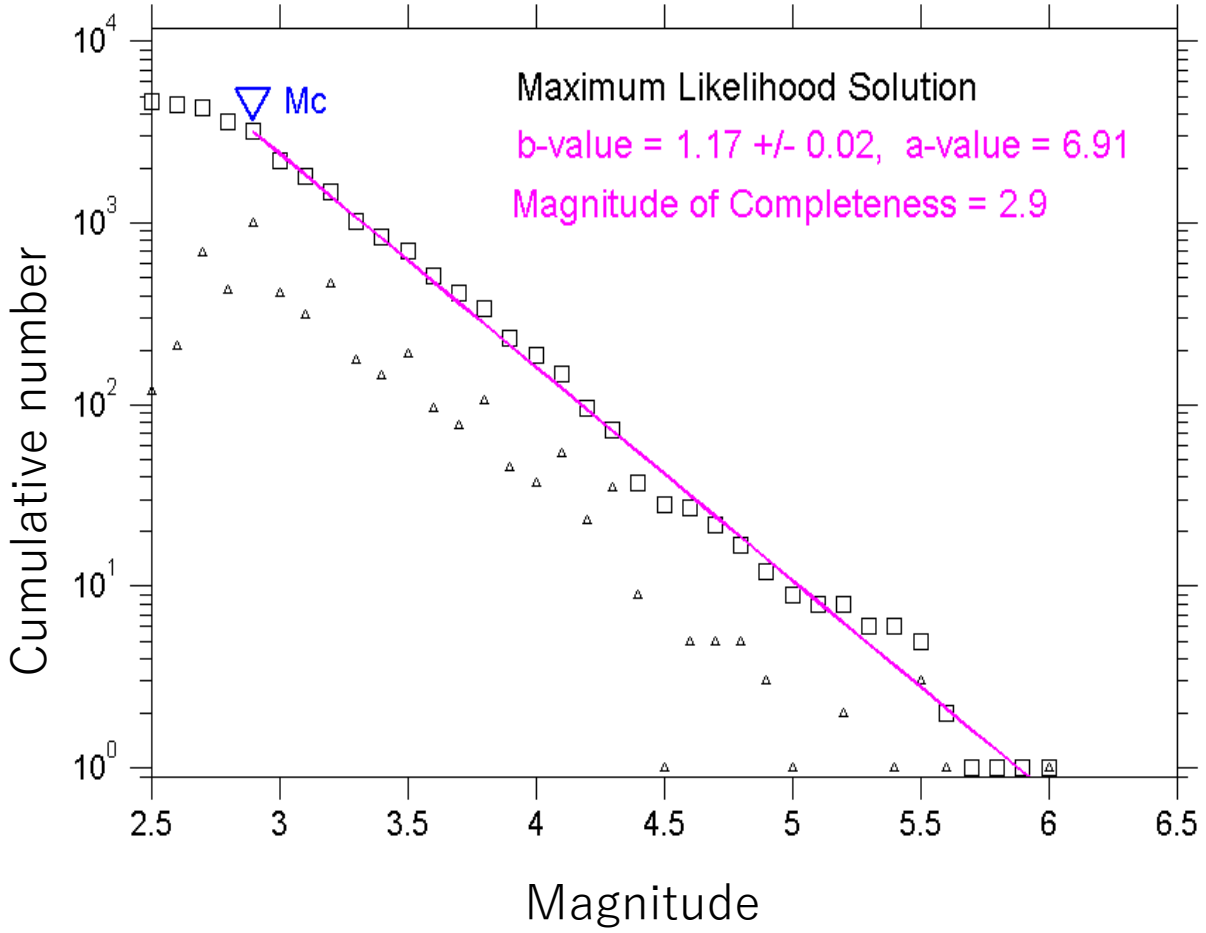


Seismicity distribution is sparser at shallower depth (60 – 100/120 km) compared to the deeper region (100/120 – 180 km)

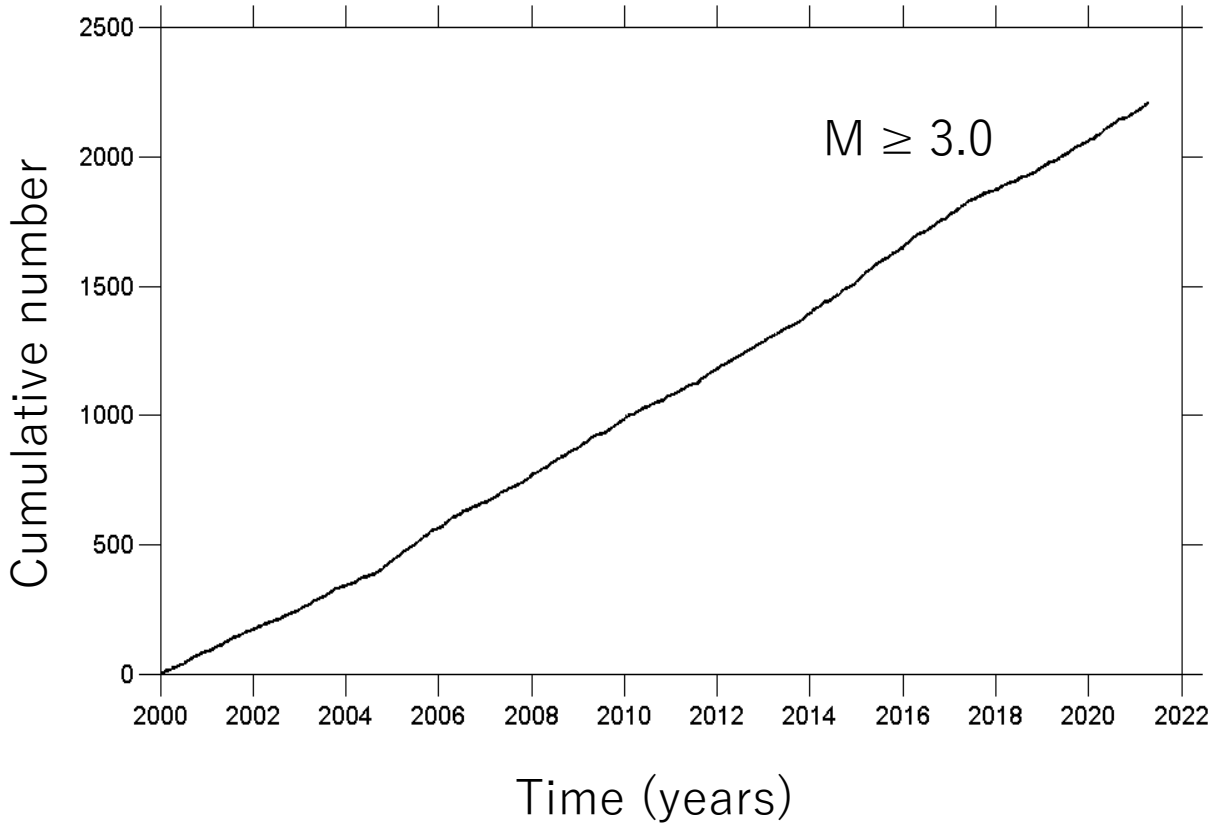
Clustering of Vrancea intermediate-depth earthquakes, using two different algorithms (K-means si DBSCAN); different colors indicate different clusters



Vrancea intermediate-depth earthquakes: cumulative number and b-value (2000 – 2021; depth ≥ 60km)

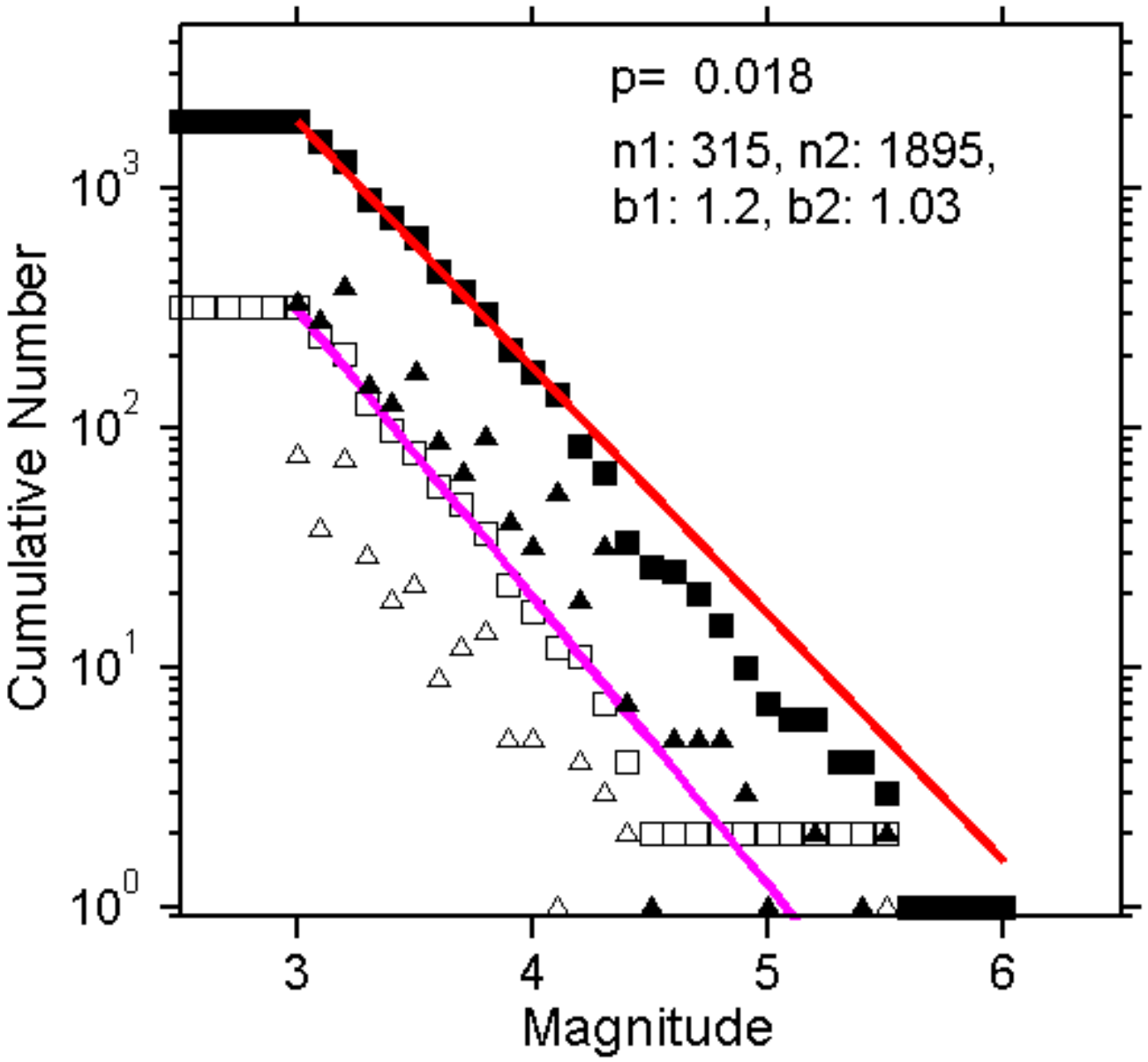


Note the relatively large b-value (~ 1.17)



Note the relatively straight line: scarceness of aftershocks

b-value comparison: shallow region (60 – 100 km, 315 EQs) with deeper region (100 – 180 km; 1895 EQs)



Maximum Likelihood Solution

b-value = 1.20 +/- 0.07, a-value = 6.10

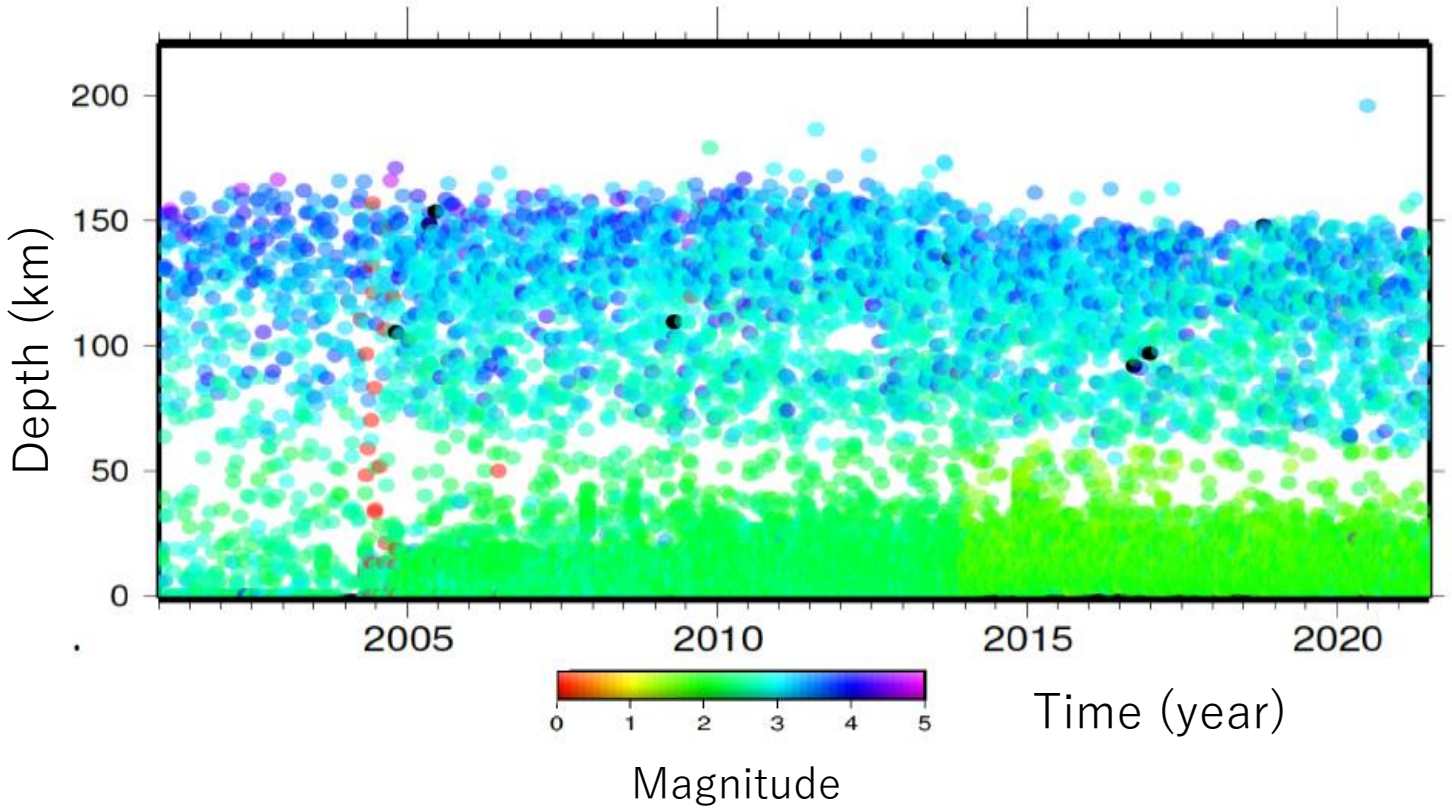
b-value =1.03 +/- 0.02, a-value = 6.36

Smaller b-value (=1.03) for the deeper segment compared to the shallow one (b-value = 1.2).

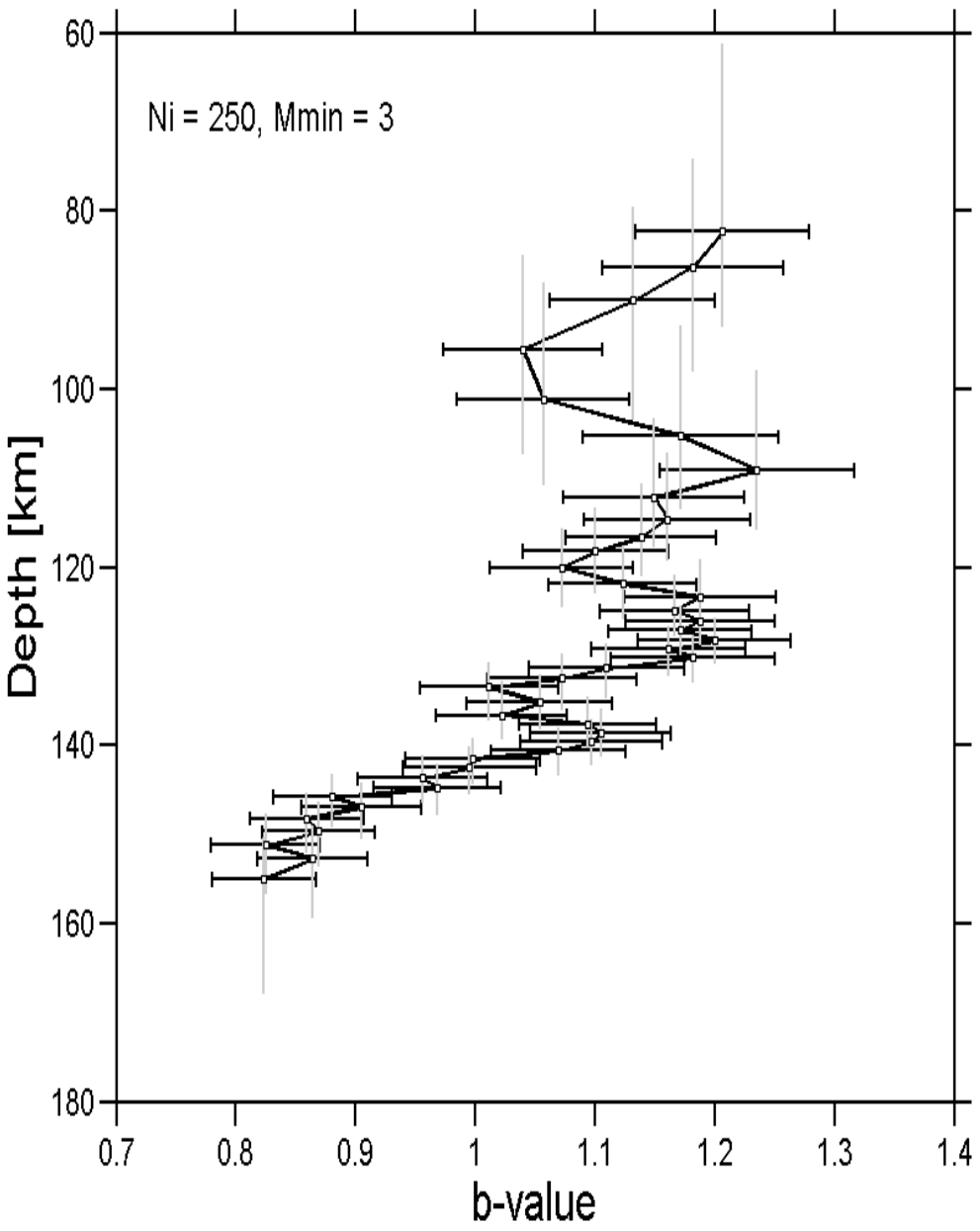
The activity in the deeper segment is more energetic.

Vrancea EQs: depth characteristics

Time versus depth

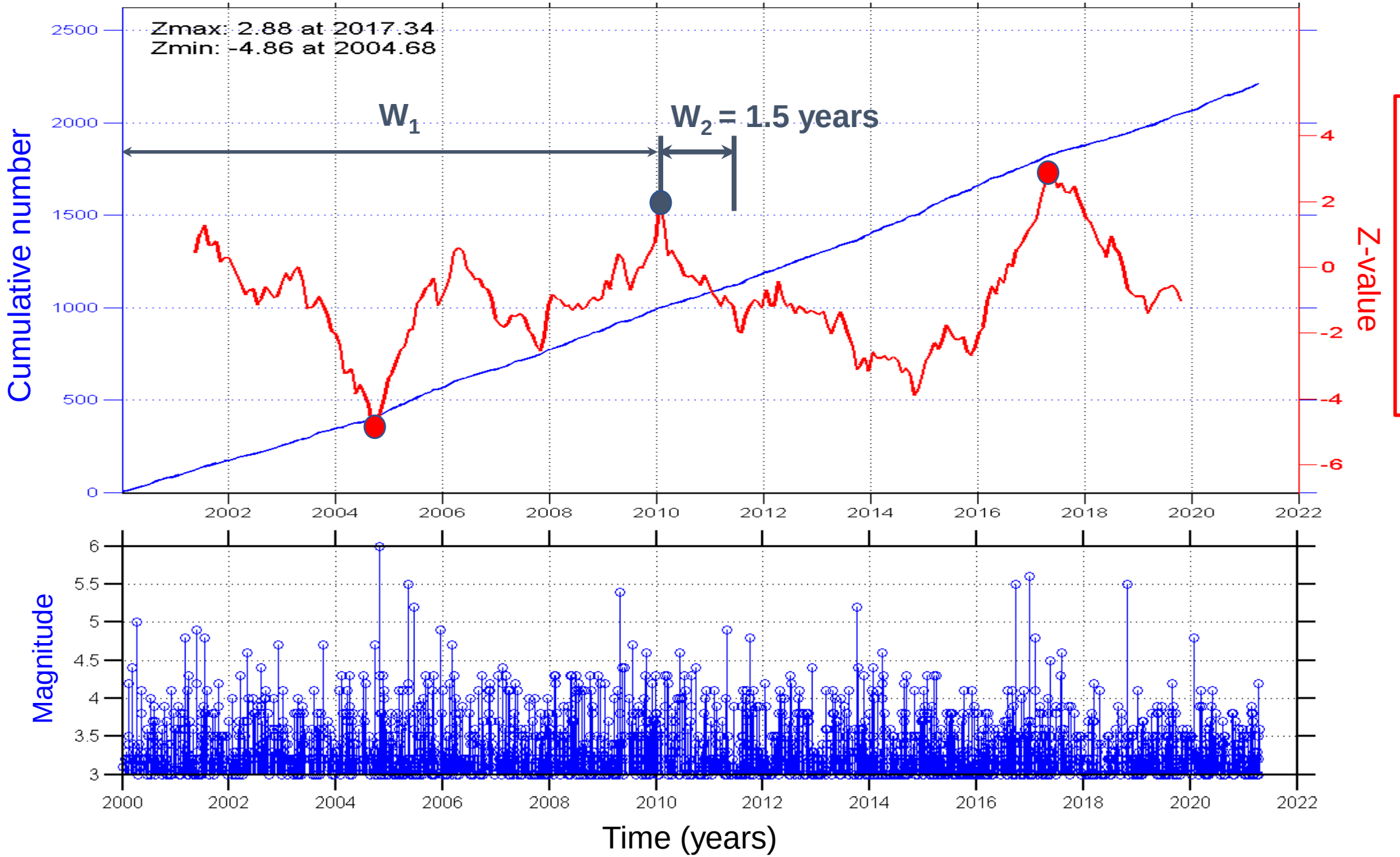


b-value versus depth



Time versus depth graph (left): notice that the lower part of the intermediate-depth seismogenic zone has relatively large events. The same conclusion is supported by the b-value versus depth analysis (right).

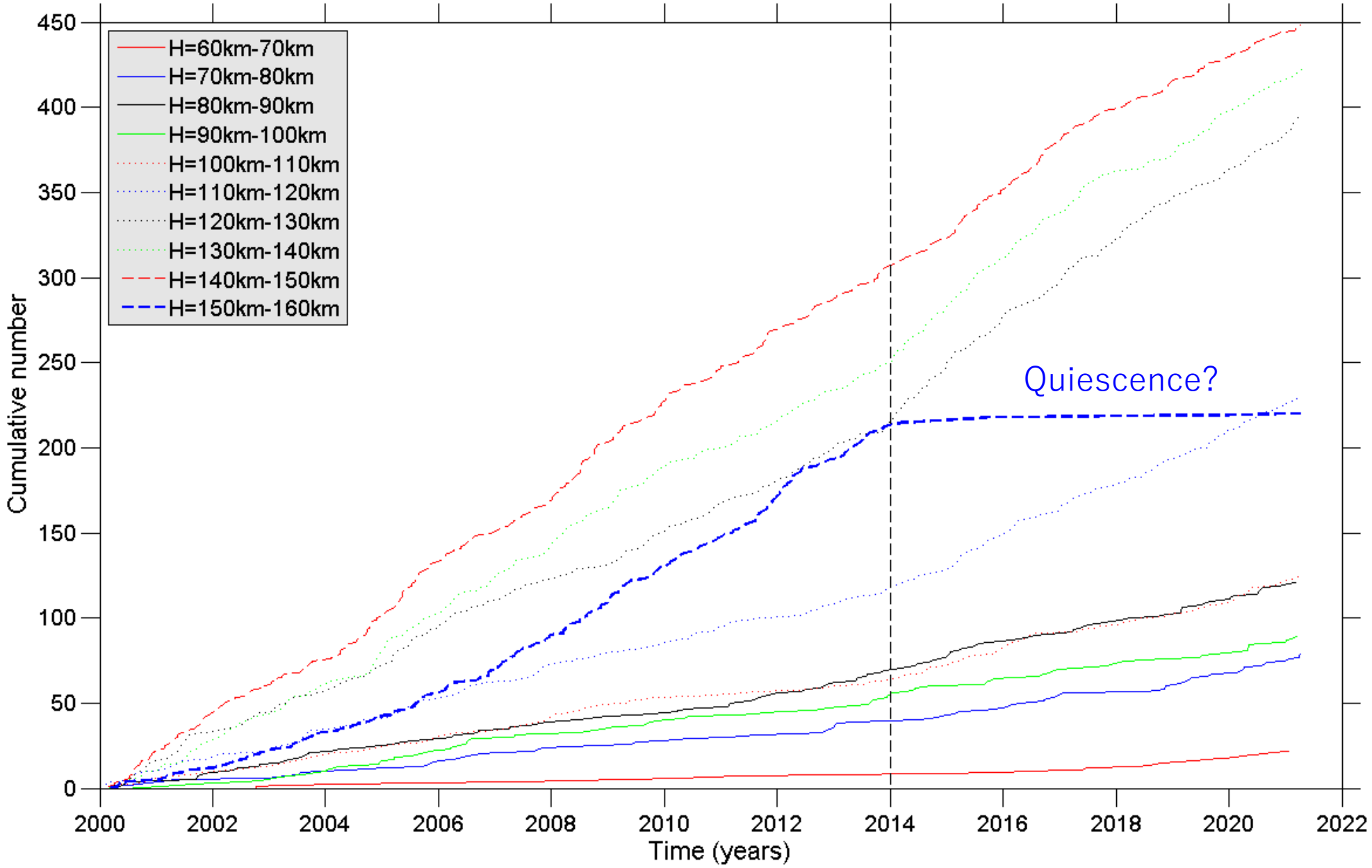
Seismicity rate changes, Vrancea intermediate-depth earthquakes, M ≥ 3.0



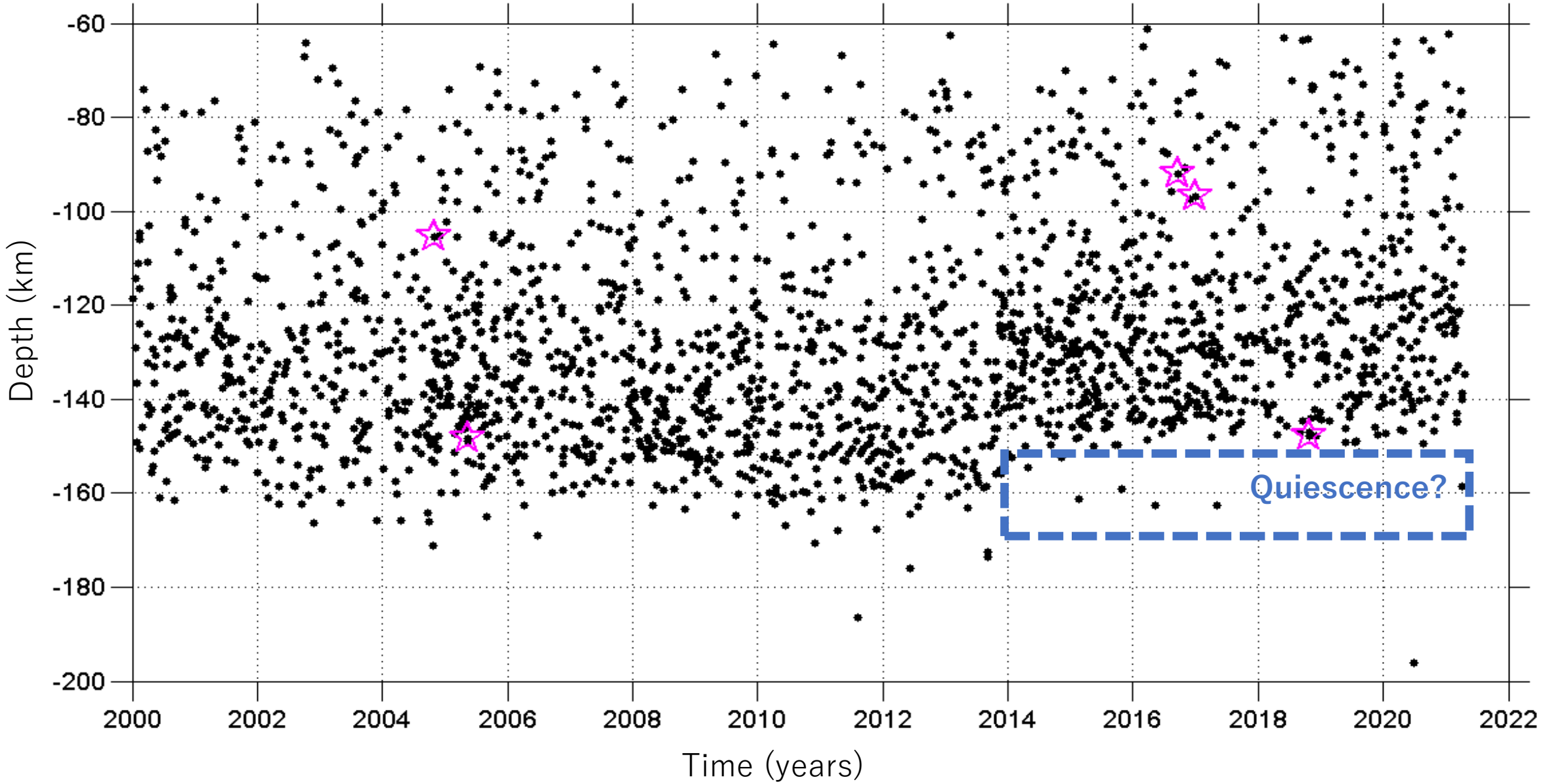
Positive values: quiescence

Negative values: activation

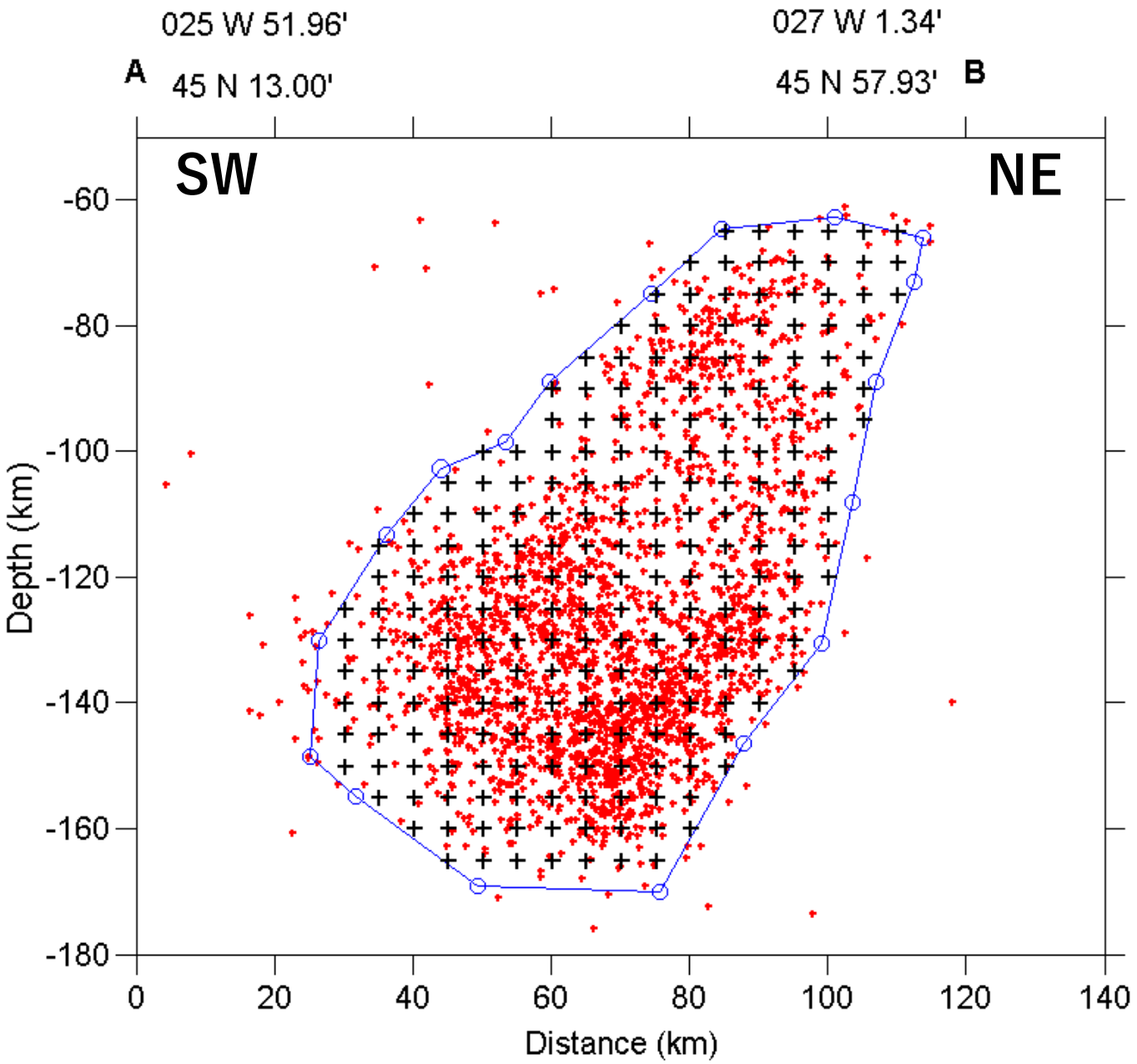
Vrancea subcrustal earthquakes (depth ≥ 60 km; M ≥ 3.0; 2000 – 2021)



Time-depth distribution of Vrancea intermediate-depths earthquakes (M ≥ 3.0; stars: M ≥ 5.5)

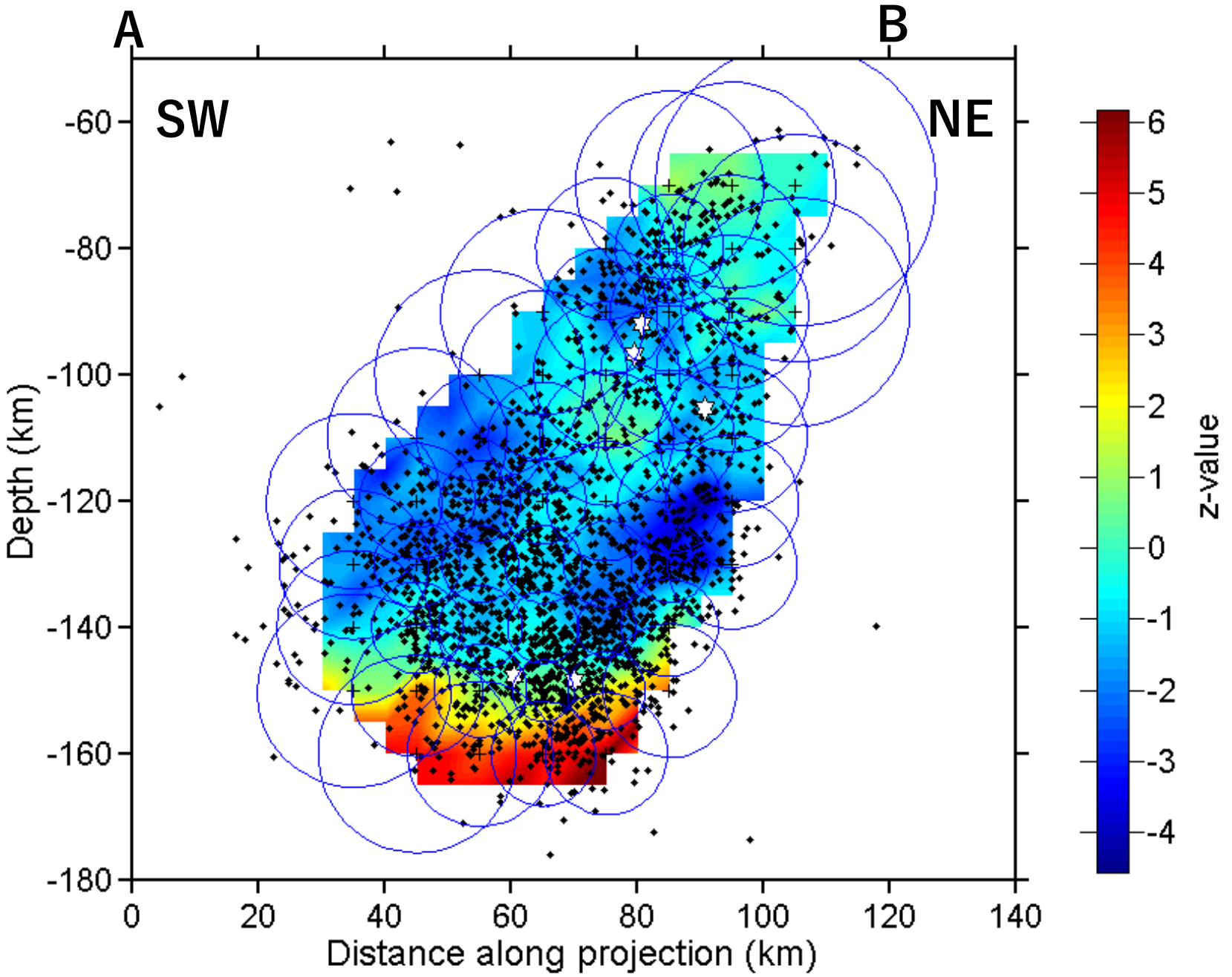


Grid used for the z-value cross-section (next figure) (M ≥ 3.0, 2000-2021)



- 5km spacing
- Ni = 100 earthquakes for each node

Z-value distribution on cross-section (see previous figure)(M ≥ 3.0; 2000-2021)



Cut time: 2014.0
W2 = 1.5 years

White stars:
M >= 5.5

Large, positive z-values at depth: Quiescence?

Table 1. EQs localized using 2 different programs (Antelope & HYPOPLUS)

No.	Date	Origin time	Latitude	Longitude	Depth	Mw	Location program
1	01.09.2016	07:49:21.38	45.607	26.394	144.1	4.1	Antelope
			45.607	26.373	155.0		HYPOPLUS
2	04.08.2016	10:54:40.84	45.587	26.549	140.1	4.1	Antelope
			45.607	26.533	153.8		HYPOPLUS
3	19.11.2016	11:30:39.22	45.641	26.508	140.8	4.1	Antelope
			45.675	26.477	152.2		HYPOPLUS
4	24.08.2014	07:12:49.66	45.568	26.368	147.3	4.2	Antelope
			45.592	26.351	158.4		HYPOPLUS
5	25.04.2018	17:15:48.98	45.607	26.432	147.6	4.1	Antelope
			45.625	26.412	156.9		HYPOPLUS
6	28.10.2018	00:38:11.39	45.608	26.407	147.8	5.5	Antelope
			45.614	26.397	161.6		HYPOPLUS
7	29.03.2014	01:55:16.61	45.346	26.231	144.1	4.0	Antelope
			45.350	26.226	158.1		HYPOPLUS
8	29.03.2015	00:44:58.44	45.619	26.478	145.4	4.3	Antelope
			45.657	26.457	156.7		HYPOPLUS

Antelope is used after the year 2014

Note that the estimated depth differs by more than 9 km, for the same earthquake, when using different location programs

Conclusions

- We have analyzed in detail the intermediate-depth seismicity in Vrancea region (Romania), according to the ROMPLUS seismic catalog, and characterized its space-time structure, its magnitude of completeness, seismicity rate changes and b-value as a function of time and depth.

- Our results reveal a clear clustering of seismicity, as indicated by the visual inspection of earthquakes' distribution, histograms, as well as the application of two different clustering algorithms. We found that in the deeper part of the subcrustal seismogenic zone, larger earthquakes occur more often.

- We have used a grid-based technique to monitor the changes of the z-value statistical parameter.

- Besides the monitoring of the z-value, we are also actively monitoring the b-value parameter as a function of space and time, for the Vrancea subcrustal seismicity.

- During the analysis of seismicity, we have found some location and magnitude determination issues, which are currently tackled.

Acknowledgements

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