Romanian Reports in Physics, Vol. 62, No. 4, P. 865–877, 2010

THE STATISTICAL TIDAL TOMOGRAPHY – A NEW INVESTIGATION METHOD FOR THE INTERMEDIATE-DEPTH SEISMIC ACTIVITY*

NICOLETA CADICHEANU

The Institute of the Geodynamics of the Romanian Academy
E-mail: nicoleta_cadichian@yahoo.com

(Received June 30, 2009)

Abstract. The influences of the tidal semidiurnal waves on the intermediate depth seismic activity were found. In addition, certain long-term periodicities, called synchronization intervals, have been noted. Starting from these results, we have questioned the sensibility of the statistical parameter *p* to transient features around strong seismic events for three long time series of earthquakes in Vrancea (Romania), Bucaramanga (Columbia) and Hindu Kush (Afghanistan) seismic zones. The statistical coefficient *p* was calculated by means of two statistical tests (the Schuster's test and permutation test) assuming null hypothesis for random distribution. These tests have been applied on the seismic event distributions obtained with the aid of HiCum method in sliding windows. We have extended this methodology to different layers in the case of intermediate–depth seismic zones, using the relatively new concept of "statistical tidal tomography".

Key word: long time series, earth-tide, earthquakes, HiCum, statistical tidal tomography.

1. INTRODUCTION

The geology and tectonics have, without doubt, a leading part in the complex and diverse processes of energy accumulation in a seismic zone. Geophysics supports the effects that earth-tides induce on parameters at different scales like atmospheric pressure, fluid flow (water, lava, etc.), thermo-mechanical or tectonic phenomena. The hypothesis that Earth-tides trigger seismic events has been investigated by many authors, one of the invoked triggering reasons being the induced gravitational modulations of the earth tides [1, 2, 3]. At the depth of intermediate (70 km to 300 km) and deep earthquakes (focal depth > 300 km) the Earth tides are the main external force with very deep modulation, which could affect the dynamic of the Earth with periodicities as shorter as 24 hours (diurnal band) or 12 hours (semi-diurnal band) [1].

---

* Paper presented at the Annual Scientific Session of Faculty of Physics, University of Bucharest, June 5, 2009, Bucharest-Măgurele, Romania.

The influences of the tidal semidiurnal waves on the intermediate depth seismic activity were found previously. In the analyzed cases, the coupling between semidiurnal *M2* component and earthquake occurrences was supposed [4, 5]. Starting from these results, we question the sensibility of a statistical parameter *p* to transient features around strong seismic events for three long time series of earthquakes in Vrancea (Romania), Bucaramanga (Columbia) and Hindu Kush (Afghanistan) seismic zones (Fig.1).

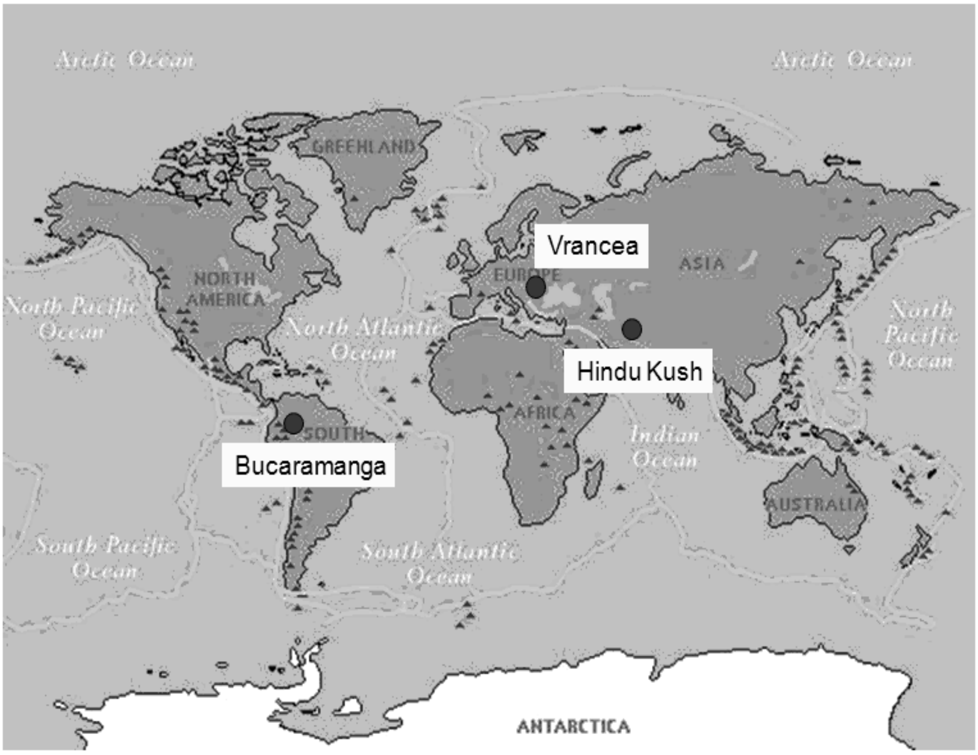


Fig. 1 – The analysed intermediate-depth seismic zones.

The parameter *p* used to validate this coupling was statistically defined by means of two statistical tests. Moreover, using sliding time windows certain long-term periodicities of the synchronization between earthquake occurrences and M2 tidal waves have been noted [6].

2. DATA

The input data for our study were obtained from the USGS catalogue of seismic events occurred between 1973 and 2008, with $M_w \geq 2.5$, for Bucaramanga

(1758 events) and Hindu Kush (9997 events) seismic zones, and from the RomPlus catalogue for Vrancea seismic zone, from 1934 to 2008 (4248 events). All the earthquakes were taken in account: crustal and subcrustal activity, main shocks and aftershocks.

The nest intermediate-depth seismic activity represents the common feature of the three analysed seismic zones [7], tectonically very different.

These seismic zones are localised in the North hemisphere of the Earth.

The catalogues cover the following geographical rectangles:

1) Vrancea (Romania): 45.0° – 46.0°N, 26.0° – 27.0°E,

2) Bucaramanga (Colombia): 5.0° – 9.5°N, 72.5° – 74.5°W,

3) Hindu Kush (Afganistan): 30.0°N – 42.0°N, 68.0°E – 78.0°E.

3. METHOD

3.1. HiCum METHOD AND STATISTICAL TESTS

We statistically investigate the hypothesis of the seismic activity modulation/synchronization by the selected tidal wave period using classical approach of the Schuster's test which is largely applied [4, 8]. To avoid the risk of spurious conclusions, we introduce another statistical test [5], permutation test, intensively used by biologists and geneticists [9]. We consider that the null hypothesis of a significant relationship between seismic activity and selected semidiurnal tidal periodicity is rejected when the statistical *p*-values obtained by the two tests are less than the 5% level.

The results are validated by comparison with the application of the same algorithms to synthetically generated random events series. The statistical tests are applied on the events distributions obtained following the method of van Ruymbeke et al. (2003) [10]: each event E_i occurred at time t_i is characterized by a phase α_i defined in the interval 360°, corresponding to the phase of a selected harmonic signal (Fig. 2). For this work, we choose the *M2* main tidal component with its original phase fixed from astronomical data.

HiCum is dependent on the availability of large amount of data and on the frequency of the wave to be detected. As each earth-tide component can be defined with high accuracy, HiCum is a useful tool for determining whether Earth-tides are influencing any of the parameters recorded in a series of events.

The stacking analysis method HiCum (Histogram Cumulating) consists in adjusting a cosine function to the histogram of the α_i (Fig. 3).

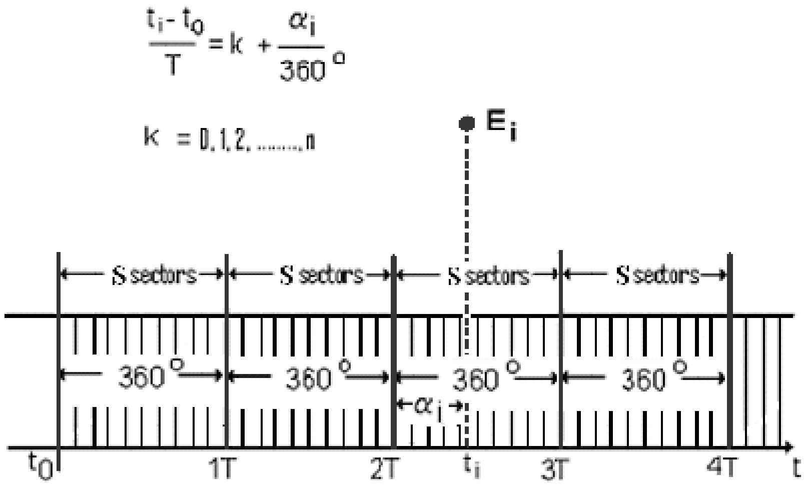


Fig. 2 – Time series partition into selected time period *T*.
An event E_i occurring at time t_i is defined by an angle α_i.

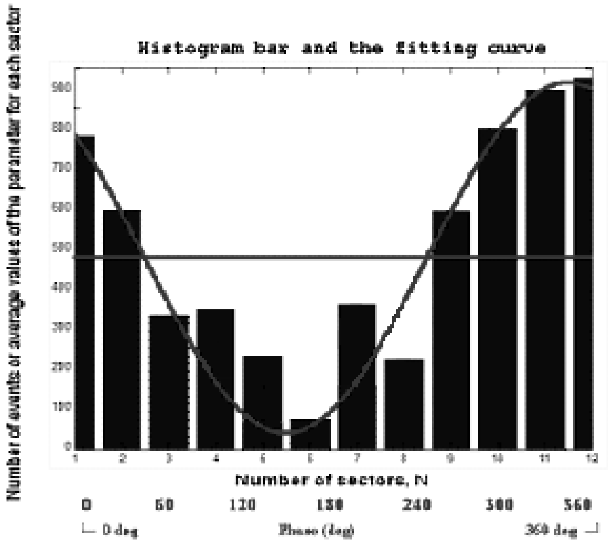


Fig. 3 – The fitting curve of the HiCum stacking by a sinusoidal function.

The amplitude and phase of this cosine show the links, in terms of modulation, between the stacked events and the semidiurnal tidal component.

The stacking function is applied in sliding windows in the time domain and in the space domain. The phase distribution of events was tested by two independent methods that evaluate the statistical *p*-value:

a) Schuster's test [11]

$$p = \exp\left(-\frac{D^2}{N}\right), \quad (1)$$

where N is the number of earthquakes and D represents the length of the vectorial sum of all unit length vectors defined by their angle phase.

b) Permutation test [9]

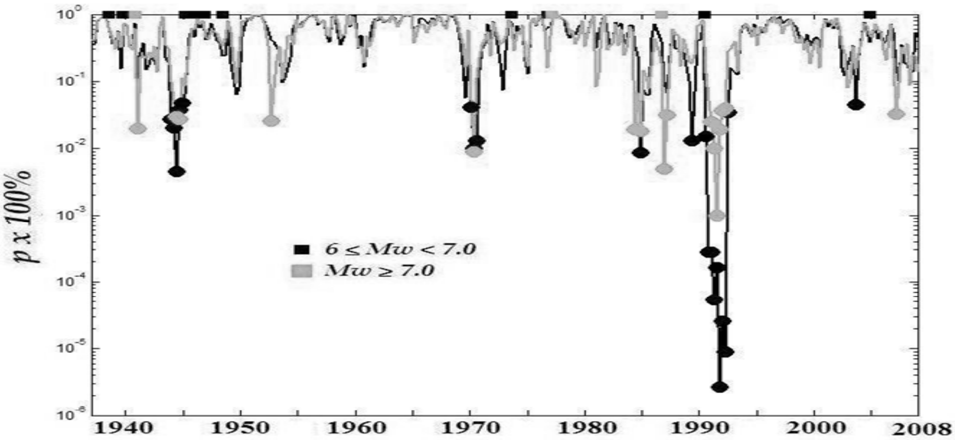
$$\text{for } A_j > A_0 \ (j=0, 1, 2\ldots\ldots m);\ \ p=m/n, \quad (2)$$

where A_j represents the amplitude of the sinusoids obtained for every permutation in the HiCum initial distribution (A_0 is the amplitude of the initial seismic event distribution), n is the number of permutation, $m \le n$. The results are validated by series of applications to synthetically series of random events.

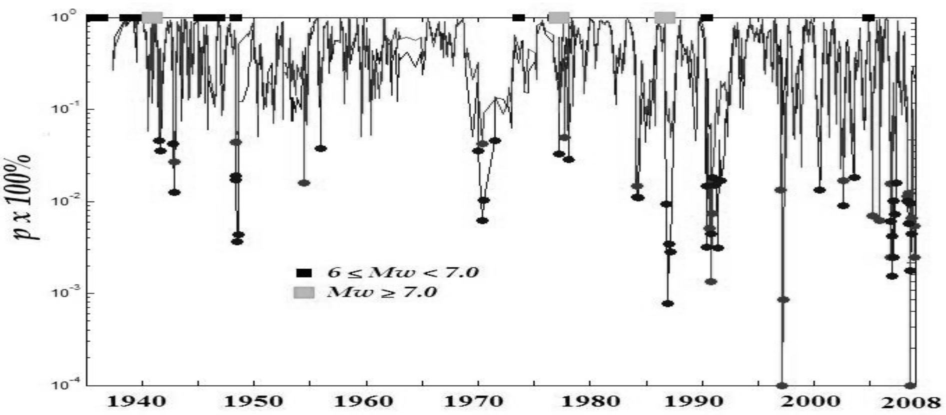
3.2. TEMPORAL AND 3D SLIDING WINDOWS

We introduce (Fig. 4) the temporal variability of the two statistical coefficients p applied on two kinds of temporal sliding windows defined respectively with constant time intervals (two years) shifted by 90 days, and windows containing constant number of events and shifted also by constant number of events. The p-values are plotted at the end of each window.

In both cases the variation of p-values has the same behaviour. This can be considered a good result concerning the choice of the method.



a)



b)

Fig. 4 – Vrancea seismic zone exemple.
Statistical coefficient p values for Schuster's test (in light grey) and permutation test (in dark grey), marked with circles for $p < 5\%$. Earthquakes with magnitude $6.0 \leq M_w < 7.0$ are represented by black squares. The light grey squares are for earthquakes with $M_w \geq 7.0$. The upper graph (a) shows results for the sliding windows defined by the fixed time interval of two years shifted by 90 days. The lower graph (b) corresponds to sliding windows with fixed number of events (100 seismic events) shifted with a fixed number of events of 10 events.

In addition to the temporal sliding windows, we introduce the concept of *3-D statistical tidal tomography* [6]. In this case, the p-coefficients are calculated for events located within parallelepipedic volumes defined in Fig. 5. Only the series equal or larger than 20 events are considered.

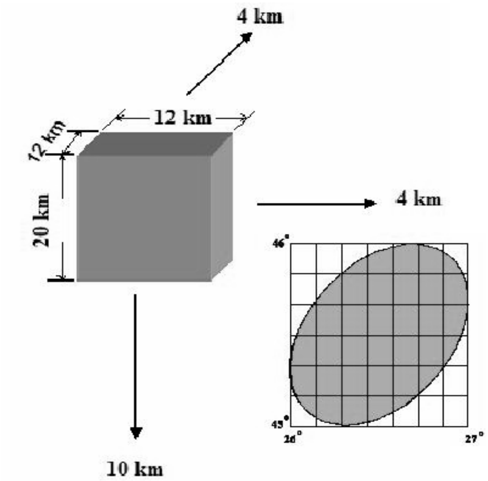
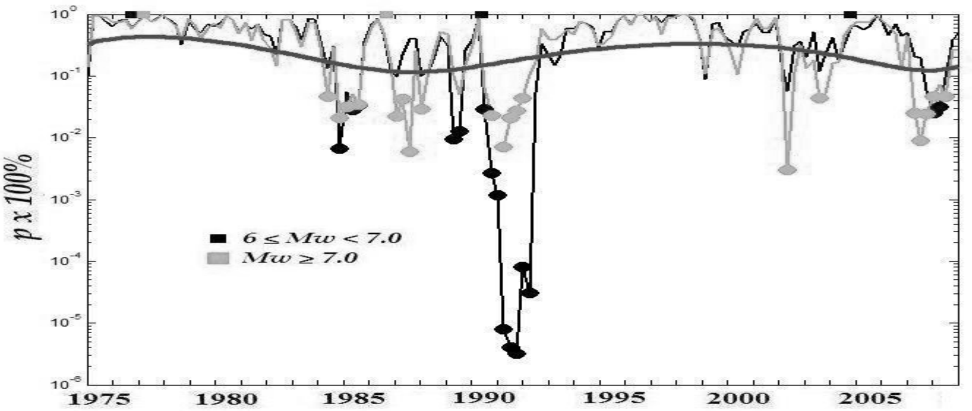


Fig. 5 – The "statistical tidal tomography" map of p statistical coefficients is obtained when stacking function is applied to 3-D geometry following the earthquake distribution. The calculations are carried out for $12 \times 12 \times 20$ km³ windows covering the entire hypocentre zone area. The sliding steps are respectively 4 by 4 km horizontally and 10 km vertically, according to the reported errors of the earthquake localization.

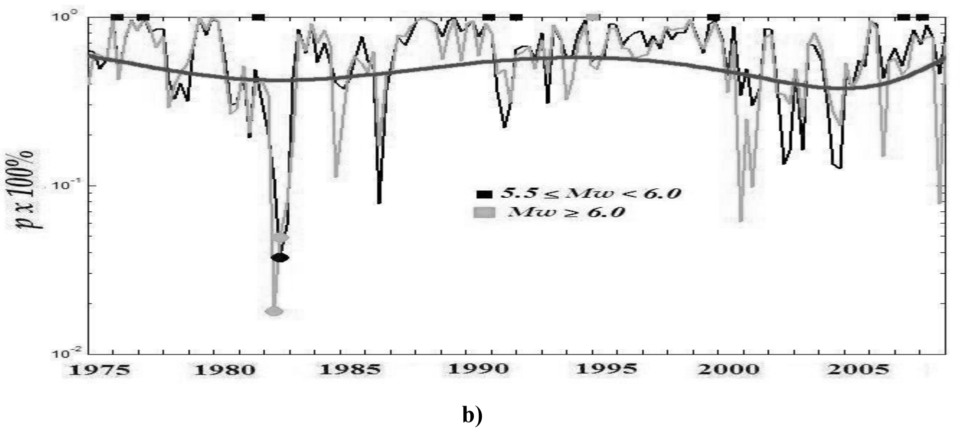
4. RESULTS

A systematic temporal pattern of the *p*-values preceding or following the meaningful earthquakes was observed for the analyzed seismic zones. It is represented by a number of temporal windows, in which *p*-values are less than the 5% or present a frequent descending tendency toward smaller values of *p*. This behaviour is observed from a few weeks in some cases, to a few years in other, before an important event or immediately after its occurrence.

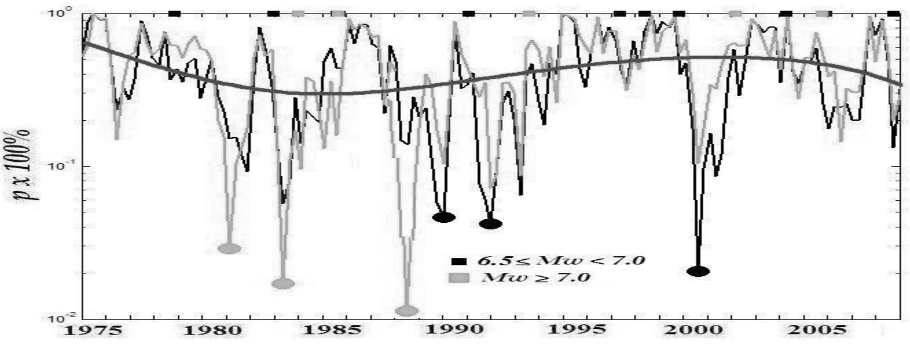
Therefore, we identify this feature for Vrancea (Romania) before the 1977, 1986, 1990 and 2004 earthquakes; for Bucaramanga (Columbia) before the 1977, 1981, 1985, 1986, 1990, 1992, 1995, 2001, 2007 and 2008 earthquakes and for Hindu Kush (Afganistan) before the 1978, 1982, 1983, 1985, 1991, 1993, 1997, 1998, 1999, 2002, 2004, 2005 and 2008 events (Fig. 6).



a)



b)



c)

Fig. 6 – Statistical *p* value variations for the intermediate-depth seismic zones: a) Vrancea; b) Bucaramanga; c) Hindu Kush. The temporal windows in which the semidiurnal period of *M2* wave synchronizes with the seismic activity are marked by circles. The squares indicates the moment of an important earthquake and the curve represents the 5 order polynomial least square fitting.

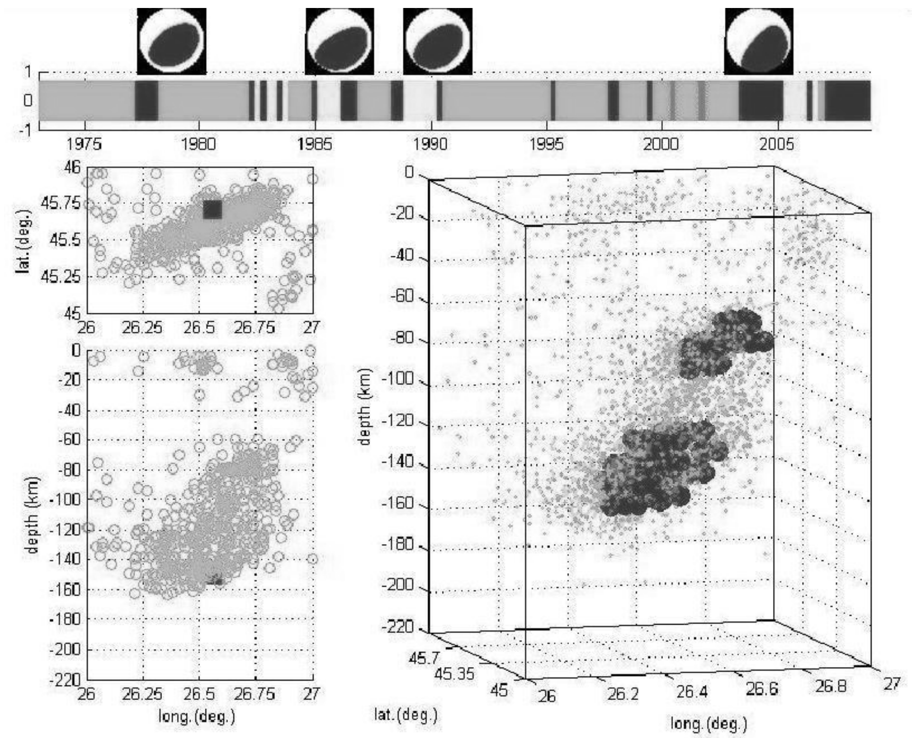
To detect long-term period of *p* variation, we perform a Fast Fourier Transform on the 5-order polynomial least squares fit (LSF) (Fig. 6). The curves corresponding to polynomial interpolation point out a component with a long-term quasi-period of 17 years for *p* variation in Vrancea and Bucaramanga seismic zones, and an other of 34 years for Hindu Kush, respectively. However, the time series are not sufficiently long for a definite conclusion.

A "statistical tidal tomography" map for each intermediate-depth seismic zone is obtained when stacking function is shifted in 3D geometry following the hypocentre distribution. We assume that the tidal tomography patterns represent the response of the regional tectonic structure to the earth-tides.

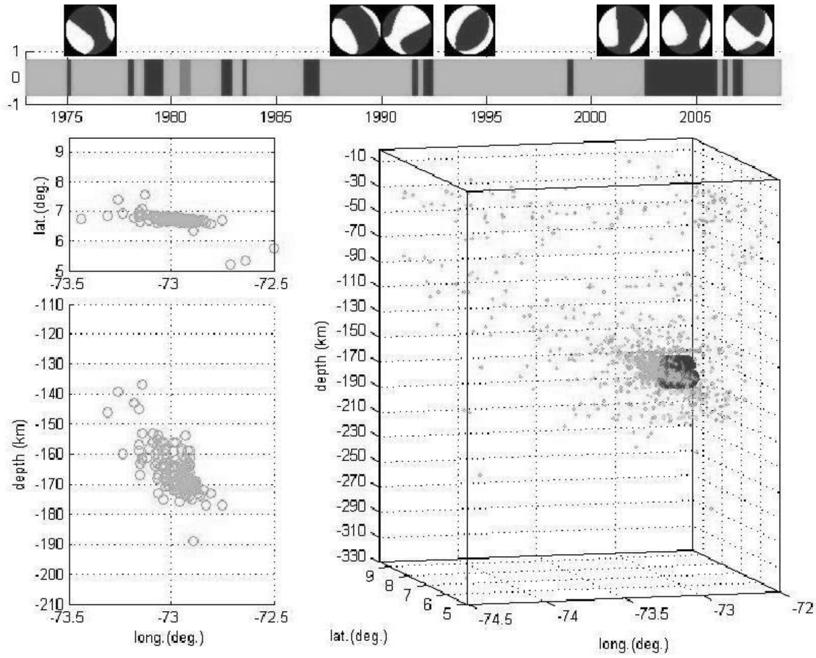
Interesting aspects are observed in time and space of the synchronization between the period of *M2* tidal wave and seismic activity characterizing each analyzed seismic zone. (Fig. 7a, b, c). In the upper part of each figure are represented different cases of synchronisation between *M2* tidal period and seismic activity and the fault plane solutions for the strong earthquakes. The black bands correspond to the windows in which the synchronisation is present only for different volumes, at different depths. The dark grey bands characterize the windows with synchronisation in the whole seismic slab. The light grey bands characterize the windows without synchronisation and the white bands indicate the presence of both types of synchronisation: in time and space sliding windows. In the box of the right part of the figure, the dark spheres emphasize the position of the synchronisation volumes for all sliding windows between 1973 and 2008. In the boxes of the left part of the figure, into a horizontal projection of the seismic activity, respectively vertical projection along a latitude parallel, is represented the same for the last analysed window (2007-2008). In the background, in light colour, the hypocentres of all earthquakes are plotted.

Following the 3-D distribution of $p < 5\%$ values in different sliding time windows, a migration of the volumes in which the seismic activity synchronize with semidiurnal tide component was observed for the Vrancea region, migration which might be related to the occurrences of strong earthquakes (Fig. 7a). Analysis of the seismicity patterns shows the same thing [12].

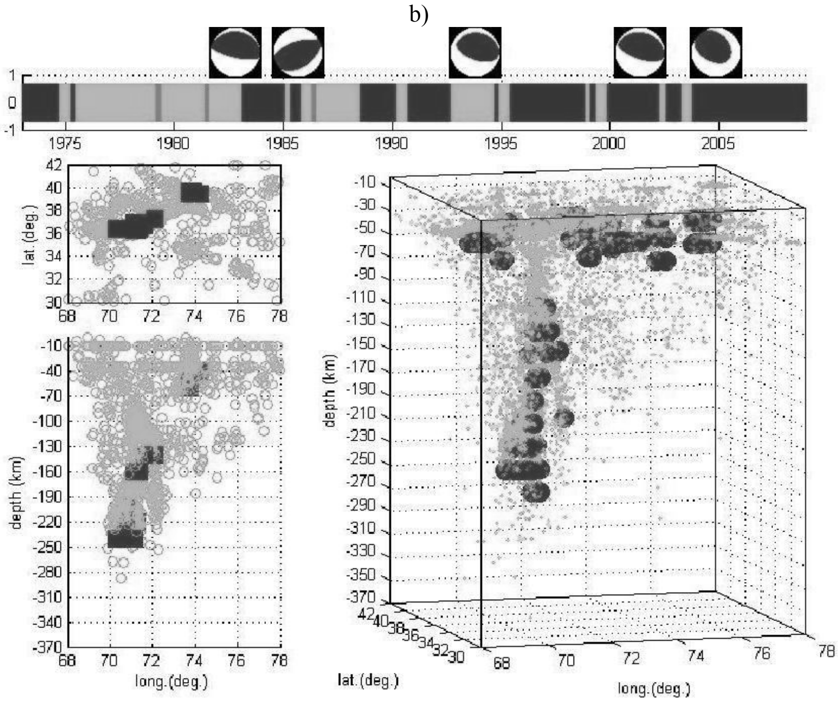
The statistical tidal tomography revealed a very concentrated volume of synchronisation with *M2* tide component in the case of Bucaramanga seismic zone (Fig. 7b). A process of double subduction is assumed in this region [13]. As regards Hindu Kush seismicity, the distribution of the synchronisation volumes is much complex and could be related to the dynamical processes of subduction present here (Fig. 7c) [14].



a)



b)



c)

Fig. 7 – Results of the statistical *M2* tidal period tomography for the seismic zones: a) Vrancea; b) Bucaramanga; c) Hindu Kush.

For certain time windows the synchronisation is not observed for the whole seismogenic zone, but it is present in some crustal or subcrustal volumes.

In the case of the Vrancea zone, the presence in the same time of the “global” and “local” synchronisation mentioned above seems to be a precursory pattern for the important earthquakes ($M_w \geq 5.0$).

5. CONCLUSIONS

The analysis of temporal and 3D variation of two kinds of statistical test coefficients *p* in the “nest” seismic zones shows certain peculiarities of the parameters:

a) Synchronisation tendencies between semidiurnal *M2* wave period and seismic activity.

b) Different signatures of the *p* variation for relatively medium and long time (from some weeks to a few years are observed in the neighbourhood of the stronger earthquakes occurred in the well-known intermediate-depth seismic zones Vrancea, Bucaramanga and Hindu Kush). These fingers are represented by a number of temporal windows, in which *p*-values are less than the 5% or present a frequent descending tendency toward smaller values of *p*.

c) These signatures are characterize by components with a long-term quasi-period (around of ~17 years or ~34 years) but the time series are not sufficiently long for a definite conclusion.

An attempt to analyze the *p*-value variations for Vrancea, 1934–2007 in sliding windows of 365 days shifted by 50 days was also performed (Fig. 8).

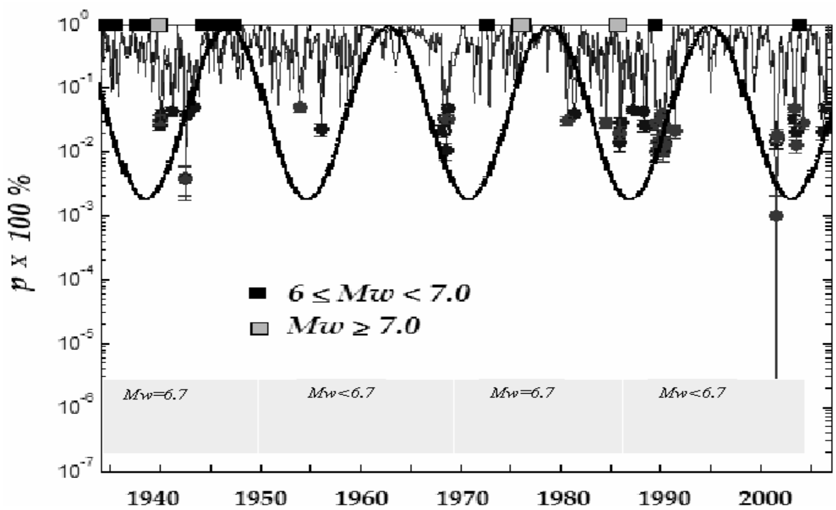


Fig. 8 – *p*-value variations for Vrancea seismic zone, 1934–2007 interval, in sliding windows of 365 days shifted by 50 days. A quasi-long period of 17 years in the variation of the *p*-value is pointed out. The same periodicity was observed by Enescu et al. [15] concerning the magnitude of the maximum observed event and predominant fault plane solutions.

By applying the FFT to the 5-order polynomial least squares fit of p-values, we obtain a period of 17 years of the synchronization of the earthquake occurrence with *M2* tidal waves. This period is in good agreement with the behaviour of other characteristics of the seismic activity (e.g. magnitude of the maximum observed event, focal mechanism) retrieved by Enescu et al. [15].

We can observe a quasi-long period of about 17 years in the variation behaviour of the *p*-value. Approximate the same pattern was observed by in the dominate magnitude and fault plane solutions alternation.

d) Statistical tidal tomography emphasizes an interesting feature, typical of every seismic zone, which could be interpreted like seismic premonitory pattern. Therefore, the presence of the "global" (entire seismicity in the time window) and "local" (different volumes, at different depths) synchronisation between semidiurnal *M2* wave period and seismic activity, seems to be related to a critical stage in the triggering of the meaningful events. We call the windows in which this phenomenon is present as "alarm windows" (black bands in Fig. 8). There could be possible a relation between the number of correlation volumes (as a "critical mass") for a defined window and the imminent triggering of the earthquakes.

e) For Vrancea seismic zone, we have found similarities between the results of CN algorithm [16] for strong earthquakes prediction and the results of the statistical *M2* tidal tomography. The alarm stage of our algorithm was confirmed by an important earthquake with $M_w = 5.3$ which occurred recently in the Vrancea seismic zone (25^{th} April, 2009).

The relationship between seismic activities and tidal periodicities could be important to understand some characteristics of the analyzed seismic zones [6]. In addition, the statistical coefficient *p* could have a potential capacity to identify the existence of transient features around strong seismic events [17].

The new concept and methodology of the statistical tidal tomography could reveal important features in the behaviour of a seismic zone; we have observed characteristic patterns (mentioned at points a), b), c) and d) above) of the coupling between tidal component and the seismic activity before and after an important earthquake.

Acknowledgments. The author expresses her deep gratitude to Prof. Michel van Ruymbeke from Royal Observatory of Belgium and to Prof. Pascal Bernard from the Institute of Earth Physics of Paris. We are very grateful to the anonymous reviewers whose objective comments have largely improved the quality of the paper. We thank Mircea Radulian and Mihaela Popa, the National Institute for Earth Physics for providing the ROMPLUS catalogue and CN algorithm results for Vrancea seismic zone.

REFERENCES

1. P. Melchior, *The Tides of the Planet Earth*, Pergamon Press, New York, 1978, p. 609.
2. M. van Ruymbeke, B. Ducarme, M. De Becker, *Parameterization of the tidal triggering of earthquakes*, B.I.M., **86**, décembre, pp. 5521–5544 (1981).

3. D. Zugrăvescu, I. Fătulescu, D. Enescu, D. Danchiv, O. Haradja, *Peculiarities of the correlation between gravity tides and earthquakes,* Rev. Roum. Géophysique, **33**, pp. 3–11 (1989).
4. S. Tanaka, H. Sato, S. Matsumura, M. Ohtake, *Tidal triggering of earthquakes in the subducting Philippine Sea plate beneath the locked zone of the plate interface in the Tokai region, Japan,* Tectonophysics, **417**, 69–80 (2006).
5. N. Cadicheanu, M. van Ruymbeke, P. Zhu, *Tidal triggering evidence of intermediate depth earthquakes in the Vrancea zone (Romania)*, Nat. Hazards Earth Syst. Sci., **7**, 733–740 (2007).
6. N. Cadicheanu, P. Zhu, M. van Ruymbeke, *Spatial and temporal variations of the correlation coefficient between M2 and S2 earth tides components and earthquake occurrence for the intermediate-depth seismic activity zones,* Acta Geodaetica et Geophysica Hungarica, **43**, *2*, Special issues (2008).
7. Z. Zarifi, J. Havskov, *Characteristics of dense nests of deep and intermediate depth seismicity* Advances in Geophysics, **46**, pp. 237–278, Academic Press., Published by Elsevier, 2003.
8. T. H. Heaton, *Tidal triggering of earthquakes,* Geophys. J. R. Astron. Soc., **43**, 307–326 (1975).
9. E. J. G. Pitman, *Significance tests which may be applied to samples from any population, Part III: The analysis of variance test,* Biometrika, **29**, 322–335 (1938).
10. M. van Ruymbeke, R. Howard, P. Putz, F. Beauducel, A. Somerhausen, J-P. Barriot, *An Introduction to the use of HICUM for signal analysis*, BIM, **138**, *10*, 955–10 966 (2003).
11. A. Schuster, *On lunar and solar periodicities of earthquakes*, Proc. R. Soc. Lond., **61**, 455–465 (1897).
12. M. Radulian, M. Popa, O. Cărbunar, M. Rogozea, *Seismicity patterns in Vrancea and predictive features*, Acta Geodaetica et Geophysica Hungarica, **43**, *2*, Special issues (2008).
13. N. Pulido, *Seismotectonics of the Northern Andes (Colombia) and the development of seismic networks,* Bulletin of the International Institute of Seismology and Earthquake Engineering, Special Edition, pp. 69–76 (2003).
14. G. Pegler, S. Das, *An enhanced image of the Pamir-Hindu Kush seismic zone from relocated earthquake hypocentres*, Geophysical Journal International, **134**, *2*, 573–595 (1998).
15. D. Enescu, D. B. Enescu, *Possible cause – effect relationships between Vrancea (Romania) earthquakes and some global geophysical phenomena,* Natural Hazards, Kluwwer Academic Publishers, **19**, 233–245 (1999).
16. C. L. Moldoveanu, O. V. Novikova, G. F. Panza, M. Radulian, *CN earthquake prediction algorithm and the monitoring of the future strong Vrancea event,* Rev. Roum. Géophysique, **48**, 31–36 (2004).
17. P. Bernard, *From the search of 'precursors' to the research on 'crustal transients'*, Tectonophysics, **338**, 225–232 (2001).