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STATISTICAL TIDAL TOMOGRAPHY OF THE VRANCEA INTERMEDIATE-DEPTH SEISMIC ZONE

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Abstract: The aim of the study is to identify specifically temporal and spatial patterns of the intermediate seismic activity in Vrancea seismic zone using new approaches. We study the influences of the principal lunar semidiurnal tidal component *M2* on intermediate seismic activity in Vrancea (Romania) sub-crustal region from 1934 to 2009 with a special regard for the time series of events from 1980 to 2009. The constituent is assigned by HiCum stacking method according to the earthquake occurrence. “Schuster” and “Permutation” independent tests are applied to distributions found by stacking. Null hypothesis between seismic activities and selected tidal periodicities is rejected when the statistical *p*-values obtained by the two tests are less than 5% level of confidence in term of statistics. The stacking function is applied to time series of events belonging to windows shifted in time and space, respectively, to evaluate the variability of correlations in both cases. In the case of 3D shifting domain, a specific algorithm, called “statistical tidal tomography”, is described. The results reveal important issues: a). There is a specific temporal footprint of the *p*-values around the larger earthquakes; b) A Fast Fourier Transform on the n-order polynomial least squares fit (LSF) of the *p* values variations emphasizes a long-term period about 17 – 18 years; c) Following the 3-D distribution of p<5% values in different sliding time windows we observe a certain pattern confirmed by the CN algorithm for the earthquake prediction and the future strong Vrancea events monitoring; d) the statistical tidal tomography of *M2* component has similar patterns with the analysis of seismicity patterns introduced by Radulian et al. 2007 for the Vrancea seismic region.

Keywords*:* statistical tidal tomography, Vrancea seismic zone, earth-tide, HiCum method, Shuster’s and Permutation tests, sliding windows

1. Introduction

Geophysical study of the Vrancea area is very important because it is a highly active seismic zone where millions of people live. Recent earthquakes of magnitude *Mw* larger than seven (1940 and 1977) have been devastating for Bucharest and for the epicentre area (Constantinescu and Enescu, 1984). The relative frequency of such events in Romania is around 30-40 years.

Many authors have investigated the possible correlation between seismic activity in some areas and earth-tides (Knopoff, 1964; Heaton, 1975; Klein, 1976; Tanaka et al., 2002, etc.), but the description of mechanisms by which earth-tides could be involved is not established. The processes of energy accumulation in a seismic zone are complex and diverse, but remain strongly linked to the geology and the tectonics of the region. Geophysics assumes that earth-tides could induce effects on parameters at different scales like atmospheric pressure, fluid flow (water, lava, etc.), thermo-mechanical or tectonic phenomena (Enescu and Enescu, 1996).

At the depth of intermediate (60km < 300km) and deep (focal depth > 300km) earthquakes, the Earth tides are the main outside force with very deep modulation depending of the solar and lunar orbital parameters which could affect, with periodicities as short as 24 hours (diurnal band) or 12 hours (semi-diurnal band), the dynamic of the Earth (Melchior, 1978).

Accordingly, we took into account the couplings between the semidiurnal M2 component and earthquake occurrences (Tanaka et al., 2006, Cadicheanu et al., 2007).

2. Methodology: HiCum spectral analysis and statistical tests

Each event E_i occurred at time t_i is characterized by a phase α_i defined in the interval 1°–360° correspondingly to the phase of a selected harmonic signal (Fig.1). For this work, we choose the M2 main tidal component with its original phase fixed from astronomical data. The stacking analysis method named HiCum (for Histogram Cumulating) (van Ruymbeke et al., 2003; Cadicheanu et al., 2007) consists to adjust a cosine function to the histogram of the α_i. The amplitude and phase of this cosine show the links, in terms of modulation, between the stacked events and the semidiurnal tidal component *M2*.

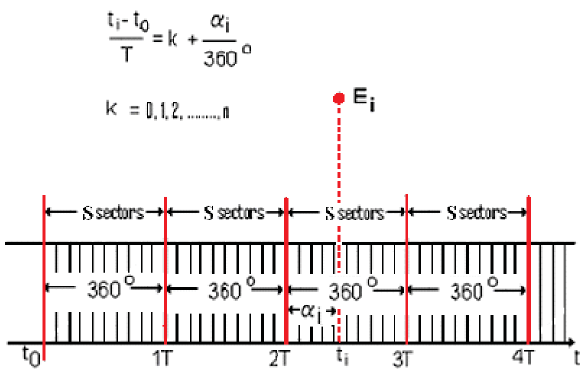

Fig. 1. Time series partition into selected time period T. An event E_i occurring at time t_i is defined by an angle α_i (Cadicheanu et al., 2007)

The stacking function is applied in sliding windows in the time domain and in the space domain. We validate statistically the hypothesis of the correlation between the M2 component and earthquake occurrences using classical approach of the *Schuster's test* (Schuster, 1897) applied largely (Heaton, 1975; Tsuruoka et al., 1995; Tanaka et al., 2006). The test evaluates the statistical p -value:

$$p = \exp(-\frac{D^2}{N}) \qquad (1)$$

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

To avoid the risk of spurious conclusions, we introduce another statistical test (Cadicheanu et al., 2007) named *permutation test*, well-known among biologists and geneticists (Pitman 1938). We consider that the null hypothesis of a significant relationship between seismic activities and selected M2 tidal periodicities is rejected when the statistical p-values obtained by the two tests are less than 5% level:

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

where Aj 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, $m \leq n$. The results are validated by series of applications to synthetically series of random events

The results are validated by comparison with the application of the same algorithms to synthetically generated random events series (Cadicheanu et al., 2007, 2008).

3. Analysis of the Rom Plus Vrancea earthquakes catalog. Results

The National Institute for Earth Physics-Bucharest has made available to us the RomPlus catalog of Vrancea earthquakes for the period 1934-2009 (May inclusive) (Oncescu et al., 1999). Our selection from January 1st, 1980 to May 29th, 2009 selection includes only earthquakes ($Mw \geq 2.5$) which presents a valuable completeness and homogeneity for data with a large number of events (about 2755 main events at intermediate depth). The aftershocks sequences are eliminated by Kossobokov-Romashkova criteria (Kossobokov and Romashkova, 2006).

Main goal of our research is to check the variability of correlation factors obtained with sliding windows which are defined in the time domain or in the space domain one.

3.1. Temporal sliding windows

We introduce the temporal variability of the two statistical coefficients p applied on two kinds of temporal sliding windows defined respectively with constant time intervals (one year) shifted by one and thirty days, and windows containing constant number of events and shifted by one and ten events, respectively (Fig.2).

In the first step, the one year window is long enough to obtain a sufficient number of quakes sufficient to apply p-tests. In addition, the annual periodicity effects induced by climatic parameters are rejected. However, the non-repetitive number of events in each window could generate spurious effects influencing p-values modulations. We confirm conclusions by comparison of previous results with results obtained by analysis of sliding windows defined with constant number of one hundred quakes.

From analysis of the four graphs, comparative results of the variability of the *p*-values for the seismic events time series from 1980 to 2009 present coherent conclusions between the statistical coefficient *p* obtained with the two statistical tests approach. These common results with such highly differentiated sampling validate the significance of conclusions.

For all the four cases proposed in the figure 2 we observe a similar pattern. The time interval between 1991 and 1996 which has no quakes with magnitude larger than five is characterized by a quasi null hypothesis. Inversely, large events occurrence seems to be related to the *p*-values modulation.

The figure 3 shows *p*-values modulation obtained for the complete data bank covering the period from 1934 to 2007 with 365 days windows shifted by 50 days steps. A systematic ~16 year oscillation appears.

A spectral analysis of the *p*-values revealed a long period oscillations of about 16 years possibly related with different long periodicities existing in the tidal modulation (elliptic or declinational components).

In addition to the temporal sliding windows, we introduce the concept of *"3-D statistical tidal tomography"* (Cadicheanu et al., 2008, Cadicheanu, 2008, Latychev et al., 2009).

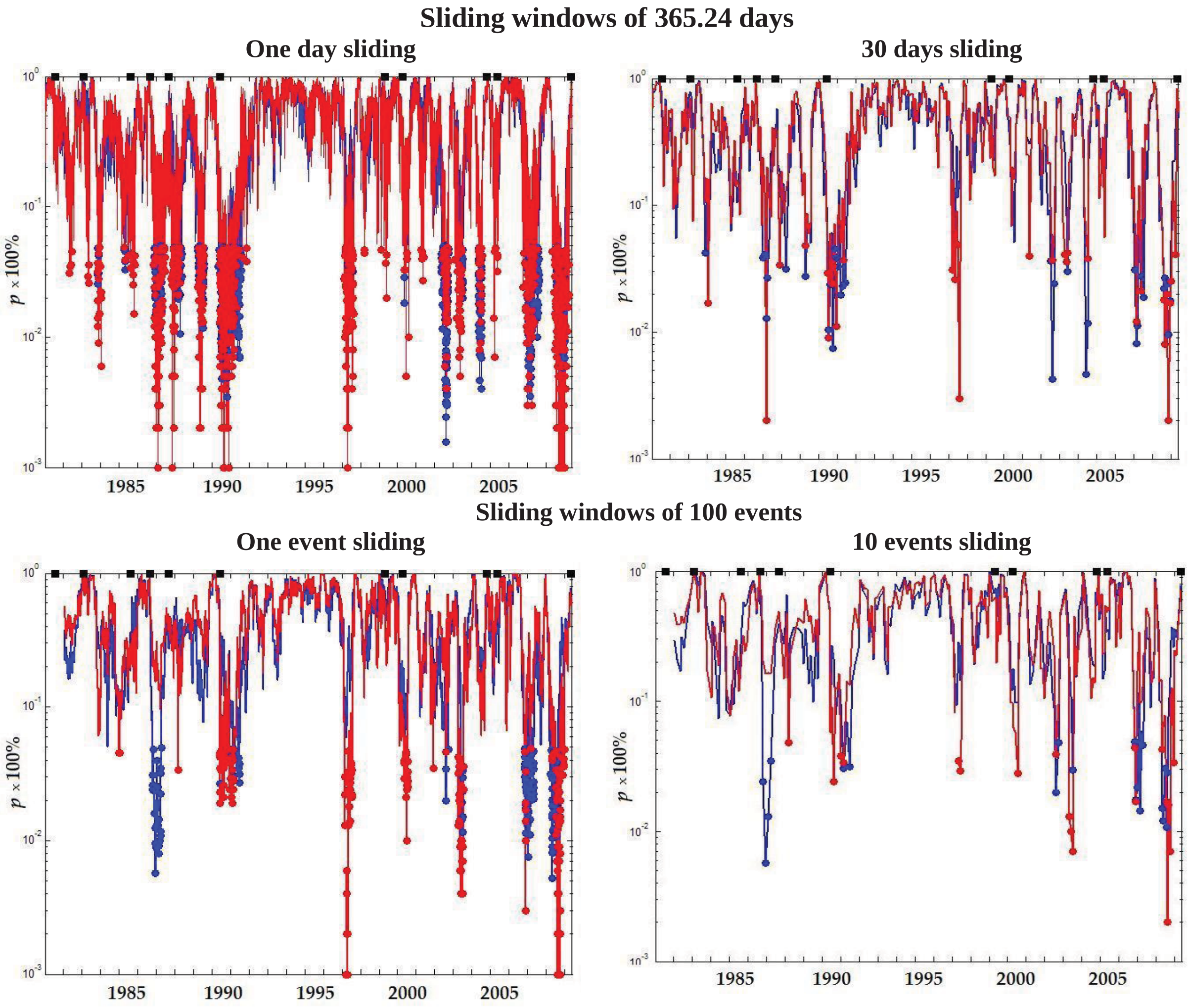

Fig. 2. Statistical coefficient *p* for Schuster's test (in blue) and permutation test (in red), marked with circles for *p* <5%. Earthquakes with magnitude Mw> 5.0 are represented with black squares. The upper graphs show results for the sliding windows defined by the fixed time interval (365.24 days) shifted by 1 day (left) and 30 days (right). The lower graphs correspond to sliding windows with fixed number of events (100 seismic events) shifted with a fixed number of events of one event (left) and 10 events (right).

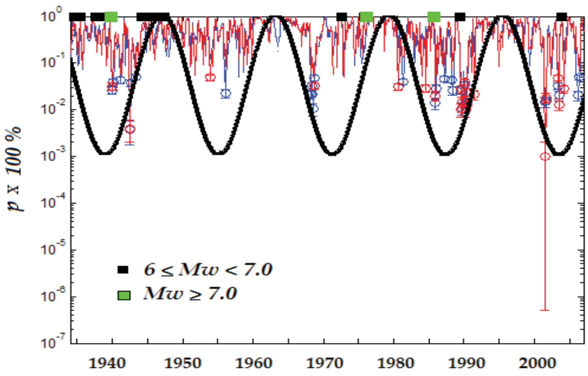

Fig. 3.Temporal variation of the statistical coefficient p obtained by Schuster's' test (in blue) and Permutation test (in red) from 1934 to 2007 time interval. Circles are for the p-values smaller than 5%. We fit the curve with a sinusoidal function of about 16 years period. Black and green squares representing the main shocks with the magnitude Mw ≥ 6.0.

For Vrancea seismic activity, the p-coefficients are calculated for events sited in standard parallelepiped volumes defined at the figure 4. Only more than 20 events series are considered.

3.2. 3-D sliding windows

Finding some specific areas of the coupling earth tides - seismic activity in the seismic slab seems to be related to a high heterogeneous structure of the seismic region and of the slab itself. Seismic tomography of the Vrancea zone (Martin et al., 2006), the heat flow models (Tumanian, 2008), and the attenuation analysis of seismic waves towards Transylvania Basin and Carpathian foreland (Popa, 2005), confirm the existence of a lateral heterogeneous structure depending of the depth. The heterogeneous structures of different nature (e.g., density, viscosity, rigidity, heat flux, etc) have an important role in reinforcing the effects of gradient and phase differences in response to different points of the seismic zone. They are implicitly linked to enhance the effects of earth tides in terms of stress variation, important parameter in the triggering of the earthquakes (Stavinschi and Souchay, 2003).

The statistical tomography referred to earth-tides, has a different meaning than tomography of the earth-tides deformations introduced by Wang (1991). This tomography is based on the 3D distribution of statistical coefficient p in the area of interaction between a component of the earth tides *(M2)* and seismic activity (Fig.5). It allows the space-time study of the earth tides effects bringing information related to the structure and seismic zones on the distribution of stress in the studied area.

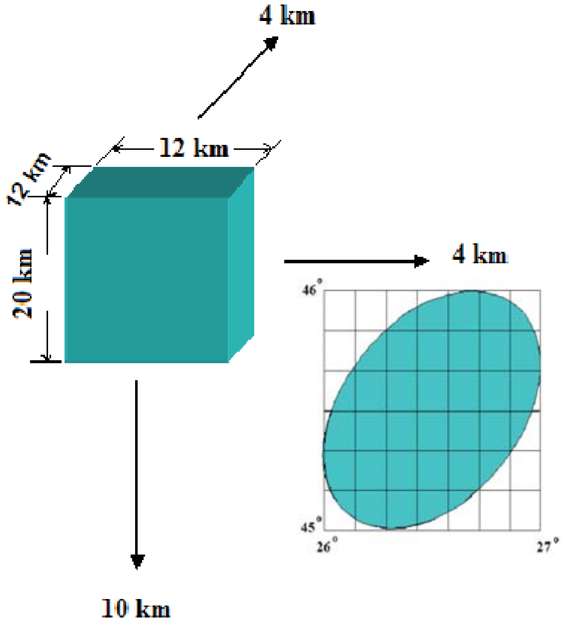

Fig. 4. The “statistical tidal tomography” map of p statistical coefficients is obtained when stacking function is applied to 3-D geometry following the epicentre distribution. The calculations are carried out for 12x12x20 km³ windows covering the entire epicentre area between the East longitudes 26° to 27°, North latitude 45° to 46° for 20km layers with depth between 60- 170km. The sliding steps are respectively 4 by 4 km horizontally and 10km vertically, respectively.

In the case of statistical tidal tomography with semidiurnal *M2* earth-tides component, two areas of distinct intermediate seismic activity are highlighted between 70-90 km and 110-170 km (Fig.5).

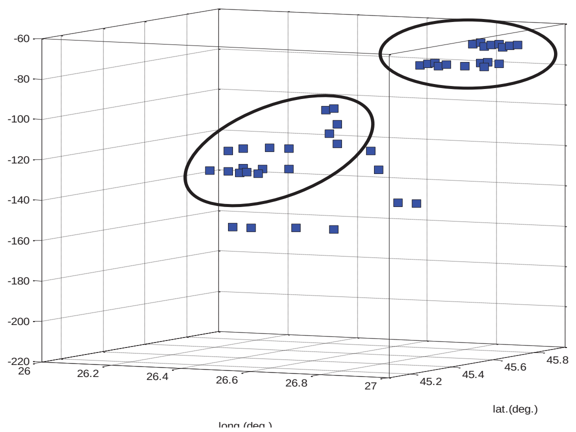

Fig. 5a. Statistical tidal tomography of the seismic activity for different layers, using semidiurnal M2 earth-tides period. Small white squares represent the positions of the elementary volumes in which p <5%.

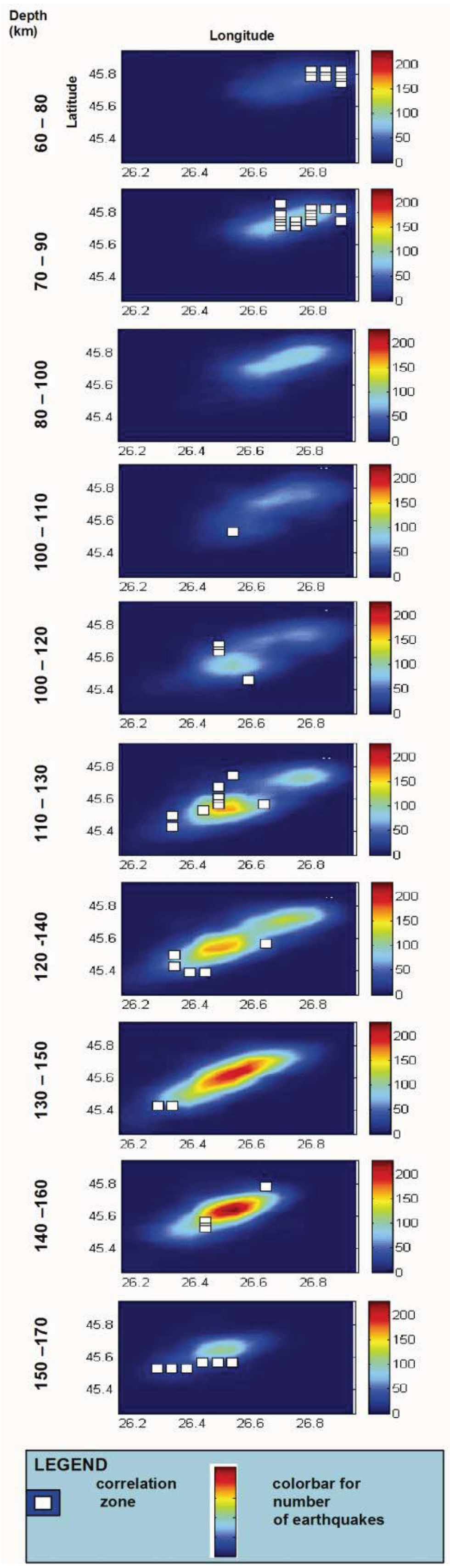

Fig. 5b. 3-D view of statistical tidal tomography. Squares are the elementary volumes with p-value <5%.

The results obtained by statistical tidal tomography, (Cadicheanu et al. 2008) using semidiurnal wave components M_2 of the lunar tide and S_2 of the solar tide, are partly confirmed by comparison with the result of seismicity patterns (Radulian et al., 2007) (Fig. 6).

The figure 7 shows the relation between the temporal sliding windows and 3D sliding windows in which $p < 5\%$.

We could observe some tendencies for the common events of the two types of sliding windows at different depth when we draw the finding number into corresponding time window at corresponding depth layer (magenta bars). Figure 7 shows when this number characterizes only the low part of the seismic slab and in a small measure or not at all the upper part; it suggests an increase of major event risk in the near future. First, this observation should be confirmed by the same kind of analysis applied to the similar seismic regions. After that, this common number of events could represent additional information to the research of precursory factor.

4. Discussion

We applied the HiCum method on the RomPlus Vrancea data bank (1934 - 2007). From homogeneities and completeness reasons related to the seismic catalogue, we detailed in our analyses the 1980 – 2007 time intervals of events. It confirms the modulation of the seismic activity induced by the principal earth-tides lunar component *M2* (Fig.5a).

A systematic temporal pattern of the *p*-values preceding and following the occurrence of $Mw \geq 5.0$ earthquakes was also observed. A possible geodynamical scenario could be described in function of the coupling between rock boundaries and fluid flow patterns. Heterogeneity of rigidity in the cracks could enlarge their tidal deformation. After a large quake we have a compaction of rocks with a decrease of fluid flow. Under tectonic action, deformation of medium induces new micro cracks in the medium allowing fluid flow to restart. Disequilibrium of medium under flow allows small quakes influenced by tidal stain to release local stress (small quakes activity). At a critical level of fractures opening, fluid flow becomes a "without delay" process due to an enlargement of pipes section. Tidal admittance starts to decreases. Global synchronized process becomes an important process of strain accumulation until the relaxation by larger quake which restarts the cycle.

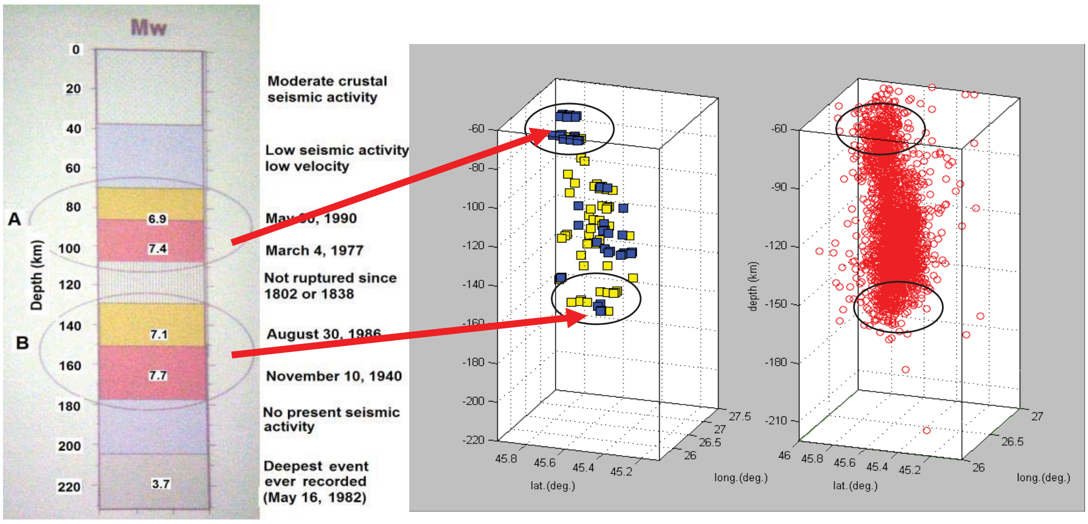

Fig. 6. Two specific zones are obtained by seismicity pattern analysis (Radulian et al. 2007) (left of the figure) and also by statistical tidal tomography with semidiurnal M_2 (blue squares), respectively S_2 (yellow squares) waves (center of the figure). Squares are the elementary volumes with *p*-value <5%. We observe relatively larger density volumes of the synchronization between seismic activity and the two kind of semidiurnal tidal frequencies for the two intermediate-depth seismic areas (80-100 km and 140-160 km). In the right part of the figure are represented the distribution of the all hypocenters from 1980 to 2009.

A "statistical tidal tomography" map for the Vrancea intermediate-depth seismic zone is obtained when stacking function is shifted in 3D geometry following the epicentre's distribution. Possibly, tidal tomography patterns of the represent reaction of regional tectonic structure to the earth-tides. Especially for Vrancea, the tidal tomography of *M2* component has similar patterns with the analysis of seismicity patterns introduced in (Radulian at al., 2007).

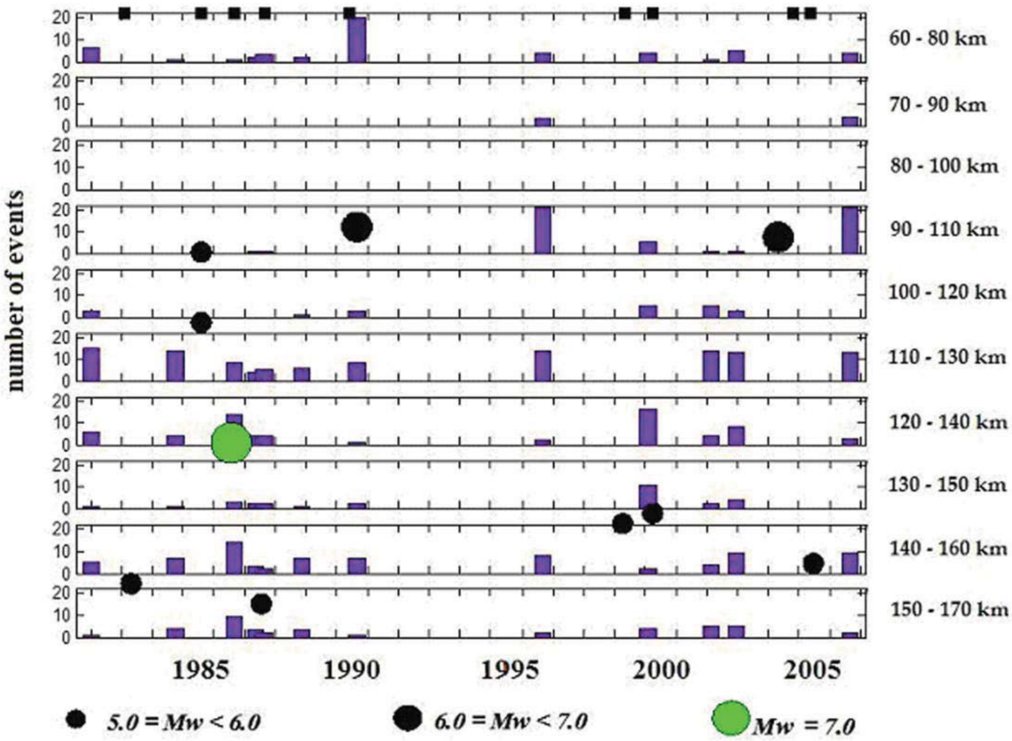

Fig. 7. Common number of events of the spatial sliding windows and temporal sliding windows characterised by the p<5%. Earthquakes with magnitude Mw> 5.0 are represented with black squares in the upper part of the figure.

For example, we observe a great density of elementary volume of correlation with $p<5\%$ (Figs. 5.b and 6) in the upper part of the seismic slab (60 – 80 km). No similar correlation exists in the 80 – 100 km layer. This fact demonstrate the potentiality of our method to constrain hypothesis about rheological patterns determined by other geophysical techniques like seismic wave velocity, ground deformation, magnetism, self potential, etc.

The possible physical consequences of the tidal effect reveal by observed small p-values, can constrain the hypothesis in the research on the seismic source characteristics and its dynamical patterns.

5. Conclusions

The parallel analysis of temporal and 3D variation of two kinds of statistical tests coefficients p in the Vrancea seismic zone shows unusual fingers of this parameter.

The results prove a temporal and spatial selection of the coupling between the *M2* tidal component and intermediate-depth seismic activity in the Vrancea zone:

1. Different signatures of the p variation for relatively medium and long time (from some weeks to a few years) in the neighbourhood of the stronger seismic events.
2. A long term tendency with a periodicity from about 16 years.

The relationship between seismic activities and tidal periodicities could be important to understand some characteristic of the seismic zone analyzed (Cadicheanu et al., 2008). In addition, the statistical coefficient p could have a potential capacity of a precursor factor (Bernard, 2001).

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References

Bernard P., 2001. From the search of 'precursors' to the research on 'crustal transients', Tectonophysics, 338, 225–232.

Cadicheanu N., van Ruymbeke M., and Zhu P., 2007. Tidal triggering evidence of intermediate depth earthquakes in the Vrancea zone (Romania), Nat. Hazards Earth Syst. Sci., 7, 733-740.

Cadicheanu, N. Zhu P. and van Ruymbeke M., 2008, 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, vol. 43, 2, Special issues.

Cadicheanu N., 2008. Study of the gravimetrical influences induced by Earth tides on the intermediate-depth seismic activity in the Vrancea zone, Ph.D. Thesis*,* Bucharest.

Constantinescu L. and Enescu, D., 1984. A tentative approach to possibly explaining the occurrence of Vrancea earthquakes. Rev.Roum. Geol., Geophys, Geogr., Geophys. 28.

Enescu D. and Enescu D.B., 1996. Focal mechanism, global geophysical phenomena and Vrancea (Romania) earthquake prediction. A model for predicting these earthquakes, Revue Roumaine de Geophysique, Tome 40, p 11-31.

Heaton T. H., 1975.Tidal triggering of earthquakes, Geophys. J. R. Astron. Soc., 43, 307–326.

Klein F. W., 1976. Earthquake swarms and the semidiurnal solid earth tide. Geophys. J. R. Astr. Soc., 45, 245-295.

Knopoff L., 1964. Earth tides as a triggering mechanism for earthquakes, Bull. Seismol. Soc. Am., 54, 1865–1870.

Kossobokov V. and Romashkova L., 2006. Re-establishing intermediate-term real-time prediction of strong earthquakes in the Vrancea region, CE-Project, Extreme Events: Causes and Consequences, Perugia 2–6 September.

Latychev K., Mitrovica J.X., Ishii M., Chan Ngai-Ham, Davis L.J., 2009. Body tides on a 3-D elastic earth: Toward a tidal tomography. Earth and Planetary Science Letters 277, 86–90.

Martin M., Wenzel F. and the CALIXTO working group, 2006. High-resolution teleseismic body wave tomography beneath SE-Romania – II. Imaging of a slab detachment scenario, Geophys. J. Int. 164, 579–595.

Melchior P., 1978.The Tides of the Planet Earth, Pergamon Press, New York, 456p.

Oncescu M. C., Marza V. I., Rizescu M., and Popa M., 1999. The Romanian Earthquake Catalogue between 984–1999, in Vrancea Earthquakes: Tectonics, Hazard and Risk Mitigation, edited by: Wenzel, F. and

Lungu, D., and Novak, O., 43–47, Kluwer Academic Publishers, Dordrecht, Netherlands, (Catalogue under continuous update).

Pitman E. J. G., 1938. Significance tests which may be applied to samples from any population, Part III: The analysis of variance test, Biometrika, 29, 322–335.

Popa M., Radulian M., Grecu B., Popescu E. and Placinta A.O., 2005. Attenuation in Southeastern Carpathians area: Result of upper mantle inhomogeneity, Tectonophysics, Volume 410, Issues 1-4, 9 December 2005, Pages 235-249.

Radulian M., Bonjer K.-P., Popa M., Popescu E., 2007. Seismicity patterns in SE Carpathians at crustal and subcrustal domains: tectonic and geodynamic implications, International Symposium on Strong Vrancea Earthquakes and Risk Mitigation Oct. 4-6, 2007, Bucharest, Romania

Schuster, A., 1987. On lunar and solar periodicities of earthquakes, Proc. R. Soc. Lond., 61, 455–465.

Stavinschi M. and Souchay J., 2003. Some correlations between Earthquakes and Earth Tides, Acta Geod. Geoph. Hung., 38(1), 77–92.

Tanaka S., Ohtake M., and Sato H., 2002. Evidence for tidal triggering of earthquakes as revealed from statistical analysis of global data, J. Geophys. Res., 107(5B10), 2211, doi: 10.1029/2001JB001577.

Tanaka S., Sato H., Matsumura S., and Ohtake M., 2006. 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.

Tsuruoka H., Ohtake M., and Sato H., 1995. Statistical test of the tidal triggering of earthquakes: contribution of the ocean tide loading effect, Geophys. J. Int., 122, 183–194.

Tumanian, M., 2008. Thermal models simulating the tectonic processes in the extra-carpathian area (on the romanian territory): rheological models and their interpretation in relation with the local seismic wave attenuation models, Acta Geod. Geoph. Hung., Vol. 43(2–3), pp. 183–194.

van Ruymbeke M., Howard R., Putz P., Beauducel F., Somerhausen A. and Barriot J-P., 2003. An Introduction to the use of HICUM for signal analysis, BIM 138, 10 955–10 966.

Wang, R., 1991. Tidal Deformations on a Rotating, Spherically Asymmetric, Visco-Elastic and Laterally Heterogeneous Earth. In: European University Studies, Series XVII, Earth Sciences Vol. 5, Peter Lang, Frankfurt am Main.