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Revisiting Vrancea (Romania) Intermediate-Depth Seismicity: Some Statistical Characteristics and Seismic Quiescence Testing

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Abstract: Background: The intermediate-depth seismicity in the Vrancea region (Romania) is characterized by localized and persistent earthquake activity that culminates about two or three times in a century with the occurrence of a large event (M $\geq$ 6.5). Here we have revisited some important seismicity characteristics, using earthquake catalog data spanning two different time periods: 1960–1999 and 2005–2013. Methods: we have determined the *b*-value of the frequency-magnitude distribution of earthquakes, using a maximum likelihood procedure, and estimated the parameter β to quantify anomalous seismicity rate decreases and increases. Results: by using data from the first period, we have confirmed the existence of a decreased *b*-value in the deepest part of the seismogenic zone; by using data from the second period, we have statistically confirmed the seismic quiescence that preceded the occurrence of the 1977 M7.4 Vrancea earthquake. Conclusions: the decreased *b*-value has been interpreted either in terms of an increased lithostatic stress with depth or as an indicator of the depth range where the next major Vrancea earthquake may occur. The time variation of the seismicity parameter β may reveal anomalous seismic quiescence and increased earthquake rates that may precede the occurrence of large earthquakes.

Keywords: seismicity; *b*-value; seismic quiescence; Vrancea intermediate-depth earthquakes

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1. Introduction

The seismicity of Romania is either crustal, occurring at relatively shallow depths mainly on faults located along the Southeastern Carpathians and Pannonian Depression (e.g., [1]), or sub-crustal, with earthquakes that occur at depths between 60 and 180 km, in a relatively narrow epicentral area known as Vrancea region (e.g., [2,3]). While shallow crustal faults do experience rare large events, like the recent February 2023 earthquake of magnitude (M) 5.7 in Oltenia (Gorj prefecture), the strongest earthquakes in Romania (M $\geq$ 6.5) occur at intermediate-depth, between 60 and 180 km, at the Carpathian Arc bend, in Vrancea (note that we use everywhere in this study moment-magnitudes, as recorded in the ROMPLUS seismic catalog, [4]—see next section).

The persistent intermediate-depth seismicity in Vrancea has been documented for a long time [5]; however, the fine structure of earthquake clusters has been analyzed in detail only more recently (e.g., [6]). As previous studies reported, there are about 2–3 strong intermediate-depth earthquakes in Vrancea per century [7,8]. The seismic hazard associated with these earthquakes impact large regions of Romania, as well as some areas in neighboring countries [9].

There are several seimo-tectonic models that try to explain the occurrence of Vrancea intermediate-depth earthquakes: some of them are in favor of a paleo-subduction of oceanic or continental lithosphere, followed by a deformation phase associated with the detachment and sinking of a seismogenic mantle slab (e.g., [10]), while alternative models propose an ongoing lithosphere delamination (e.g., [11,12]). In a recent study, [13] suggest that Vrancea earthquakes are the result of dehydration of an oceanic slab, beneath the Carpathian arc bend, with limited continental delamination due to the slab pull.

Many researchers have studied possible precursory patterns of large Vrancea earthquakes, thus [14] revealing a long-term seismic quiescence pattern preceding the 1977 M7.4 Vrancea earthquake, by examining time versus depth plots for the intermediate-depth seismicity. Marza [15] reported a seismic quiescence preceding the M7.1 1986 Vrancea earthquake, while [16] documented, in addition, precursory migrating seismicity, short-term foreshock activity, and b-value changes before the same large event.

Radulian and Trifu [17] studied the variation of two parameters, one of them, γ, expressing the relative variation of small versus moderate events, the other one being the fractal dimension of the depth distribution of earthquakes, and found significant precursory variations before the occurrence of the 1986 M7.1 Vrancea earthquake. However, no similar precursory variations were observed before the 1977 and 1990 major shocks [18].

While in this paper we do not discuss the shallow seismicity (0–60 km) in the Vrancea region, we note that it is less energetic (largest known earthquakes have magnitudes M < 6.0) compared to the intermediate-depth earthquake activity. Mitrofan et al. [19] have documented an interesting correlation between the occurrence of strong Vrancea intermediate-depth earthquakes and subsequent significant seismicity in the crustal domain, interpreted as possible delayed triggering.

The aim of this study is two-fold. In the first part, we use a recent data set of earthquakes, from 2005 to 2013, to reveal the spatial structure of intermediate-depth earthquake hypocenters as well as the variation in the *b*-value parameter (i.e., the slope of the frequency-magnitude distribution of earthquakes; [20]) with depth. The *b*-value parameter is useful for monitoring the state of stress of seismogenic zones (e.g., [21,22] and references therein). In the second part, we use a data set of earthquakes occurring from 1960 to 1999 to quantify, in a statistical way, possible quiescence and activation patterns of seismicity associated with the large Vrancea earthquakes occurred in 1977, 1986, and 1990.

2. Materials and Methods

2.1. Materials

We start with an overview of the Romanian seismic network capabilities. Since the beginning of the 19th century, among all the seismic regions of Romania, particular attention has been given to the monitoring of the Vrancea zone. As documented by [23], the 1940 M7.7 Vrancea earthquake marks an important moment for the development of seismological observations in Romania, with seven permanent observatories being installed by 1952, six of them within less than 200 km from the Vrancea region. Another pivotal moment is represented by the occurrence of the 1977 M7.4 Vrancea earthquake: after this large event, additional seismic stations were installed and pre-existing ones were modernized [24], leading to the establishment between 1980–1982 of the first Romanian telemetry seismic network, consisting of 18 short-period seismic stations [25]. In the 1990s and afterwards, the Romanian seismic network has continued to develop and modernize [26]; besides the short-period seismic stations, the network included by the end of 2013 at least a dozen broad-band seismic stations surrounding the Vrancea region [25]. For the current status of Romania's and neighboring countries seismic networks, we refer to [27] (see also Supplementary Materials, Figure S1).

In this study, we use the ROMPLUS seismic catalog of [4] that is being constantly updated [28] by the National Institute for Earthquake Physics (NIEP), Romania. The catalog spans the entire territory of Romania, from 984 to October 2022. Figure 1 shows the epicentral distribution of earthquakes with magnitudes M $\geq$ 3.0 in the catalog, together with the most important seismic regions of Romania, while Figure 2 presents N–S and W–E cross-sections of seismicity (distance versus depth distributions of earthquakes along two profiles).

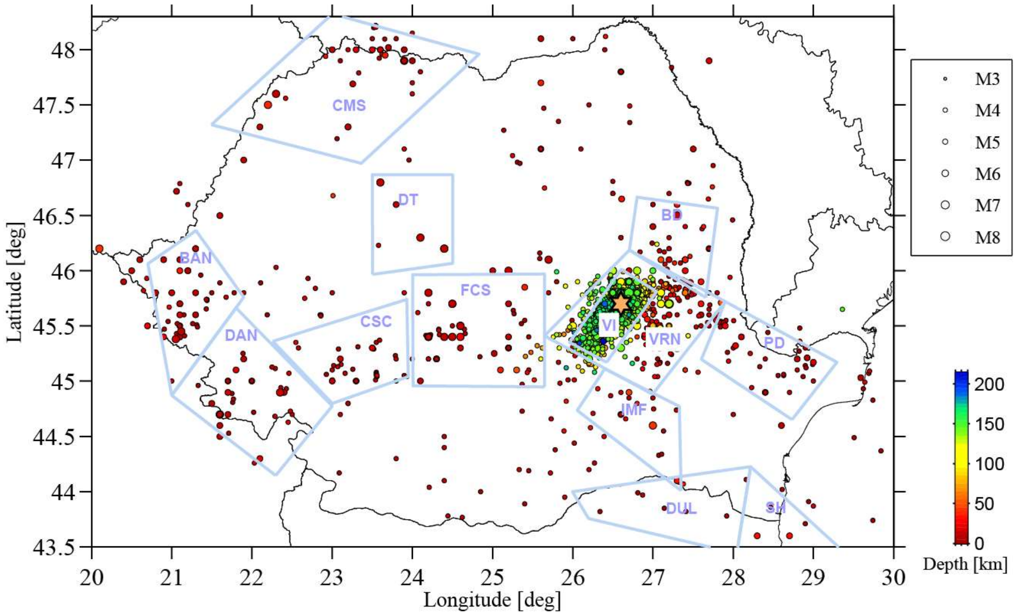

Figure 1. Seismicity of Romania (M $\geq$ 3.0), between 984 and 2022, according to the ROMPLUS catalog ([4,28]). The epicenters of earthquakes are shown by circles, colored as a function of the hypocentral depth and with their size scaling with the magnitude of the earthquake. The yellow star represents the largest historic earthquake that occurred in the Vrancea region in 1802, with an estimated magnitude of 7.9. The blue rectangles indicate seismic areas of Romania (modified after [29]): CMS: Crișana-Maramureș, DT: Transylvanian Depression, BAN: Banat, DAN: Danube Zone, FCS: Făgăraș-Câmpulung-Sinaia, VRN: Vrancea, VI: Vrancea subcrustal, IMF: Intra-Moesian Fault, PD: Depression Predoborgeană, BD: Bârlad Depression; SH: Shabla and DUL: Dulovo. We have added the CSC region (modified after [30]), where a recent M5.7 earthquake occurred in 2023.

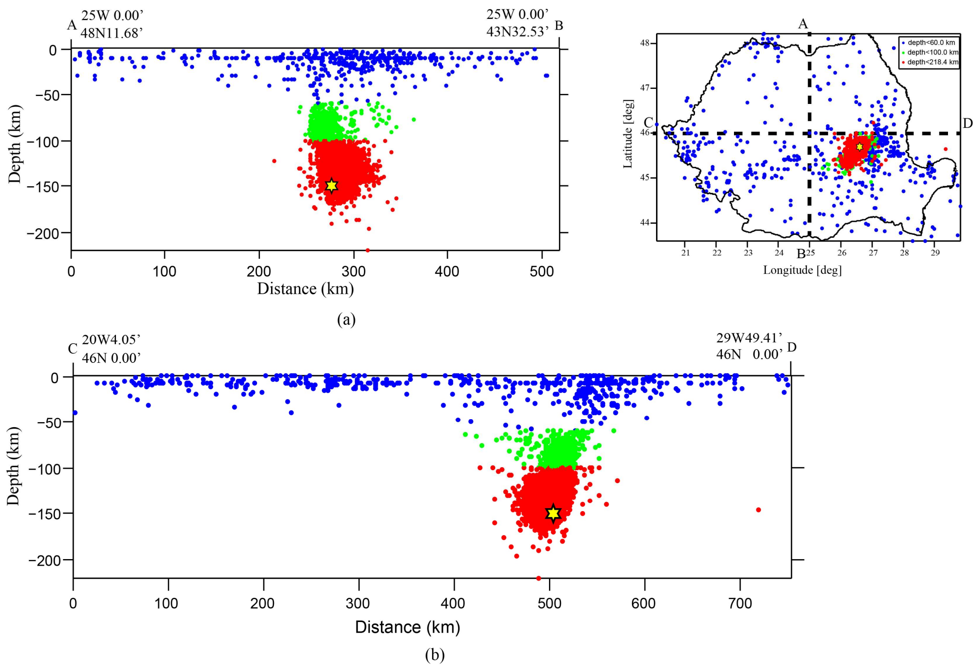

Figure 2. Transverse cross-sections (distance-depth) of seismicity (M $\geq$ 3.0) on the territory of Romania (984–2022), oriented (**a**) N–S and (**b**) W–E. The profiles A–B and C–D are shown on the inset map (**upper right**). The epicenters in the inset map and cross-sections are colored function of depth, as indicated in the inset legend. Yellow star has the same meaning as in Figure 1.

The ROMPLUS catalog data from the period 984–1979 are compiled from the catalogue of [31]. Although various types of magnitudes have been used throughout the development of these catalogues, all the ROMPLUS earthquakes have a listed moment magnitude, which is used in this paper (we do not perform any magnitude conversion in this study). The calibrated relationships used for magnitude conversions are presented and discussed in [4]. Previous research [15] estimated that intermediate-depth earthquake reporting is complete for magnitudes $M \geq 3.6$, for the period 1961–1977. Ardeleanu and Neagoe (2016) [32] performed a detailed analysis of network capabilities and seismicity, estimating a magnitude of completeness (*Mc*) of ~3.0, for the interval 2000–2006, for the Vrancea intermediate-depth earthquakes, followed by a gradual decreasing trend in the following years (2008–2013). In another study, [33] estimated that as of August 2011 the Romanian seismic network was capable of detecting any earthquake with $M_L > 2.0$ ($M_W > 2.3$) in the Vrancea intermediate-depth seismic region.

Since the number of seismic stations increased after the year 2004, we selected first for our analysis a catalog that starts from 2005. We limited the period of analysis to 2013 (so our first data set spans 9 years), because from 2014 there is an artificial change of earthquakes' depth in the catalog, due to the use of a different velocity model and earthquake location procedure [34]. This first set of data is used to infer some general characteristics of seismicity. We also use a data set spanning 40 years, from 1960 to 1999, in order to test some seismicity patterns (in particular, seismic quiescence) before the three large earthquakes of $M \geq 6.5$ that occur in this period, in 1977, 1986, and 1990.

Different magnitude thresholds have been used for the first and second data set, in order to account for the magnitude of completeness, *Mc*, of the data (see Section 3. Results). Since the depth location uncertainties are larger for the early period (in particular before 1980; [31]), we do not perform a depth-dependent analysis for the 1960–1999 interval. An insufficient number of recorded arrival times and larger errors associated with the arrival time picking, in particular on analogue seismograms, are among the reasons for poorly constrained hypocenters [35].

2.2. Methods

We use the Gutenberg–Richter law [20] to describe the frequency-magnitude distribution of earthquakes:

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

where *N* is the cumulative number of earthquakes with magnitudes larger or equal than *M* and *a*, *b* are constants. The parameter *b* and *a* describe the relative proportion of larger earthquakes compared to smaller ones and the total number of earthquakes, respectively. The parameters *a* and *b* are determined using a maximum likelihood procedure [36,37], together with parameters' standard deviation [38]. The magnitude of completeness (*Mc*) is calculated using the Entire Magnitude Range (EMR) technique [39], and the parameters in (1) are determined for magnitudes equal or larger than *Mc*. As discussed in [39], the EMR technique provides relatively stable results and has a superior performance compared to other three often used methods for estimating *Mc*: the MAXimum Curvature (MAXC) technique [40], the Goodness-of-Fit Test (GFT, [40]), and the Mc by *B*-value Stability (MBS) technique [41]. All computations in this study are performed using the MATLAB programming language and the ZMAP software [42], version 6.

For quantifying the change in the *b*-value as a function of depth, we use a sliding-window technique, with each window containing $ni = 150$ earthquakes and a sliding $step = 30$ events (an overlap factor, defined as $ni/step$, of 5, in ZMAP). We have checked the stability of our results for *ni* values from 100–200 and overlap factors between 5 and 10.

The quantification of changes in seismicity rate is calculated by using the β-value statistic [43], which is sensitive to the difference of average seismicity rates in two time periods and is defined as follows:

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

where N is the number of earthquakes in a background time window, T, and N_a is the number of events in a time period of interest, T_a. The method has been applied to detect both seismicity activation and quiescence (e.g., [44]). We consider the background window, T, spanning the whole period of the analyzed data set, except T_a, and move the T_a window, chosen here as 1.5 years, along the entire period with a time step of 14 days (we use the LTA(t) function approach of [45]). The choice of T_a = 1.5 years is somehow arbitrary; we have avoided choosing too-large windows that may miss significant, relatively short increases or decreases of seismicity rate, as well as too-short windows that may reveal very local seismicity fluctuations. Nevertheless, in order to test the stability of our results for different window lengths, we have varied T_a from 1.5 to 3.0 years.

In the case of shallow earthquake sequences, dominated by aftershocks, the catalog is usually declustered before computing the β-values since the aftershocks may bias the analysis. However, the Vrancea intermediate-depth seismicity has much less pronounced and shorter aftershock sequences [46,47], as it is the typical behavior for the intermediate-depth and deep earthquakes [48]; therefore, we do not decluster the catalog in this study. To estimate the statistical significance of the obtained β-values, we simulate 10,000 random (Poisson-type distribution) earthquake data sets having the same time span and number of events as the real data and estimate the β-values in the same way as we did for the real data set. The β-values obtained for the random Poisson earthquake catalogs follow a normal distribution [43]. Then, the statistical significance of the β-values obtained for the real data is interpreted in terms of deviations from the mean of the normal distribution. We have also followed an alternative approach to estimate the β-value statistical significance, by using 10,000 earthquake data sets with inter-event times drawn randomly from the real catalog, having the same number of events as the real data, since this kind of catalog simulation might be more realistic.

3. Results

3.1. Some General Characteristics of Intermediate-Depth Seismicity

Figure 3a shows the cumulative number of earthquakes versus magnitude for the intermediate-depth Vrancea earthquakes (depth $\geq$ 60 km, M $\geq$ 3.0), from 2005 to 2013. As we have checked by using the EMR procedure, the data set is complete above a magnitude M = 3.0. Nevertheless, checking *Mc* for shorter periods, we have noticed that for some earlier times, it is slightly higher (up to M3.2). The slope of the frequency-magnitude distribution in the linear-log scale, *b*-value, equals 1.02 $\pm$ 0.03. for a threshold magnitude M = 3.0. If the threshold magnitude is set at 3.2, the *b*-value is similar, 1.06 $\pm$ 0.04. Figure 3b shows the cumulative number of earthquakes versus time for the studied period (2005–2013) for two threshold magnitudes, M3.0 and M3.2. The almost linear trend of both cumulative distributions can be noticed; note that the largest event during the studied period has a magnitude of 5.5.

Since subtle variations of the magnitude of completeness, *Mc*, may affect the interpretation of seismicity variations, in particular *b*-values, in the following two figures we use a threshold magnitude of 3.2 after carefully checking that this value is suitable for various depth intervals during the analyzed time period.

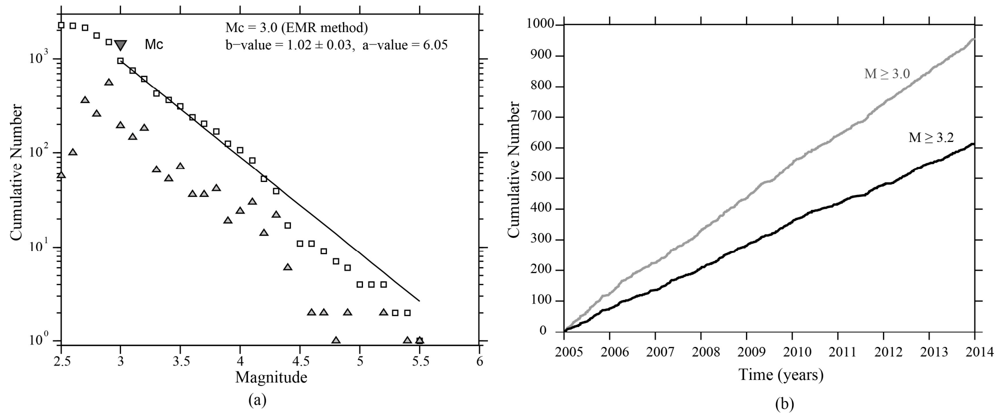

Figure 3. (**a**) Cumulative (empty rectangles) and non-cumulative (full triangles) number of earthquakes versus magnitude for the intermediate-depth Vrancea earthquakes (ROMPLUS catalog, 60–220 km depth), period 2005–2013, M ≥ 3.0. The earthquake data are complete above *Mc* = 3.0 (indicated by an inverted triangle). The black curve is a fit to the data, with the *a*- and *b*-values of the frequency-magnitude relation determined using a maximum likelihood procedure. (**b**) Cumulative number of earthquakes with time (years), for two threshold magnitudes (3.0 and 3.2).

Figure 4 shows the histogram of the cumulative number of subcrustal Vrancea earthquakes (M ≥ 3.2) as a function of depth. As one can notice, the number of events has a first peak around 90 km depth, followed by a short decrease and another marked increase that peaks around 130–150 km.

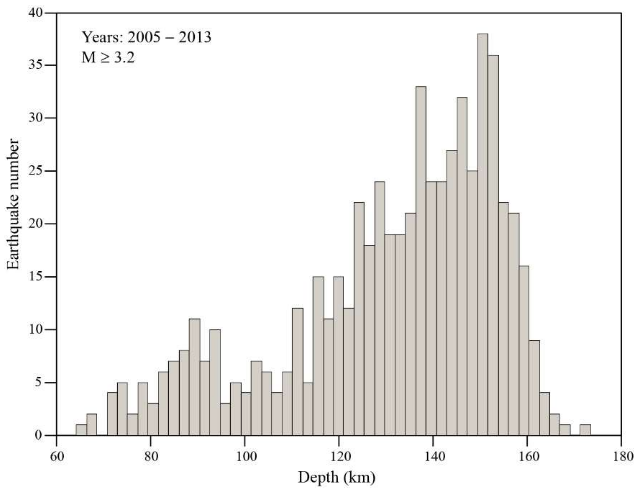

Figure 4. Histogram of earthquakes (2005–2013, M ≥ 3.2) as a function of depth for Vrancea intermediate-depth earthquakes.

The variation with depth of the *b*-value for the intermediate-depth seismicity is shown in Figure 5. The shallower part of the depth interval (60–140 km) is characterized by larger *b*-values than the deepest part of the earthquake cluster (140–160 km).

We have also checked that *b*-value results are not dependent on the chosen window length, by using *ni* value from 100–200, and chosen window sliding steps, by using overlap factors between 5 and 10. Figure S2 shows an example that uses *ni* = 200 events and an overlap factor of 10. We note that the differences between results are within the estimated errors.

In order to further validate our findings, we present in Figure S3 the frequency-magnitude distribution for the seismicity in two depth intervals: 120–140 km and 140–160 km. As one can notice, the *b*-values determined for earthquakes with magnitudes larger or equal to *Mc* (calculated using the EMR method) agree with the results presented in Figure 5.

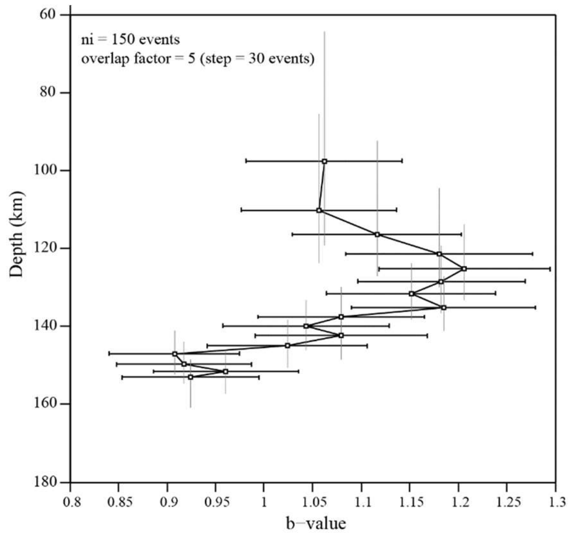

Figure 5. *b*-value variation with depth for the intermediate-depth Vrancea earthquakes. There are *ni* = 150 events in a window that is shifted along the entire depth range with a step of 30 events. The horizontal bars show estimation uncertainties, while the vertical ones show the depth span of each window.

3.2. Checking for Seismicity Rate Changes for Vrancea Intermediate-Depth Earthquakes

As explained in Section 2. Materials and Methods, we analyze next a data set of intermediate-depth earthquakes (ROMPLUS catalogue data) that occurred from 1960 to 1999, with magnitudes M $\geq$ 3.0. As one can see in Figure 6, the data set is complete above *Mc* = 3.5, as determined by the EMR method. The *b*-value equals 0.91 $\pm$ 0.03, a value that is smaller than the one for the interval studied in the Section 3.1 Some General Characteristics of Intermediate-Depth Seismicity. In order to account for possible variations of *Mc* values with time, we have selected M = 4.0 as a threshold for further analysis. The *b*-value for a magnitude threshold M = 4.0 is 0.82 $\pm$ 0.05.

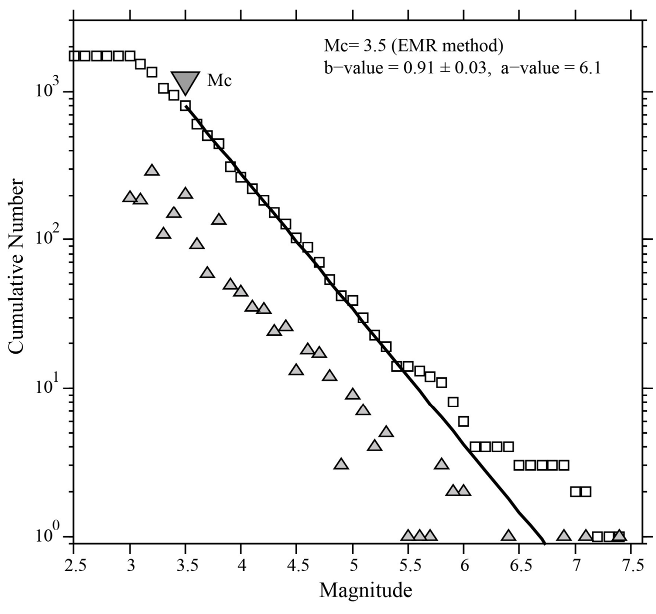

Figure 6. Cumulative (empty rectangles) and non-cumulative (full triangles) number of earthquakes versus magnitude for the intermediate-depth Vrancea earthquakes, ROMPLUS catalog, period 1960–1999, M $\geq$ 3.0. The earthquake data are complete above Mc = 3.5 (indicated by an inverted triangle). The black curve is a fit to the data, with the *a*- and *b*-values of the frequency-magnitude relation determined using a maximum likelihood procedure.

Figure 7 presents the magnitude versus time variation of intermediate-depth seismicity, during the studied interval. Several features of seismic activity can be recognized by visual inspection. The clearest one is a relatively quiescent period starting before 1970 and continuing until the 4 March 1977 M7.4 Vrancea earthquake.

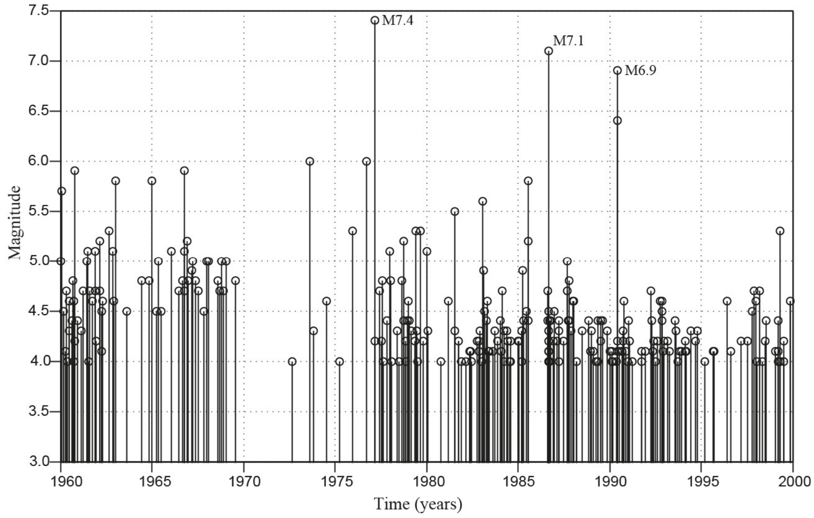

Figure 7. Magnitude versus time for the intermediate-depth Vrancea earthquakes, from 1960–1999. The threshold magnitude is M = 4.0. The three largest earthquakes during the studied period are marked in the figure (1977 M7.4, 1986 M7.1, and 1990 M6.9 Vrancea earthquakes).

Figure 8 shows the variation in the cumulative number and β-value parameter versus time for the 1960–1999 interval. Some slight increase in seismicity can be noticed after the three largest earthquakes occurred during this period, in particular immediately after the 1986 M7.1 Vrancea earthquake. The β-values are plotted at the end of the 1.5-year long moving window. One can notice that the most prominent negative β-values, which indicate a relative seismicity decrease that started around 1970 (with a minimum of −3.21 reached at the beginning of February 1971) and continued until the time of the 1977 M7.4 Vrancea earthquake, when the parameter started abruptly increasing. The largest positive β-value (of +6.81) was recorded in January 1988, in a window (of 1.5 years) that includes the M7.1 Vrancea earthquake that occurred on 30 August.

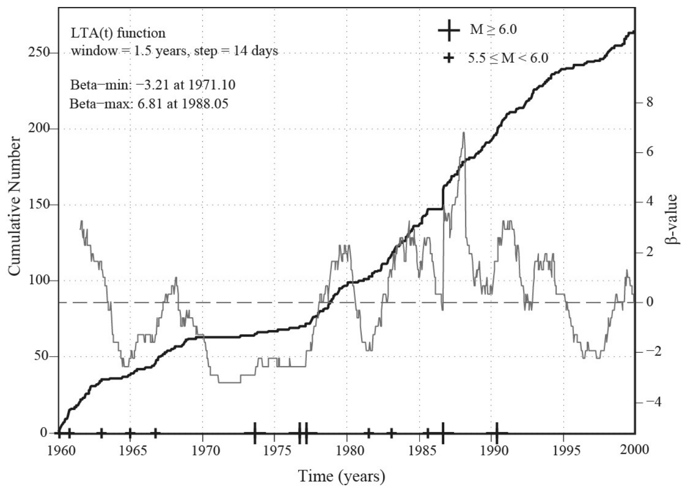

Figure 8. Cumulative number of earthquakes (black curve) and β-value variation (LTA(t) function, gray curve) for the Vrancea intermediate-depth earthquakes (M $\geq$ 4.0, 1960–1999). The window-used to calculate the β-value is 1.5 years, moved along the entire time interval with a step of 14 days. The large and small crosses on the time axis indicate events with magnitudes M $\geq$ 6.0 and 5.5 $\leq$ M < 6.0, respectively.

The statistical significance of the relative seismicity decreases and increases has been assessed using two different procedures, as explained in the Section 2.2 Methods, and the results are presented in Figure 9.

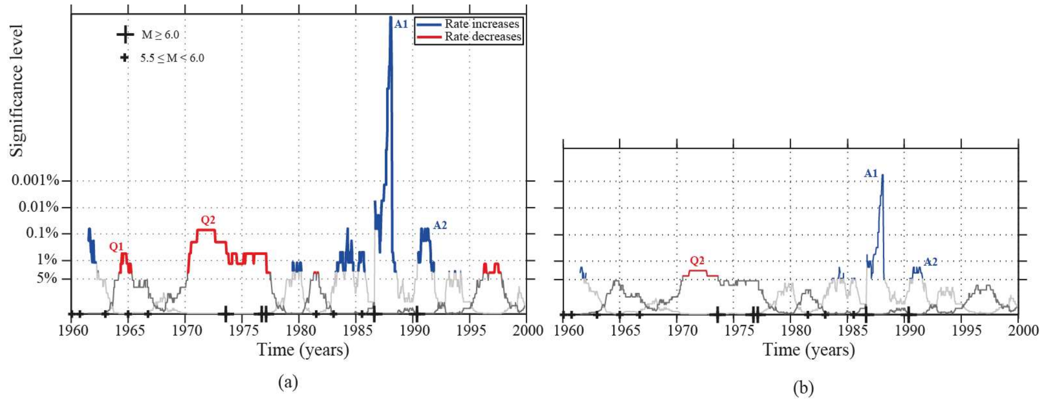

Figure 9. (**a**) Significance of rate increases and decreases (same window length and step as in Figure 8; gray curves) for the Vrancea intermediate-depth earthquakes (M $\geq$ 4.0, 1960–1999), based on random, Poisson, catalog simulation. Blue and red colors indicate windows of rate increase and decrease, respectively, that have significance levels below 5% (confidence levels above 95%). (**b**) Same as in (**a**), when using catalog inter-event time to perform the significance estimations. The symbols (Q1, Q2, A1, A2) are referred in the text.

The seismicity decreases marked with Q1 and Q2 in Figure 9a precede the occurrence of the 4 March 1977 M7.4 Vrancea earthquake and are significant at a 95% confidence level (with some parts being significant at even higher confidence levels). The seismic activations marked with A1 and A2 in the same figure correspond to time periods immediately following the 30 August 1986 and 30 May 1990 Vrancea earthquakes and are highly significant from a statistical point of view. Note however that there are a few other significant decreases and increases of seismicity rates during the 40 years interval (see the discussion in the next section).

The significance test that uses inter-event times from the real earthquake catalog produces three significant anomalies (Figure 9b): Q2 anomaly (rate decrease preceding the 1977 M7.4 Vrancea earthquake–similar with Q2 in Figure 9a, but having a shorter duration) and A1 and A2 anomalies (rate increases following the 1986 M7.1 and 1990 M6.9 Vrancea earthquakes). Figure S4a presents β-value results obtained for a window *Ta* = 2.0 years, while Figure S4b shows a significance test similar to that in Figure 9b.

4. Discussion

The Vrancea intermediate-depth seismicity occurs in a relatively narrow epicentral area (Figure 1), with hypocentral distribution dipping at a quasi-vertical angle towards south-west (Figure 2), being located at depths between 60 and 220 km (but mostly between 60 and 180 km, Figures 2 and 4). It is one of the three well-known intermediate-depth earthquake nests (areas of relatively high seismicity, isolated from the nearby seismic areas), together with the Bucaramanga (Columbia) and Hindu-Kush (Afghanistan) regions (e.g., [49]). The histogram of earthquakes' depth distribution (Figure 5) has two peaks, around 90 km and 130–150 km, as has been also described in previous studies (e.g., [50]). A double-peaked depth histogram is most clear in the case of the Hindu-Kush nest [49], which spreads over a depth range between about 75–250 km, while the Bucaramanga nest is the most concentrated.

The slope of the frequency-magnitude distribution of earthquakes in a linear-log scale, *b*-value, expresses the relative proportion of larger earthquakes compared to smaller ones (i.e., a smaller *b*-value signifies a higher proportion of larger events and vice versa). Relatively small *b*-values have been interpreted as an increase in differential stress (e.g., [51]) and significant *b*-value variations have been reported in relation to some large earthquakes (e.g., [52]). A *b*-value around 1.0 is the average value observed for both shallow and deep word-wide seismicity (e.g., [53]). The result for the intermediate-depth seismicity ($M \geq 3.0$) in the Vrancea region, for the 2005–2013 interval (Figure 3a), agrees with the world-wide findings.

While in the case of shallow, crustal seismicity one can usually see a clear aftershock signature even in the case of smaller earthquakes, the linear trend in Figure 3b suggests that aftershock activity is either lacking or is extremely weak during the 2005–2013 period, for the intermediate-depth Vrancea earthquakes. For the period 1960–1990, the seismicity rate increases denoted by A1 and A2 in Figure 9 following the 1986 and 1990 large Vrancea earthquakes, respectively; these periods correspond to relatively intense aftershock activity reported in previous studies [46,47]. One can therefore infer that the seismicity in the 2005–2013 period is essentially background seismicity.

While the *b*-value for the background intermediate-depth seismicity in Vrancea is close to 1.0 (Figure 3a), variations can be seen as a function of depth (Figure 5). The *b*-value variation with depth proves stable when using different parameters for the computations (see Section 3.1 Some General Characteristics of Intermediate-Depth Seismicity). A significant decrease in the *b*-value in the deepest part of the Vrancea seismogenic zone has been also reported by [54], using a different time period. This behavior agrees with an increase in lithostatic stress and stress drop, as a function of depth [55]. A low *b*-value in the deepest part of the intermediate-depth seismogenic region is also consistent with models assessing that the next large Vrancea earthquake will occur at depths between 140–160 km (e.g., [56]), since smaller b-values may indicate regions under larger differential stresses (e.g., [21]).

The analysis of seismicity from 1960 to 1999 revealed a smaller *b*-value than for the 2005–2013 interval. One possible explanation for this relatively low *b*-value is the more energetic intermediate-depth seismic activity during the 1960–1999 period, when three large Vrancea earthquakes occurred in 1977, 1986, and 1990. However, such differences should be interpreted with caution, due to the different magnitude thresholds and sample lengths used in each case.

The visualization of the magnitude versus time plot in Figure 7 as well as the β-value analysis (Figures 8 and 9) reveal a seismic quiescence pattern before the 4 March 1977 M7.4 Vrancea earthquake.

The symbols Q1 and Q2 in Figure 9a correspond approximately to the decreased seismicity in two distinct time intervals identified by [14] as the first and second stage, respectively, of abnormal seismic quiescence (seismic gap), in the depth interval 85–130 km, before the occurrence of the 1977 mainshock, at a depth of 94 km. The two intervals lasted, according to [14], from 1963–1967 and 1968–4 March 1997 Vrancea earthquake, respectively. A possibly more realistic significance analysis that uses inter-event times from the real catalog to simulate earthquake data sets produces less statistically significant anomalous seismicity patterns, as shown in Figure 9b. The Q1 anomaly disappears and the Q2 anomaly becomes significantly shorter. As already explained in the Section 2.2 Methods, we have also varied the *Ta* window from 1.5 to 3.0 years to check the stability of the anomalous seismicity patterns. A result for *Ta* = 2.0 is presented in Figure S4. As the significance test shows, the Q2 anomaly appears clearly defined and having a slightly longer duration (Figure S4b) compared to the results in Figure 9b. We have found a similar result when using *Ta* = 3 years.

While a depth-dependent analysis can reveal more physical insight, we did not perform such an analysis here since the depth locations may be associated with significant uncertainties (see Section 2.1, Materials). Indeed, Koch [57] employed a more refined earthquake location procedure for the intermediate-depth seismicity and showed that the quiescence anomaly preceding the 1977 M7.4 earthquake might have been shorter than that defined by [14]. In any case, we find it remarkable that when using no depth-selection of earthquakes, the quiescence anomaly before the 1977 event is still present at a statistically significant confidence level, although its length is dependent on parameter choices.

We also note that our analysis could not confirm statistically the quiescence pattern reported by [15] before the 1986 M7.1 Vrancea earthquake, although the visual inspection of the magnitude versus time plot in Figure 7 shows a brief quiescent period about one year before the large event. There is however a significant increase in seismicity rate (Figures 7– 9a) from around 1983–1985, which we could not associate with any previous findings. We note that some precursory variations of seismicity, starting around 1985, have been reported before this event by [17]: in particular, the increase in the parameter γ, which implies a scarcity of larger events that might be related with the brief quiescence that is visible in Figure 7. Further analyses are necessary to confirm the correlation of various seismicity patterns.

We also note (Figures 8 and 9) the relatively brief but highly significant increases of β-value immediately after the 1986 and 1990 large Vrancea earthquakes, likely corresponding to the short aftershock activity following these events (see [45] that uses declustering to reveal the aftershock activity in Vrancea region, as well as [46]). Besides the seismicity rate decreases and increases discussed so far, there are a few other statistically significant, but very brief, seismicity rate changes (Figure 9a) that are difficult to associate with the occurrence of some larger events. Note that these brief changes tend to disappear when using more realistic significance testing (Figure 9b) or longer *Ta* windows (Figure S3). We also note that some of the M6.0 events before the 1977 M7.4 Vrancea earthquake (Figure 7) have very few aftershocks. While in general aftershock activity was almost entirely found following the largest (M $\geq$ 6.5) Vrancea earthquakes [45], we cannot exclude subtle short-term aftershock incompleteness [58] as an additional cause.

The results obtained in this work support the active monitoring of seismicity parameters as a tool that may contribute to a better assessment of earthquake hazard before the occurrence of large Vrancea events. In order to improve the accuracy of seismicity parameters estimation, in particular their space–time variation, it is also necessary to further improve the quality of seismic catalogues. It is also necessary to further test different approaches for seismicity analysis and determine the optimal parameters that could be used for forecasting purposes.

5. Conclusions

In this study we have revisited some important statistical characteristics of Vrancea intermediate-depth seismicity.

In the first part, we have selected from the NIEP's ROMPLUS seismic catalog a data set spanning from 2005 to 2013, complete for magnitudes M $\geq$ 3.2, to infer the spatial distribution of seismicity, in particular the depth distribution of earthquake activity that has two characteristic peaks around 90 km and 130–150 km. The slope of the frequency-magnitude distribution of earthquakes, *b*-value, has been found to decrease at the deepest part of the seismogenic zone (140–160 km depth), which was interpreted either in terms of an increased lithostatic stress and stress drop with depth [55] or as an indicator of the depth range where the next major Vrancea earthquake may occur [56].

In the second part, we have selected a data set spanning from 1960 to 1999, complete for magnitudes M $\geq$ 4.0, to statistically verify the possible existence of rate decreases and increases in the used data set. We have used, for the first time to our knowledge, a β-value statistical test to investigate the changes in seismicity rate for the intermediate-depth Vrancea seismicity. The data interval includes three Vrancea major shocks occurred on March 1977 (M7.4), August 1986 (M7.1), and May 1990 (M6.9). The most notable result is a whole depth-range (60–180 km) seismic quiescence pattern (i.e., anomalous decrease in seismicity rate) preceding the occurrence of the 1977 M7.4 Vrancea earthquake, confirming statistically the early results of [15]. Nevertheless, the length of the anomaly varies when using different statistical tests and time windows, which shows that further research is needed to assess the optimal set of parameters.

Clear short-term increases in earthquake rates correspond to the aftershock activities following the 1986 M7.1 and 1990 M6.9 intermediate-depth Vrancea earthquakes. Our analysis does not reveal any statistically significant abnormal decrease in seismicity (quiescence) before the 1986 large event, as suggested by previous investigations, and the 1990 event. This proves the difficulty of approaching the problem of earthquake forecasting when looking for precursory parameters claiming for their universal validity. The behavior of the seismogenic system, even in the case of a source as concentrated as in Vrancea and over a short period of time (40 years), proves to be complex and difficult to predict.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/geosciences13070219/s1. A PDF file that contains four figures referred in the text. Figure S1: The Romanian Seismic Network, as of June 2023 (see also Marmureanu et al., 2021 [27] for more details on the characteristics of stations. Figure S2: *b*-value variation with depth for the intermediate-depth Vrancea seismicity, during the period 2005–2013, $M \geq 3.2$. The *b*-value is obtained for windows of ni = 200 events, shifted by 20 events (overlap factor = 10). The overall *b*-value variation trend is similar to the one in Figure 5, obtained for a different set of parameters. Figure S3: Comparison of frequency-magnitude distributions for the deeper (120–140 km, empty rectangles, 254 events) and deepest (140–160 km, full rectngles, 304 events) parts of the intermediate-depth Vrancea seismicity (period 2005–2013), with the corresponding maximum likelihood fits shown by pink and red colors, respectively, above the magnitude of completeness (Mc = 3.1 in both cases) determined using the EMR method (see main text). The 120–140 km depth range is characterized by a *b*-value of 1.22 ± 0.07, while the 140–160 depth range has a *b*-value of 0.94 ± 0.05. These results are in agreement with those in Figures 5 and S1. The *p* value (= 0.0035) indicates the probability that the two samples come from the same distribution, calculated using Utsu's (1992) [59] test. The very small *p* value indicates that the two samples likely belong to different populations. Figure S4. (a) Cumulative number of earthquakes (black curve) and β-value variation (LTA(t) function, gray curve) for the Vrancea intermediate-depth earthquakes ($M \geq 4.0$, 1960–2000). The window-used to calculate the β-value is 2.0 years, moved along the entire time interval with a step of 14 days. The large and small crosses on the time axis indicate events with magnitudes $M \geq 6.0$ and $5.5 \leq M < 6.0$, respectively. (b) Significance of rate increases and decreases in (a) obtained using a similar procedure to that used to obtain Figure 9b. Blue and red colors indicate windows of rate increase and decrease, respectively, that have significance levels below 5% (confidence levels above 95%). The large and small crosses on the time axis indicate events with magnitudes $M \geq 6.0$ and $5.5 \leq M < 6.0$, respectively. The Q2 rate decrease anomaly corresponds to a period before the 1977 M7.4 Vrancea earthquake, while the A1 and A2 anomalies correspond to seismicity activations (rate increases) following the 1986 M7.1 and 1990 M6.9 Vrancea earthquakes.

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