TIME CLUSTERING PROPERTIES OF THE VRANCEA (ROMANIA) SUBCRUSTAL EARTHQUAKES

EMILIA POPESCU, OLIVIA BAZACLIU, MIRCEA RADULIAN
National Institute for Earth Physics, P.O. Box MG-2, 76900, Bucharest, Romania
epopescu@infp.ro olivia@infp.ro mircea@infp.ro
(Received October 22, 2001)

Abstract. Clustering properties of the time series of Vrancea intermediate depth earthquakes are analyzed using several statistical tests. A catalog of 5449 events (M ≥ 1.5) spanning the time interval January 1974-April 2001 is considered. At the scale of the whole subducting slab the time occurrence series behaves like a pure random process. When the analysis was focused on the two active seismogenic segments delimited in the subducting lithosphere, one around 90 km (where the major shocks of March 1977 and May 1990 were generated), the other around 130 km depth (where the major shock of August 1986 was generated), we found discernable clustering effects. Our results are in favor of the presence of different earthquake mechanisms in the two seismic active segments, complementing earlier results on the Vrancea subcrustal earthquake regime.

Key words: earthquake clusters, Vrancea seismic area, intermediate depth earthquakes, segmentation of the subducting slab.

INTRODUCTION

Systematic investigation of the seismic regime in the Vrancea region at different space and time scales outlines important constraints as concerns the modelling of the seismogenic process over an extended domain, from microearthquakes to major seismic events.

The Vrancea seismic zone is located in Romania at the South-Eastern Carpathians arc (Fig. 1), where at least three major tectonic units are in contact: the East-European plate, the Intra-Alpine subplate and the Moesian subplate [1]. The seismicity in the Vrancea zone consists of both crustal and intermediate depth earthquakes. The crustal events are moderate (Mw≤5.5) and generally occur in clusters in space (the subzones Râmnicu Sărat and Vrâncioaia, situated in the Vrancea epicentral area and adjacent to it) and in time (main shocks accompanied by aftershocks and sometimes by preshocks or swarms). The accumulated deformation is almost entirely released by earthquake generation in the subcrustal domain (60≤h<220 km). Here 2-5 shocks with magnitude Mw ~ 7 occur per century producing a lot of casualties and severe damage.
A growing body of evidence supports the idea of time, space and energy clustering in the seismogenic process, which must reflect specific physical, geodynamic and geological phenomena acting at different scale lengths. At the same time, the clusters are related to the presence of inhomogeneities at different scales. For example, several studies show that the seismic activity in Vrancea exhibits a pronounced seismic gap in the 40-60 km depth range [3], which separates the crustal seismicity from the subducted one. The subducted slab itself is broken up into two [7] or even three [2], [4], [5] segments. These spatial inhomogeneities are by all means connected to significant differences of the geological and physical properties of the subducted material (thermal regime, phase transitions, fluid flow).

The present paper carries out an analysis of the time distribution of the Vrancea earthquakes with special emphasis on the two well-delineated subcrustal volumes where the major shocks of March 1977 and May 1990 (MW = 7.4 and MW = 6.9 in the depth range 60 ≤ h < 110 km), and August 1986 (MW = 7.1 in the depth range 110 ≤ h < 220 km), respectively, were generated. Different statistical measures and methods are applied in order to outline clustering properties in the earthquake time series or in the inter-event time interval distribution.

OBSERVATIONAL DATA

A catalog of 5449 Vrancea intermediate depth earthquakes with local magnitude ML ≥ 1.5 occurred between January 1974 and April 2001 is considered. The events are identified and localized only on depth using a calibration procedure proposed by [8]. For a subset of most recent earthquakes (January 1998-April 2001) complete locations are performed (depth, epicentral coordinates and origin time).

The seismic activity represented in Fig. 2a, outlines the anomalies associated with the clusters of aftershocks of the major events of 1977, 1986 and 1990. If we plot the background seismicity (removing the aftershocks) separately for the upper segment of the subducted lithosphere (60 ≤ h ≤ 100 km), where the shocks of 1977 and 1990 were generated, and for the lower segment (h ≥ 110 km), where the shock of 1986 was generated (Fig. 2b), we notice approximate constant rates for the seismogenic zones differing by a factor of about 5. The significantly higher rate of earthquake generation in the lower lithosphere cannot be simply explained by a geometrical factor [9]; it is probably in relation with a difference in the intimate physical mechanism responsible for the earthquake generation. One of the purposes of this study is to check this hypothesis by analysing the earthquake time series.

TIME DISTRIBUTION OF SEISMICITY

In order to detect clustering in time versus a random behavior of Poissonian type we use first a simple analysis of the considered catalog. For a Poissonian distribution the probability \( P \) that \( k \) events are produced in the time interval \( \Delta t \) is given by:
\[
P(k; \lambda) = \frac{(\lambda \Delta t)^k}{k!} \exp(-\lambda \Delta t)
\]  

Fig. 2 – a) Seismic activity rate: number of events with \( M \geq 3.0 \) per month occurred in the time interval 1974-2001; b) background activity rate: number of events with \( M \geq 3.0 \) per six months, occurred in the time interval 1974-2001 (without aftershocks) for
upper (60 ≤ h < 110 km) and lower (110 ≤ h < 220 km) lithosphere.

where the parameter \( \lambda \) is a constant correlated with the events density on the time axis. If \( T \) is the total duration of the catalog and \( N \) is the total number of events, then:

\[
\lambda \Delta t \cong T/N \tag{2}
\]

The observed distribution is well approximated by the theoretical distribution at a lower time scale (\( \Delta t < 60 \) days), but can seriously deviate from a random process at a larger time scale (\( \Delta t > 60 \) days), indicating clustering tendencies especially in the upper segment (Fig. 3). To test these tendencies, we consider subsequently the distribution of the time interval between successive events in the following cases:

(i) entire subcrustal domain (60≤h<220 km);
(ii) the upper segment (60≤h≤110 km);
(iii) the lower segment (h>110 km);
(iv) the events occurred in 1986 (anomalous seismic activity for the lower segment);
(v) the events occurred in 1990 (anomalous seismic activity for the upper segment).

As is known, the inter-event time distribution for a Poisson process is an exponential function, while for a clustered process is a power law. The distributions corresponding to cases (i)-(v) mentioned above are represented in Fig. 4 in log-log axes to test the power function and log-linear axes to test the exponential function. The distribution for the entire depth domain is better approximated by an exponential function (Fig. 4b), meaning that the global time series is close to a random process. The exponential behavior is also better fitting the inter-event time distribution when analyzed on separate upper and lower parts of the subducting lithosphere. If the analysis is restrained to a single year time interval that contains the major shocks of 1986 in the lower slab and 1990 in the upper slab, the distributions tend to power-laws, for the reason that clustering properties are prevailing in these cases, and the events become mutually dependent. This is not surprising, having in mind the fact that the occurrence of the major shocks is accompanied by an intense aftershock activity.

Another possible measure of the earthquake time clustering is given by the coefficient of variation \( C_v \), defined as the ratio between the standard deviation and the average of the inter-event time,

\[
C_v = \frac{\sigma}{\langle T \rangle} \tag{3}
\]

Coefficient \( C_v=0 \) for periodic process, \( C_v<1 \) for random process and \( C_v>1 \) for clustered process.
depth 60 - 220 km; $M_{\text{min}} = 2.8$

depth 60 - 110 km; $M_{\text{min}} = 2.5$

depth 110 - 220 km; $M_{\text{min}} = 2.8$

depth 60 - 220 km; $M_{\text{min}} = 2.8$
We compute $C_v$ for the cases (ii)-(v) mentioned before and look for its dependence on the threshold magnitude. The variation of the coefficient of variation as a function of the threshold magnitude for the whole earthquake catalog (1974-2001) considering the two separate subzones, is represented in Fig. 5. The coefficient values lie around 1, being higher when aftershock sequences are included. The $C_v$ variation shows a completely different behavior for the upper and lower portions of the subducted slab: (1) for magnitudes below 3.5-3.7, the $C_v$ is almost constant in both subzones showing slightly more clustering in the upper segment; (2) for larger events ($M>3.7$) $C_v$ is decreasing below 1.0 in the upper segment, while it is increasing in the lower segment. It is noteworthy that the same behavior is obtained when considering earthquake subsets with anomalous activity in 1986 and 1990 (Fig. 6). Even though the amplitude of the $C_v$ variation when the
threshold magnitude is above M~3.7 is not too large (10-30%), it is enough coherent to be considered as not a simple random fluctuation.

Fig. 4 – Test of the inter-event time distribution with a power law function (a) and exponential function (b). Five cases are plotted (see text) on the basis of the entire catalog: (i) entire seismic
domain \((M \geq 2.5)\), (ii) upper zone \((60 \leq h < 110 \text{ km}, M \geq 2.5 \text{ km})\), (iii) lower zone \((110 \leq h < 220 \text{ km}, M \geq 2.8)\), (iv) seismicity in the lower zone restricted to 1986 \((M \geq 2.8)\), and (v) seismicity in the upper zone restricted to 1990 \((M \geq 2.5)\).

In agreement with the modelling of the Vrancea seismic regime proposed by [9], we may speculate that the difference in \(C_v\) behavior is caused by a different mechanism of generating earthquakes in the upper relatively to the lower lithosphere. Starting from the departure from a linear frequency-magnitude distribution, [7] assumed the existence of two families of characteristic earthquake
mechanisms: crack-like faulting mechanism, controlling the generation of smaller earthquakes (M below ~ 3.5) and asperity-like faulting mechanism, controlling the generation of moderate earthquakes (M above ~ 3.5). When analysing the seismic regime in the two subzones [9] found several arguments supporting the idea of a strong discrepancy between the mechanisms of generating earthquakes in the upper and lower active segments of the Vrancea seismogenic volume. Our results confirm this hypothesis. The smaller events (crack-like) are more clustered in the upper zone probably due to a stress diffusion process at this scale. The moderate events (asperity-like) are less abundant in the upper zone in comparison with the lower zone, and are more randomly generated. It seems that distinct earthquake generating processes are acting in the two depth ranges, indicating a different physical background (phase transition, fluid migration, etc.).

![Fig. 6 – The coefficient of variation as a function of the threshold magnitude estimated for one year time interval of anomalous seismic activity related to the 1986 major shock (solid line) and 1990 major shock (dashed line) occurrences in the lower and upper subducting lithosphere, respectively.](image)

CONCLUSIONS

Our analysis of the time series extracted from an extended catalog of Vrancea intermediate depth earthquakes outlines significant clustering tendencies at
different scalelengths for the two seismic active segments delimited in the
subducting slab (centered at 90 km depth and 140 km depth, respectively). Various
statistical procedures are applied in order to detect clustering features. Even if the
deviations from a purely random process revealed by the present study have
relatively small amplitudes, we feel that they are important in explaining the
differences in the earthquake generation process along the subducting slab.
Application of supplementary techniques like running mean technique or
multifractal statistics will be of much help to confirm our results. At the same time,
concentrated efforts are needed to explain the physical processes responsible for
the clustering effects.

As shown by our results, the moderate-magnitude earthquakes (M ~ 4) tend
to occur in clusters in the lower lithosphere (h > 110 km) in contrast with the upper
lithosphere (h < 110 km), where they seem to be randomly generated. The situation
is opposite if we look at the seismic regime at low magnitudes: random process in
the lower segment, while clustered process in the upper segment.

At this stage, we may speculate on a sort of metastable process (phase
transformation of olivine) in the lower segment, randomly generating crack-like
slips which stimulate the generation of asperity-like earthquakes (like in a
percolation process). The asperity-like earthquakes (M ~ 4) are stronger
interconnected as compared with crack-like earthquakes (M<3.6). By contrast, the
small earthquakes (crack-like) are more clustered (due to fluid migration or
dehydration reaction?) in the upper segment than the moderate earthquakes, whose
occurrence seems to be poorly correlated.

This difference supports the result of [6] concerning the behavior of the ratio
between asperity-like and crack-like earthquakes in the lower and upper segments
of the subducting lithosphere. They observed a complete different behavior of this
ratio between the two segments, but they could not put forward any consistent
explanation.

REFERENCES
1. L. Constantinescu, P. Constantinescu, I. Cornea, V. Lăzărescu, Recent seismic information on the
2. D. Enescu, B. D. Enescu, Seismotectonic model regarding the genesis and the occurrence of
Merkler, T. Moldoveanu, G. Tudorache, The Romanian earthquake of March 4, 1977,
4. M. C. Oncescu, Some source and medium properties of the Vrancea seismic region, Romania,
Tectonophysics, 126, 245-258 (1986).


