京都大学防災研究所年報　第42号 B-1 平成11年4月
Annuals of Disas. Prev. Res. Inst., Kyoto Univ., No. 42 B-1, 1999

Precursory Phenomena of Seismicity in the Vrancea Region, Romania

Bogdan ENESCU* and Kiyoshi ITO

*National Institute for Earth Physics, Romania

Synopsis

The Vrancea seismic region contains an isolated cluster of events beneath the Carpathian Arc Bend in Romania, dipping down to about 200 km depth. Seismic activity mainly belongs to intermediate depths ($h \geq 60$ km). This paper aims at identifying the so called man-made changes in seismicity, included in the studied catalogue, to reveal possible real changes of seismicity. The magnitude of completeness of the catalog is found to vary significantly from 3 to 3.8, for the time period studied (1978-1998). However, taking the minimum magnitude as 3.7, the two big earthquakes which occurred in this period show possible premonitory patterns of quiescence and b-value changes.

Keywords: Vrancea seismic region, man-made changes in seismicity, seismicity in time and space, b-value, seismic quiescence

1. Introduction

Studies of seismicity evolution of Vrancea (Romania) region in time and space have a quite long history. Some papers were devoted to analyze, from a statistical point of view, the major earthquake occurrences, in order to find some useful periodicity for earthquake forecasting (for example, Enescu et al., 1974). Other papers dealt with the recognition of different patterns of seismicity as premonitory phenomena for big Vrancea earthquakes (for example, Marza, 1979, Radulian and Trifu, 1991). Several papers tried to relate the characteristics of seismicity with tectonics (for example, Fuchs et al., 1978, Constantinescu and Enescu, 1985).

Recently, the Romanian Earthquake Catalog, between 984-present, was published (Oncescu et al., 1998). Based on this up-to-date and most complete catalogue, we will tackle in this paper two main problems :

(1) Man-made changes in seismicity, identification and removal from the studied catalogue ;

(2) Possible premonitory changes in seismicity (evolution in time and space) before the last two big Vrancea earthquakes which occurred in 1986 (M_W = 7.1) and 1990 (M_W = 6.9) : rate changes (identify seismic quiescence patterns) and b-value variation in time. We will also discuss about a quite clear anomaly in occurrence rate and b-value which is manifesting in the present.

We will give in the next chapter a brief description of Vrancea's seismicity and tectonics. The earthquake data which we used for some of the figures in the next chapter, are those presented in Chapter 3 from the Romanian Earthquake Catalog (Oncescu et al., 1998).

2. General features of Vrancea seismicity and tectonics.

The Vrancea seismic region is situated beneath the Eastern Carpathians in Romania and is characterized by well confined and persistent intermediate depth activity. The epicenters of the Vrancea earthquakes are situated in 44.9°-46.5° range of latitude and 25.5°-28° range of longitude respectively (see Fig 1).

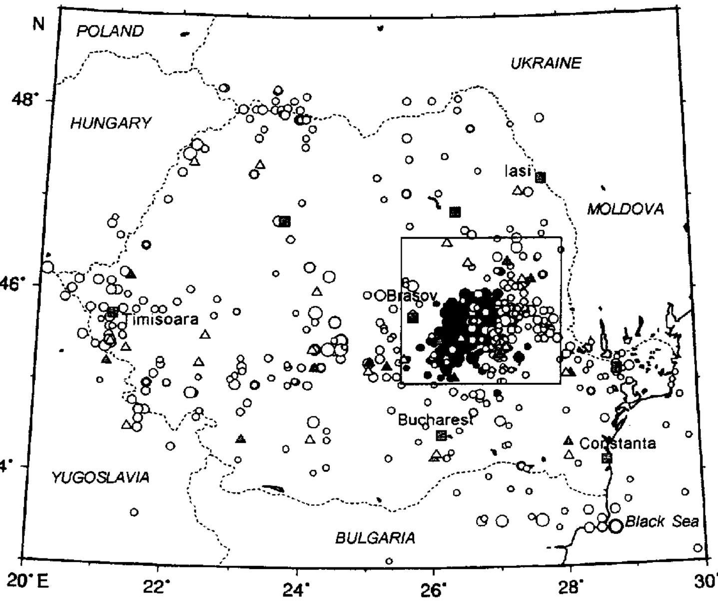

Fig. 1 The seismicity (events with magnitude $M_W \geq 3$ from Romanian Earthquake Catalog, Oncescu et al, 1998) and the distribution of seismic stations in Romania. Crustal earthquakes are represented by open circles and the intermediate depth ($h \geq 60$ km) events by solid circles. Shaded rectangles represent major cities. The telemetered stations are represented by shaded triangles and the conventional ones by open triangles. The enclosed area by a big rectangle delineates the Vrancea seismic region studied in this paper.

The depths of the events range from 0 to 220 km, but the main seismic activity belongs to intermediate depth ($h \geq 60$ km) as we can see in the depth histogram in Fig. 2. This figure shows a sharp increase in seismic activity around 110 km and a relative gap between 35 and 65 km. The sharp increase around 110-120 km is the transition between two different seismic regimes (Trifu and Radulian, 1994). The seismic activity is almost entirely limited at depth shallower than 180 km. Indeed, only one event was proved to have occurred at greater depths (May 16, 1982: depth = 218 km, M_W = 4.1). The crustal seismic activity is rather low with maximum magnitudes in the range 5.0-5.5 (Radu, 1979).

The seismogenic volume dips nearly vertically as shown in the two cross sections (NW-SE and SW-NE respectively) presented in Fig. 3a and b. The main focal mechanism characteristics for Vrancea earthquakes are : quasiverticality of the tension axes (T) and quasihorizontality of the compression axes (P), NW-SE and NE-SW fault plane orientation, and predominance of the dip-slip of the inverse fault. Different seismotectonic models, based on the characteristics of tectonics, distribution in space of earthquakes and their focal mechanism solutions, have been proposed for Vrancea region (for example, Roman, 1970; Fuchs et al., 1978; Constantinescu and Enescu, 1985). Most of them agree, however, that the Vrancea subcrustal earthquakes occur in an old subducted lithospheric slab, sinking gravitationally.

3. Data

The catalog used in this study is the one published by Oncescu et al. (1998). The reasons why we chose this catalogue are (1) it is the most complete in information ; (2) it is up-to-date and continuously updated ; (3) it is homogeneous both in the location procedure and in the magnitude scale ; (4) it is acces-

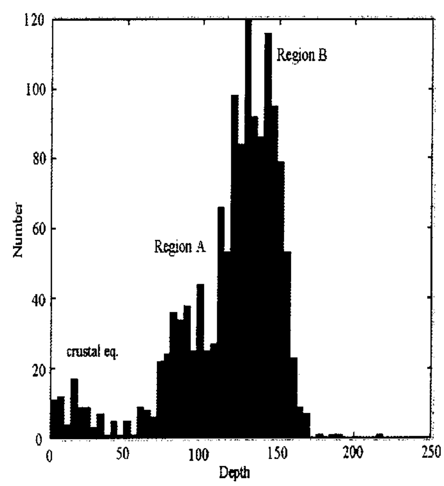

Fig. 2 Depth-frequency distribution of Vrancea earthquakes ($M_W \geq 3$, 1978-1998). Events are classified with their depth as crustal earthquakes (0 - 40 km) and intermediate depth earthquakes divided in Region A (60-115 km) and Region B (115-170 (220) km).

sible, being distributed via Internet or floppy discs and (5) integrates the information available in other catalogues in a unitary form.

Fig. 3 SW-NE (a) and NW-SE (b) vertical projections of Vrancea earthquake hypocentral distribution ($M_W \geq 3$, 1978-1998). AB and CD lines define the directions of the cross-sections. The stars represent the two big Vrancea earthquakes of August, 1986 with depth of 131 km and May 1990 with depth of 91 km.

The catalogue comprise, with different degrees of completeness in time, the earthquakes occurred on Romanian territory and some important earthquakes from the immediate neighborhood, between 984 and present. We will consider in this study only the Vrancea subcrustal earthquakes (depth ≥ 60 km).

We will focus our attention on the time period 1978-1998, when two major earthquakes occurred in Vrancea region, on August 30, 1986 (M_W = 7.1, depth = 131 km) and May 30, 1990 (M_W = 6.9, depth = 91 km). It is worth to note that the second earthquake was followed by another big earthquake (May 31, 1990, M_W = 6.4, depth = 87 km) in less than 24 hours. The magnitude of completeness (M_C) reported by the authors (Oncescu et al., 1998) for this time interval (1978-1998) is 3.0. The errors associated with earthquake locations and magnitudes are less then 3 km for epicenter coordinates, less then 5 km for earthquake depth and around 0.1 for earthquake magnitude.

In order to give some information regarding the distribution of seismic stations on Romanian territory (and especially in and around Vrancea zone), the station locations of Romanian Seismic Network (telemetered and conventional stations) is shown in Fig. 1. The telemetered network, which was installed between 1980-1982, consists of 19 short-period stations (S-13 type). 15 of them are operating in the Eastern and Southern Carpathians being telemetered to Bucharest, while the other four stations are operated in the southwestern part of Romania, in the Banat region, being telemetered to Timisoara. The first telemetered sub-network (15 stations) is especially and primarily designed to survey Vrancea seismic activity and gives the most part of information regarding Vrancea earthquakes. In the period of this study, 1978-1998, the improvements of the network and also some periods of malfunctioning have their own, artificial influence on seismicity rates. It is one of the purposes of this paper to identify and remove these man-made changes of seismicity from the catalog. It is important to mention here that the economical and financial difficulties in Romania during these years made impossible sometimes to maintain the network fully functional, in spite of the constant care of the specialists to maintain and improve the network, and therefore, periods of malfunctioning occurred.

Before the analyses of the data, the aftershock sequences of August 1986 and May 1990 big Vrancea earthquakes were detected by use of the Omori's formula and removed from the catalog.

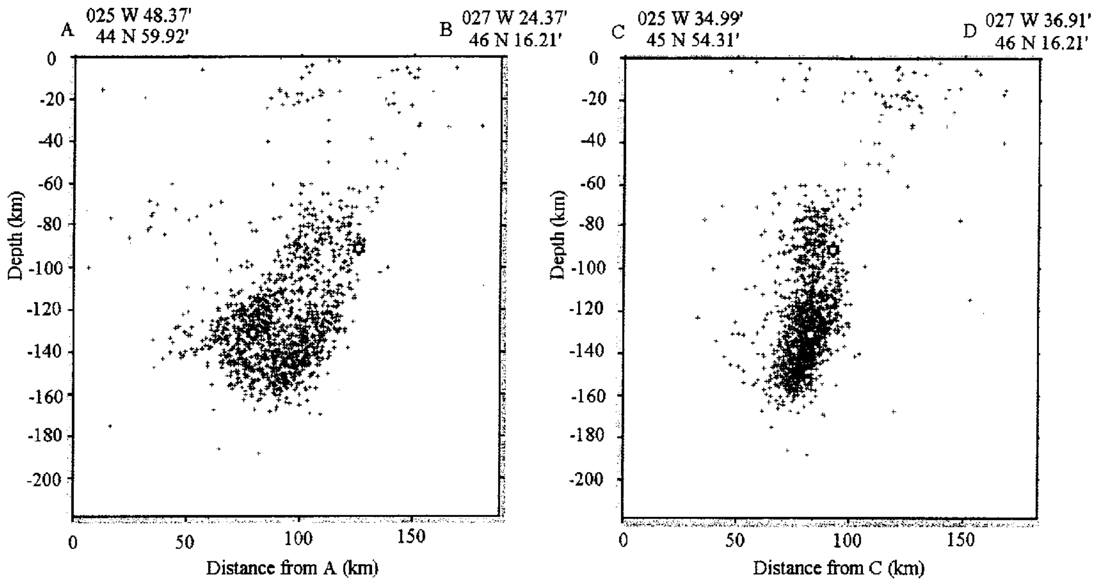

Fig. 3 SW-NE (a) and NW-SE (b) vertical projections of Vrancea earthquake hypocentral distribution ($M_W \geq 3$, 1978-1998). AB and CD lines define the directions of the cross-sections. The stars represent the two big Vrancea earthquakes of August, 1986 with depth of 131 km and May 1990 with depth of 91 km.

4. Method of analysis

The rate changes in seismicity have two sources of occurrence : man-made or caused by some natural processes. In order to detect possible real seismicity changes, the man-made changes must be identified and removed from the catalog. The change of detection capability of a network leads to the change of the minimum magnitude above which all events are completely reported. This magnitude is termed magnitude of completeness (M_C). Therefore, M_C was determined using the maximum of the derivative of the frequency -magnitude distribution between M_W = 3-7.1. Using a sliding-window technique, the variation in time of M_C was determined. In order to give more confidence to our result, the characteristic of rate changes in seismicity was discussed for different M_C. The events with magnitude smaller than M_C were removed from the catalog. Another type of man-made changes in seismicity is recognized by shifts or stretches of the magnitude scale (see, for example, Zuniga and Wyss, 1995). The catalogue was checked with a technique developed by Zuniga and Wyss (1995) in order to identify such possible man-made changes. The method is based on the assumption that the frequency-magnitude relationship and the rate of the independent background seismicity do not change as a function of time. For the time periods when shifts or stretches of the magnitude scale occur, a simple, linear magnitude transformation is applied as correction.

In order to search for possible rate changes in seismic activity, we used plots of cumulative number of earthquakes in time, and depth-time plots of seismic activity. These representations give a subjective idea of important changes in seismicity during time. In order to quantify somehow these rate changes, a z-value parametric statistical test was used. This test compares the means of two independent samples. Because we want to compare seismicity rate changes, the means are in this case the average rates during two time periods (see, for example, Habermann, 1987). Z is defined as,

$$z = \frac{m_1 - m_2}{\sqrt{\left(\frac{\sigma_1^2}{n_1}\right) - \left(\frac{\sigma_2^2}{n_2}\right)}} \qquad (1)$$

where m_1 and m_2 are the mean rates during two periods which we want to compare, σ_1 and σ_2 are the standard deviations of those rates, and n_1 and n_2 are the number of samples in each period.

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. Anyway, as pointed out by Matthews and Reasenberg (1987) the absolute values of z may not be so reliable. One technique is to determine the significance of a given value of the statistical test through a series of simulations, using data with a known distribution (Habermann and Wyss, 1987). In this paper, we will compare the target z-value with all other z-values (an approach suggested by Wyss and Fu, 1989). In order to apply the method, it is needed to choose a windowing scheme. We have chosen the Rubberband function. This scheme slides a fixed duration window (W_1) through the data one sample at a time, and compares the rate in that window to the rate in a background window (W_2), which expands behind the first window. This scheme is used because it is possible at any given time to take the longest possible period for a background estimate. Positive z-values mean a decrease in seismicity rate in W_1 comparing with W_2. Negative z-values suggest an increase in W_1 comparing with W_2.

In the case of the detecting seismic quiescence, which have been taking place in the present, another kind of statistical testing approach (Ohtake et al., 1981) was preferred. Giving the assumption of a Poissonian process of the seismicity, the probability (p) of observing x events in the time interval t, is given by the formula :

$$p(x) = [(k\,t)^x\, e^{-k\,t}] / x!\,, \qquad (2)$$

where k is the mean rate of occurrence.

The b-value is determined by two different techniques. One is weighted least square fit to the slope of the frequency-magnitude distribution. The b-value is calculated using the point of maximum curvature of the frequency-magnitude distribution (as measured by the derivative) and the point half way toward high magnitude end of the b-value curve. The other is maximum likelihood estimation, based on the minimum magnitude (Utsu, 1965 and Aki, 1965),

$$b = 0.4343/(\langle M\rangle - M_{min})\,, \qquad (3)$$

where $\langle M\rangle$ is the mean value of all magnitudes of n events within the selected ranges. This method is applied to all the events. For the first method the confidence intervals are determined taking into account the deviation of the data points from the linear curve. For the second method, the errors were estimated following an approach suggested by Shi and Bolt (1982). To estimate b value as a function of time, we defined a window size of n_i events, the window being moved by $n_i/5$ earthquake steps (sliding-window technique). The values were assigned to the end of the correspondent time interval.

We chose as a tool for most of the above described computations the software package ZMAP (Wiemer and Zuniga, 1994), a powerful software for seismicity analyses.

5. Results and Discussion.

5.1 Man-made changes in seismicity represented in magnitude-frequency relationship.

Figure 4 shows the cumulative number of earthquakes for all the events (1978-1998, h ≥ 60km, M_W ≥ 3), together with a z-value curve. The sliding win-

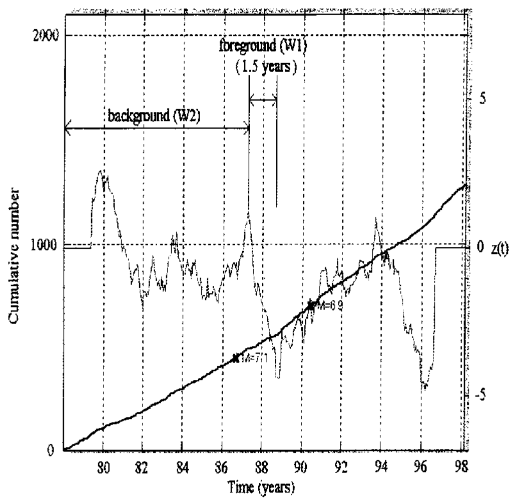

Fig. 4 Cumulative number of earthquakes together with z-value curve, for all intermediate depth events, h ≥ 60 km, in the catalogue. The sliding window length (W_1) for z-value determination is 1.5 years. Crosses represent the two big Vrancea earthquakes in 1986 and 1990.

dow length (W_1), for z-value determination is 1.5 years. It should be emphasized that z-value is almost all the time negative, which point out that the seismicity rate steadily increase during all the time. A careful check at the cumulative number curve, for all the period, may lead to the same conclusion. This shows that the data set with $M_W \geq 3.0$ is not sufficient to detect natural seismicity changes.

Figure 5 represent the frequency-magnitude relation. It is noticed that the data depart from the linear trend for magnitudes smaller then 3.2. This observation suggests that the catalog is not complete for magnitudes smaller than 3.2. The b-value for the events with $M_W \geq 3.2$ is 0.96 ± 0.06, as determined by weighted least square technique and 0.94 ± 0.03, as determined by maximum likelihood method.

As described before, for all data set, M_C is around 3.2. In order to study the evolution of seismicity in time, one has to know if the magnitude of completeness changed in time. In Fig. 6, M_C is represented as a function of time. We chose 150 events in a sliding window, which correspond roughly with two years of data, because we appreciate this number to be big enough in order to give reliable results for frequency-magnitude distribution and for M_C determination. The window is moved with a step of 15 events. As seen from Fig. 6, values of M_C vary significantly, between 3 and 3.8, although 3.2 seem to be the predominant value. As we have chosen also smaller or bigger numbers of events for the sliding window, the results are the same. It is certain that the M_C changes in time, with values between 3 and 3.8 and M_C tends to be stable as 3.2 or less after 1986.

The cumulative number of earthquakes together with z-value curve for M_W >= 3.7 were represented in

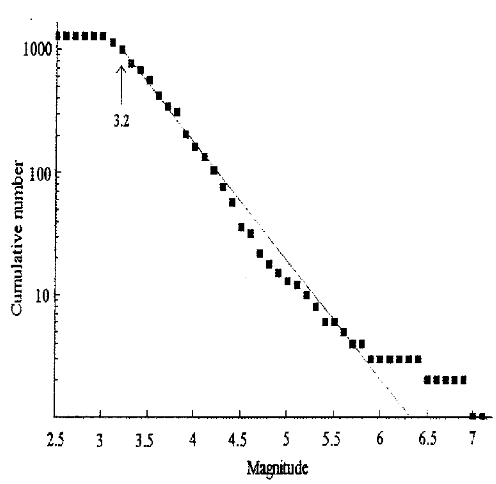

Fig.5 Cumulative frequency-magnitude distribution for all intermediate depth events in the catalogue. The line fitting the data is obtained by weighted least square method as shown in the text.

Fig. 7. The sliding window length (W_1) is 1.5 years, which is the same as in Fig. 4. In this case, comparing with Fig. 4, the cumulative number curve has a linear trend, with some changes pointing out the existence of relatively short periods with increased or decreased seismicity rates. Z-values show some maxima or minima, but, generally, the data is "centered" on zero. Changing magnitude of completeness (M_C) between 3.5-3.8, all results are almost the same as shown in Fig. 7. Therefore, we chose as magnitude of completeness for further studies M_W = 3.7, in order to have a high degree of reliability.

As mentioned before, other possible man-made effects on magnitude are the shifts and stretches of magnitude scale during time. Applying the technique mentioned in Chapter 4 for the catalogue with $M_W \geq$ 3.7, we didn't find any such change. Anyway, the

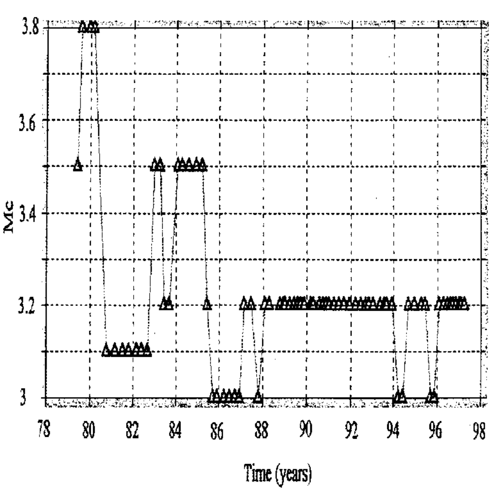

Fig. 6 Magnitude of completeness (M_C) change in time for all intermediate depth events in the catalogue. The number of earthquakes in a sliding window is 150.

cumulative number curve and the associated z-value for the catalogue with $M_W \geq 3.7$, together with the known history of the catalogue do not favor the existence of such systematic man-made changes in seismicity.

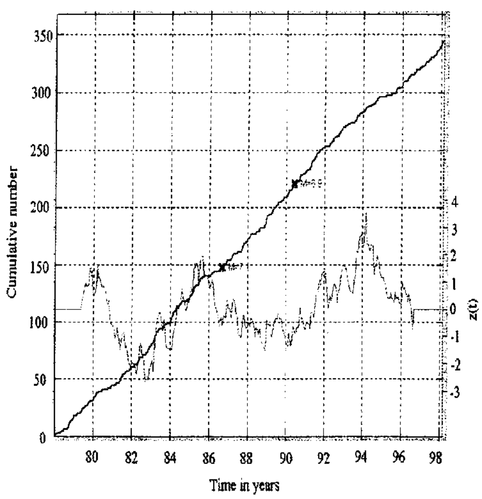

Fig. 7 Cumulative number of earthquakes together with a z-value curve for events in the depth 60-220 km and $M_W \geq 3.7$. The sliding window length (W_l) for z-value is 1.5 years.

There is another important discussion on completeness of magnitude. Trifu and Radulian (1991), using an other earthquake catalog, found an important change in the magnitude-frequency relation around M_W = 3.1-3.7. Their catalogue includes also earthquakes with magnitude less than 3. They analyze the data, in order to find the completeness magnitude (M_C), with the algorithm described by Rydelek and Sacks (1989). This algorithm is based on the idea that in the magnitude ranges where the catalogue is incomplete, there should be more events logged during night than during the day time, since the cultural noise sources and winds are diminished. The finding of Trifu and Radulian (1991) is that in the magnitude range 3-3.7, the catalogue is complete, although there is a highly significant fall-off in the number of events (as shown by the frequency-magnitude relationship). Their interpretation is that this magnitude range represents the transition zone between two distinct groups of earthquakes, characterized by different types of failure (crack-like and asperity like, respectively). Our result, however, does not support their conclusion for the case of Vrancea earthquakes, but instead the change in the number of small earthquakes, in the magnitude range less than M_C, is due to the variation of M_C in time. Further studies using different testing techniques are needed to solve the problem. In any case, for the studies regarding seismic quiescence patterns or even b-value variation in time, including small magnitude earthquakes with poorly understood characteristics and time evolution may be a misleading approach.

It is noticed that a quite big amount of data was eliminated in order to have a complete data set to study the seismicity change in time. Habermann (1983), proposed as a solution to minimize the amount of eliminated data, a procedure which permits the determination of the minimum magnitude of homogeneity, the level above which some constant portion of the events which occur is consistently reported through time, which is lower than Mc. We will follow such a more sophisticated approach in further studies.

5.2 Possible natural changes in seismicity for Vrancea earthquakes.

(1) Spatio-temporal seismicity patterns and seismic quiescence.

The starting point of the search for possible natural changes in seismicity is the cumulative number of earthquakes with magnitude $M_W \geq 3.7$ (Fig. 7). There are three regions which show a certain increase in z-value around 1980, 1985 and 1994 respectively. Possible explanations for their causes are given later, whether they correspond to some seismic quiescence patterns or not. Figure 8 shows the evolution of intermediate Vrancea seismicity ($M_W \geq 3.7$) in time and depth. This kind of graphical presentation is a convenient way to look for changes in seismicity in time because the Vrancea intermediate earthquakes have a rather narrow epicentral region, but extend significantly in depth. The first thing to notice is a different occurrence rate associated with the two depth regions 60-115 and 115-170 km, as pointed out in Chapter 2 (see also Fig. 2). There is only one earthquake bellow 180 km depth (May 16, 1982: depth = 218 km, M_W = 4.1). We will refer further to the region between 60-115 km depth as "Region A" and between 115 -170 km as "Region B". As shown in Fig 8, Region A experienced two big earthquakes, EQ2 (M_W = 6.9) and EQ3 (M_W = 6.4). Due to their close spatio-temporal distribution, they are referred as a doublet. Region B experienced one big earthquake, EQ1 (M_W = 7.1). Figure 8 shows clearly that the rate of seismicity in Region B is higher than in Region A.

In the following discussion, the changes in seismicity which may be related with EQ1 is referred first, being followed by discussions regarding seismicity changes associated with EQ2 and other seismicity changes. As shown in Fig. 8, Region B shows a large number of moderate earthquakes ($M_W \geq 4.5$) before 1988 comparing with the following time period. This may be interpreted in terms of an increased number of moderate earthquakes associated with the occurrence of EQ1 (see Fig. 8) or as a substantial decrease in the number of moderate earthquakes (a seismic quiescence pattern) which follows short time after the occurrence of EQ1.

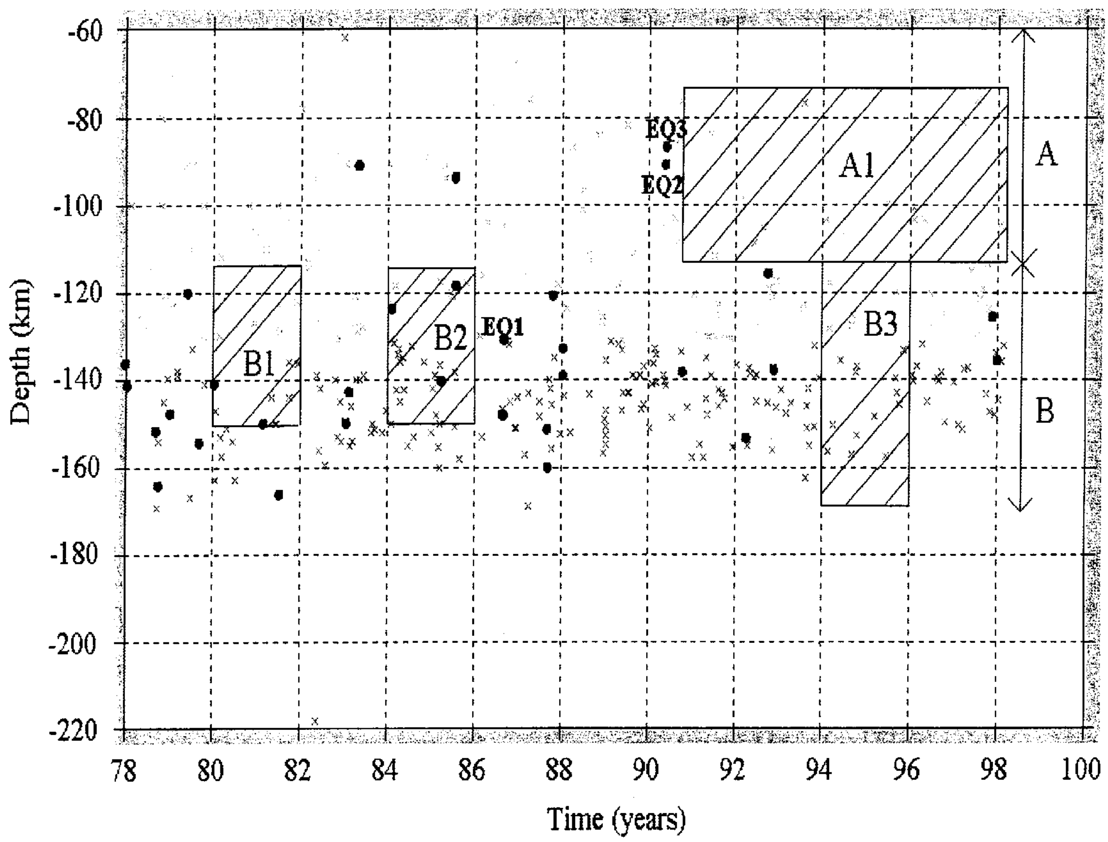

Fig. 8 Depth distribution of Vrancea earthquakes ($M_W \geq 3.7$) in time. Dots represent earthquakes with $M_W \geq 4.5$. EQ1, EQ2 and EQ3 show the big earthquakes on August 1986 ($M_W = 7.1$), May 1990 ($M_W = 6.9$) and May 1990 ($M_W = 6.4$). Hashed rectangles (A1, B1, B2 and B3) show some possible seismic quiescence, as referred in the text.

Seismic quiescence patterns seems to took place (see the corresponding hashed rectangles B1 and B2 in Fig. 8) in Region B, in the depth range 115-150 km, around 1980 and 1986. The first two peaks in z-value (around 1980 and 1985) which appear in Fig. 7 may correspond to these anomalies. These may be associated with EQ1. In order to give a statistical meaning for the hypothesis regarding the seismic quiescence pattern associated with EQ1, events were limited in the depth range 115-150 km (considered a slightly bigger threshold magnitude ($M_C = 4$)) in the following analyses. The depth cuts are justified by the above observation from Fig. 8 and by the fact that the focal region and the aftershocks depth range for EQ1 (Trifu and Oncescu, 1987) correspond roughly with the depth interval considered (115-150 km). The cut in magnitude was operated because an anomaly should be manifested especially in the range of bigger magnitudes if it really exists. Figure 9 displays the result of this analysis in the form of the cumulative number of earthquakes and z-value in time. In order to have a clear look, the results only for the time period 1978-1990 are shown, although the results for all time interval 1978-1990 will be discussed. One may notice in Fig. 9 that there are two peaks in z-value around 1980 and 1985. These two peaks correspond with the first two peaks observed in Fig. 7. The difference is that the value of z associated with the first peak in Fig. 9 is 3.2 and bigger than 2 in Fig. 7. However, the absolute values in Fig. 9 are less reliable, due to the small number of earthquakes available. What might be the conclusion then? In our opinion the decrease in seismicity rate around 1980 and 1985-1986 are rather clear as seen in cumulative curves in both Figs. 7 and 9. Because of the low seismicity rate in Region A, the peaks in Fig. 7 should be attributed to rate decreases in Region B, which has the biggest influence on the statistics. Figures 8 and 9 seem to support this hypothesis. In the same time both figures (see the cumulative number and z-value curve in Fig. 7 and especially Fig. 9) suggest that short periods, with length between half a year and one year, of increased and decreased seismicity rate followed one after another between 1980 and August 1986. Marza (1989) observed a similar pattern and concluded that it represents a precursory phenomenon of August 1986 earthquake.

Figure 7 shows another maximum (z = 3.6) at February 1994. Restricting our analysis in the depth

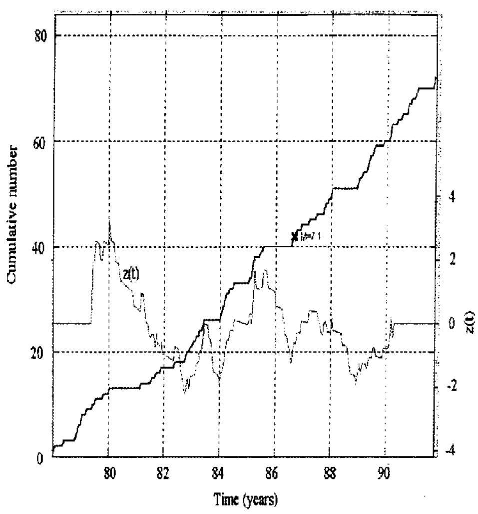

Fig. 9 Cumulative number of earthquakes together with z-value curve, for the events during 1978-1992, in the depth range h = 115-150 km, with $M_w \geq 4.0$. The cross represents the August 1986 earthquake ($M_W = 7.1$).

range 115-150, we found two peaks of z-value (at 1994.2 and 1995.7), similar or bigger than those before the 1986 earthquake. Do these rate decreases represent false alarms or do they show somehow a future big earthquake ? How statistically significant are all these decreases in seismicity ? A more complete data set, spanning on a broader time interval and in small magnitude range, together with a more advanced statistical analysis such as Monte Carlo simulations, for example, may give some answers at these questions.

Our tentative to do similar z value tests for Region A, corresponding with the occurrence of the May 1990 big Vrancea earthquake, gave inconclusive results due to the low seismicity rate in this region. The seismic activity is drastically reduced in Region A, especially in the depth range 80-100 km, beginning with 1991, as seen in Fig. 8 in the corresponding hashed rectangle A1. For this seismic quiescence, we checked the probability of observed 16 events with $M_W \geq 3.7$ between 1992 and beginning of 1998, in the depth range 60-115 km (Region A), giving a mean rate of occurrence of 3.9 earthquakes / year calculated from seismicity in the time period between 1978 and 1992. In accordance with relation (2), under the assumption of a Poissonian process, the probability is : p (13) = 0.007. In consequence, the observed seismic quiescence could scarcely occur by chance. This seismic quiescence may be regarded as a period of very low seismic activity following the May, 1990 earthquake or might be the premonitory phenomenon of a future big Vrancea earthquake. However, we may note that the duration of the seismic quiescence following another big Vrancea earthquake (M_W = 7.4), which occurred on March 4, 1977 in the same Region A, was of about five years. As seen in Fig. 8, in the time period 1991-1998 (for about seven years) only a few earthquakes occurred in the depth range 80-100 km. Therefore, the significance, the spatial extent and the time duration of the present anomaly suggest that the seismic quiescence which has been taking place in the present may be a possible precursor for a future big Vrancea earthquake. Up-to-date information is necessary in order to confirm or not our hypothesis.

In the discussion above we hypothesize that some of the observed seismicity changes may be correlated with EQ1 or EQ2. As a rule, however, there are anomalies before large earthquakes for sure but a quiescence does not always correlate with a big earthquake. Therefore, careful surveys should be taken in the interpretation of the results.

In Region B a relative decrease in occurrence rate took place between 1994-1996 (see the hashed rectangle B3) which cumulated with the quiescence in Region A gives the third peak in z-value (see Fig. 7). At the end of 1997 and beginning of 1998, in Region B, after a quite long period with no earthquake bigger than 4.5, two moderate events occurred (see Fig. 8).

(2) b-value variation in time.

The variation of b-value in time is presented in Fig. 10. We choose for the study all the events with magnitude $M_W \geq 3.7$, in the depth range 60-220 km, which occurred between 1978-1998. The b-values are discussed for the entire depth range because the precursory changes of b-value may appear not only in the depth range of the future large earthquake but also in the neighboring regions and because the number of events is too small to detect the time evolution of b-value, when the depths are divided into some regions. The length of the sliding-window was chosen as $n_i = 50$ events, the window being moved with a step of 10 (n_i / 5) events. The value of b was represented at the end of the time interval of the sliding-window. Figures 10a and 10b show determined b-values by the weighted least-square method (WLS) and the maximum likelihood method (MLM) respectively.

As shown in Fig. 10, the two kinds of approaches do not give similar values of b for short time variations. However, the changes in b-values determined by the two methods show the same general trends. We should note here that the least square approach is generally very sensitive to the presence of larger earthquakes. The second approach (MLM) was suggested as preferable for calculating the b value because it yields a more robust estimate when the number of the infrequent large earthquakes changes (Shi and Bolt, 1982). We have applied a weighted least square method which correct, somehow, the above mentioned effect.

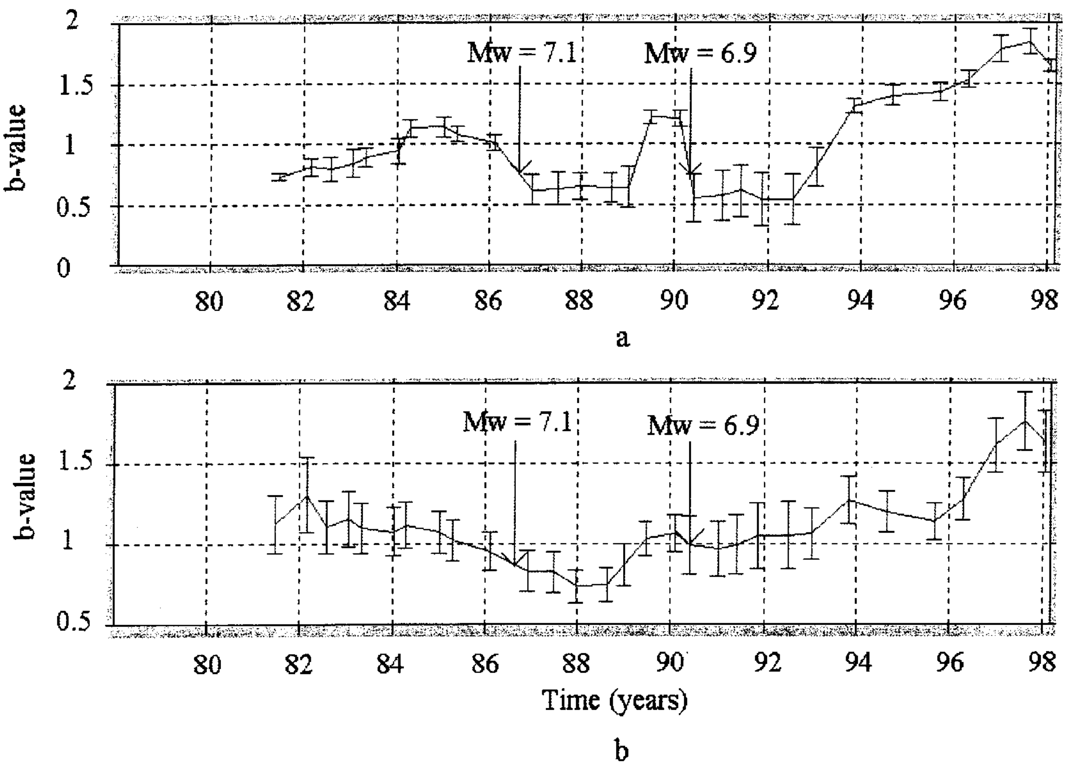

Fig. 10 B-value variations in time, using a sliding-window technique (number of events in window (n_i) = 50, n_i / 5 step), for the events in the depth range 60-220 km with $M_W \geq 3.7$, by weighted least square method (a) and maximum likelihood method (b). Arrows indicate the occurrence times of the August 1986 and the May 1990 big Vrancea earthquakes. Error bars are represented by vertical lines.

The b-value variation in time, as determined by weighted least-square method, shows clearly for both big Vrancea earthquakes in 1986 and 1990, that there is an increase in b-value, followed by a decrease just before the earthquakes (Fig. 10a). It is noted that the changes are significant even if taking into account the confidence interval limits. In Fig. 10b, the change in b-value associated with the occurrence of the two big Vrancea earthquakes is not clear. Even if MLM offers a more robust estimate, the fact that the standard errors are rather small when applying WLS, suggests both approaches can be accepted. Indeed, the evolution of seismicity in time (see Fig. 8) seems consistent with the fact that smaller b-values correspond to a relative increase in the number of bigger events and vice versa. However, a closer analysis of seismicity in Fig. 8 shows that before EQ1 some large shocks ($M_W \geq 4.5$) happened in both Regions A and B and, also, no large shocks ($M_W \geq 4.5$) occurred during 1988-1990 in both Regions A and B. The b-value significantly decreased just before EQ1 and increased between 1988-1990 associated with EQ2, as they are shown in Fig. 10a. These means that these changes are the effects of seismicity changes, especially in the range of bigger magnitudes, in both Regions A and B. As mentioned before in the previous section and in Chapter 2, the seismicity features in the two depth regions (A and B) justify the separate analyses of their seismicity. Therefore, a more complete and reliable analysis would require for the determination of b-value changes in time for different depth intervals using smaller earthquakes.

The b-value anomalies that occurred before the two big Vrancea earthquakes had similar patterns with those recorded elsewhere before large earthquakes (see, for example, Smith, 1981).

Both diagrams (Fig. 10a and b) show a big increase in b-value, which has been taking, place since 1994. This increase can be explained by the small number of moderate and big earthquakes, as shown in Fig. 8. Results from both methods indicate the same increase in b-value. Therefore, the change is thought to be quite significant. The seismic quiescence pattern pointed out in the previous section agrees with the period of this anomalous increase of b-value.

Further studies are needed using many more events including small earthquakes, in order to get reliable results. In particular, the analyses of b-values dividing depth regions are necessary to get precursory changes in b-value for sure.

6. Conclusions

1. According to the frequency-magnitude distribution (b value), the catalog for Vrancea intermediate earthquakes is shown to be incomplete in the magnitude range 3-3.7. This incompleteness is evident when we consider the cumulative number for the entire catalog and the variation of Mc in time. Even if this incompleteness is the result of a self-similarity break, we recommend for further studies to analyze separately earthquakes with Mw ≥ 3.7, otherwise misinterpretations are very easy to occur.

2. Region A of depth, 60-115 km, is characterized by a lower seismicity rate than Region B with depth 115-170 km. This rather high seismicity rate in Region B allows a more reliable statistical analysis. In this respect, there is an interesting, possible seismicity quiescence pattern before August 1986 earthquake.

3. The separate analyses of the two depth ranges, Regions A and B, give more meaningful results in the study of seismicity.

4. There is a significant decrease in the number of moderate magnitude earthquakes (Mw ≥ 4.5) in Region B, starting with 1988 to present. Beginning with 1991, there is a significant decrease in seismicity rate in Region A, especially in the depth range 80-100 km.

5. Both the August 1986 and the May 1990 Vrancea earthquakes, show premonitory patterns in b-value variation in time, according to weighted least square method estimation. However, more conclusive results would require the use of an enlarged number of events including smaller earthquakes, the analyses of different depth regions and the observation of the possible anomalous change of b-value when applying both methods (WLS and MLM).

Acknowledgments

One of the authors (Bogdan Enescu) is grateful to the Japanese Ministry of Foreign Affairs for providing him a 1-year fellowship through Japan International Cooperation Agency (JICA) for study in Disaster Prevention Research Institute (DPRI), Kyoto University, to Professor Torao Tanaka and to all the people who kindly and constantly advised and supported him during his stay in Japan.

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要　旨

ルーマニアにおけるカルパチア山地の屈曲付近のブランチャ地域では，孤立した地震群が見られる。この地震活動は中深発地震で深さ 60km 以深 200km まで，ほぼ垂直な分布をしている。この地域ではＭ７以上の地震が時々発生し，大きな被害をもたらしてきた。本研究では，この地域の地震カタログの人工的な原因による擾乱をチェックし，実際の地震活動の変化を調査した。そのために，1978　-1998 年の間の完全に観測されている地震のマグニチュードの下限（Ｍｃ）の時間的変化をを調べた。その結果，Ｍｃは全体的には 3.2 であるが，3.0 から 3.8 と期間ごとに変化することが分かった。さらに，Mc を 3.7 とすることによって，1986 年(M7.1)及び 1990 年(M6.9)の大地震前に，地震活動の低下とｂ値の変化があることが分かった。

キーワード: ブランチャ地震群，地震活動，地震活動の時空間変化，ｂ値，空白域