Tidal triggering effect on earthquakes occurrence

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Abstract: In this review we present the investigation for the tidal triggering evidence on the earthquakes at various seismic areas of Greece. The result of our analysis using the HiCum method, indicate that the monthly variation of the frequencies of earthquake occurrence is in accordance with the period of the tidal lunar monthly (Mm) variations. The same happens with the corresponding diurnal and semi-diurnal variations of the frequencies of earthquake occurrence with the diurnal (K1), (O1) and semi-diurnal solar (S2) and semidiurnal lunar (M2) tidal variations. The confidence level of the Tidal-Earthquake frequency period compliance is very sensitive to the seismicity of the area and we call it Tidal - Earthquake frequency compliance parameter. We suggest that this parameter may be used in earthquake risk evaluation.

Key words: Earth tides, Seismicity, Hi(stogram) Cum(ulation) method

1. Introduction

The question of the possible connection of earth tides with earthquake occurrence is a very old one and has been tackled by a number of researchers since more than a hundred years ago. The results were contradictory with most of the outcomes to disapprove the possibility of any correlation between earthquake occurrence and earth-tides, see for instance Shuster (1897), Knopoff (1964), Simpson(1967), Shudde and Barr (1977), Rydelek et al. (1992), Vidale et al. (1998) and many others, while the outcome of a considerable number of relatively recent works is in favor of such a correlation, see for instance Enescu and Enescu (1999), Stavinschi and Souchay (2003), Tanaka et al. (2002, 2006), Cadicheanu et al. (2007) and many others. Nevertheless, although the stress drop in an earthquake event is two or three orders higher than the amplitude of the tidal stress, the tidal stress rate is comparable or much higher than the tectonic stress accumulation in a fault. Thus, unless the earthquake event is a result of a sudden stress accumulation on a fault (Vidale et al., 1998), one has to conclude that earth tides act as a triggering mechanism in a mature fault i.e. a fault for which the stress accumulation approaches the critical point for rapture and an earthquake is to be occur. Recent analyses have point to this fact (Tanaka et al. 2002; Tanaka et al. 2006; Cadicheanu, 2007). In these papers not only the tidal triggering for global in the first paper and local in the next two papers were found but in addition in the last two papers the increase of the reliability of the tidal-earthquake occurrence correlation is indicated as precursory phenomenon for strong earthquakes.

In this review we present the results of the investigations of our group for tidal triggering evidence on the earthquakes at five seismic area in Greece, the Mygdonian basin in North Greece (Contadakis et al. 2009a) the Ionian geological zone (Contadakis et al. 2009b; Contadakis et al. 2012), the Hellenic Arc (Vergos et al. 2012) the Santorini volcanic complex (Contadakis et al. 2013) and the Fthiotida of Central Greece (Contadakis et al. 2014). In Our analysis we use the Hi(stogram)Cum(ulation) method, a very old method used in Astronomy for finding hidden periodicities, and was introduced by Cadicheanu et al. (2007) for detecting tidal triggering effects on earthquakes. **Figure 1**, quoted from Papazachos et al. (1998) displays the main morphotectonic characteristics and **Figure 2**, quoted from Papazachos et al. (1999) displays the main faulting zones and faulting type in the area of Greece. One can see the areas under study and the type of faulting. In our analysis we use the seismological data of the earthquake catalogue of NOA (http://www.gein.noa.gr).

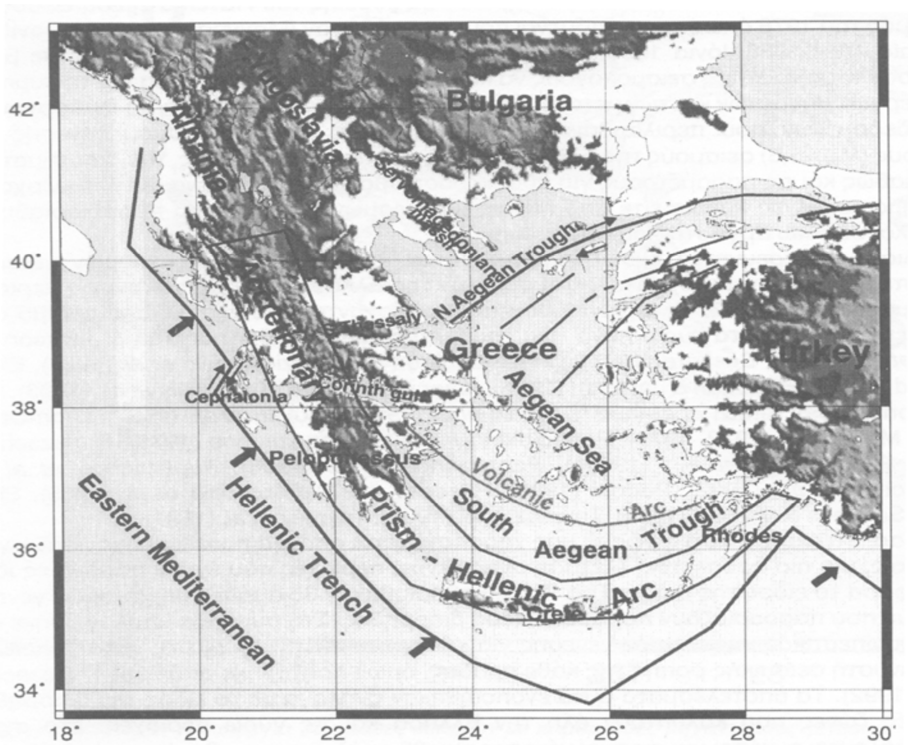


__Figure 1.__ The main morphotectonic characteristics of the broader area of Aegean. (Papazacos et al. 1998)

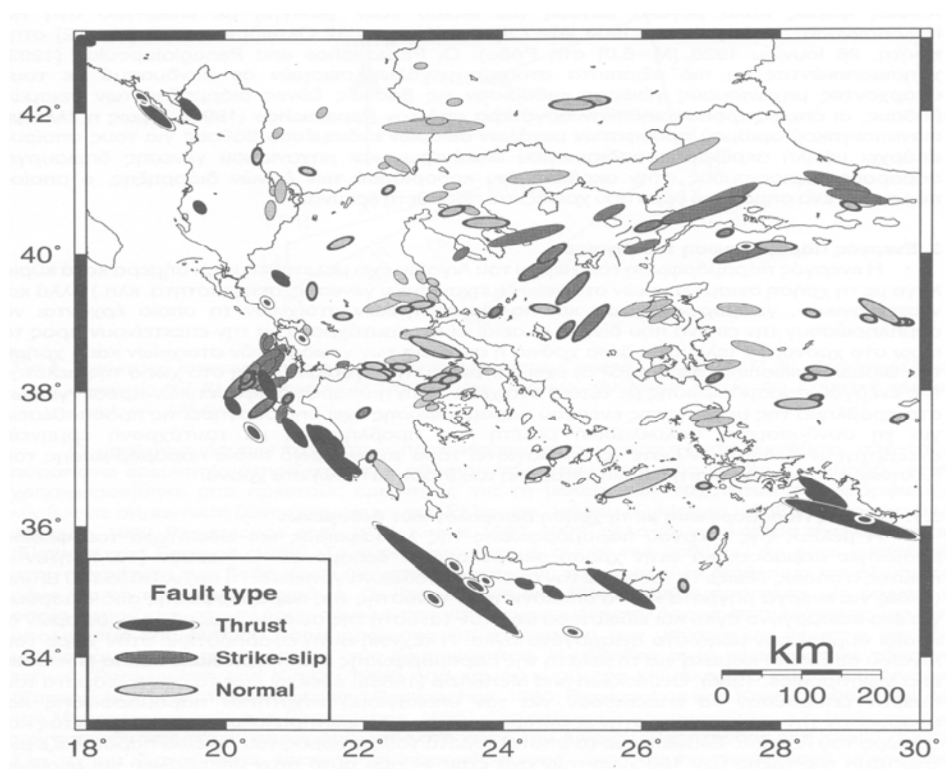


Figure 2. *Rapture zones in the area of Greece (Papazachos et al. 1999)*

2. Method of analysis

In order to check the possible correlation between Earth tides and earthquake occurrence we check the time of occurrence of each earthquake in relation to the sinusoidal variation of Earth tides and investigate the possible correlation of the time distribution of the earthquake events with Earth tides variation. Since the periods of the Earth tides component are very well known and quite accurately predictable in the local coordination system we assign a unique phase angle within the period of variation of a particular tidal component, for which the effect of earthquake triggering is under investigation, with the simple relation:

$$\phi_i = \left\{ \left[\frac{(t_i - t_0)}{T_d} \right] - \text{int}\left[\frac{(t_i - t_0)}{T_d} \right] \right\} \times 360 \tag{1}$$

where ϕ_i the phase angle of the time occurrence of the i earthquake in degrees, t_i the time of occurrence of the i earthquake in Modified Julian Days (MJD), t_o the epoch we have chosen in MJD and T_d the period of the particular tidal component in Julian Days.

We choose as epoch t_o, i.e. as reference date, the time of the upper culmination at the site of the interest, for instance in Thessaloniki of the new moon of January 7, 1989 which has $\text{MJD} = 47533.8947453704$. Thus the calculated phase angle for all the periods under study has 0 phase angle at the maximum of the corresponding tidal component (of course M2 and S2 has an upper culmination maximum every two cycles). As far as the monthly anomalistic moon concern the corresponding epoch t_o is January 14, 1989 which has $\text{MJD} = 47541.28492$.

We separate the whole period in 12 bins of 30^o and stack every event according to its phase angle in the proper bin. Thus we construct a Cumulative Histogram of earthquake events for the tidal period under study.

A crucial point of this analysis is the use of a proper statistical test which will give us arguments to decide if such a result is correct or not i.e. will provide us a proper confidence level to our decision. To this purpose we use the well known Shuster's test (Shuster 1897, see also Tanaka et al. 2002; 2006 and Cadicheanu et al. 2007). In Shuster's test, each earthquake is represented by a unit length vector in the direction of the assigned phase angle α_i. The vectorial sum D is defined as:

$$D^2 = \left(\sum_{i=1}^{N} \cos a_i\right)^2 + \left(\sum_{i=1}^{N} \sin a_i\right)^2, \tag{2}$$

where N is the number of earthquakes. When α_i is distributed randomly, the probability to be the length of a vectorial sum equal or larger than D is given by the equation:

$$p = \exp(-D^2 / N). \tag{3}$$

Thus, $p < 5\%$ represents the significance level at which the null hypothesis that the earthquakes occurred randomly with respect to the tidal phase is rejected. This

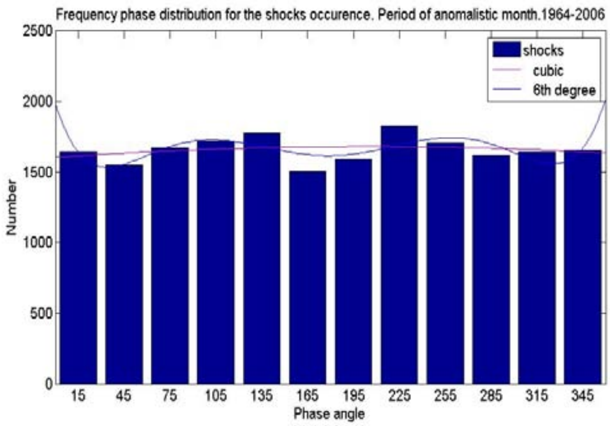


Figure 3. *Cumulating Histogram corresponding to the anomalistic month period of all the 19916 events at the Ionian geological zone, p=34.07%*

means that the smaller the p is the greater the confidence level of the results of the Cumulative Histograms is. **Figure 3** and **4** displays to paradigm for Anomalistic and Synodic Lunar month respectively at the Ionian geological zone for the period 1964-2008. It appears that Tidal triggering effect exist for the Synodic month but the existence for Anomalisic month Tidal triggering effect is quit doubtful.

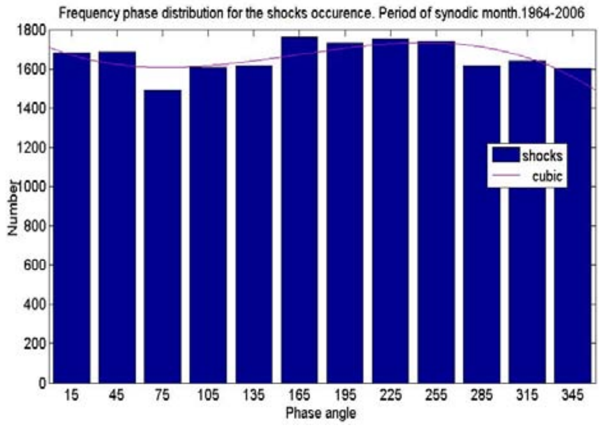


Figure 4. *Cumulating Histogram corresponding to the monthly synodic period of all the 19916 events at the Ionian geological zone, p=0.02%*

4. Results

4.1 Mygdonian basin

For the investigation of the tidal triggering effect on the shallow earthquakes of the seismic area of Mygdonia basin, North Greece using the Hi(stogram)Cum(ulation) method, we analyze the series of 471 shallow earthquakes with $M \geq 2.5$, which occurred from 1964 up to 2008 in a square area of 2500 km^2 centered on the epicenter of the strongest earthquake with magnitude 6.5 which occurred on June, 20 1978 (40.61^o N, 23.27^o E). The area is dominated by a system of shallow seismogenic faults of 10km with E-W and NW-SE direction (Contadakis et al. 2009a).

The results of our analysis are given in **Tables 1** for all the area and in **2** for the particular faults.

Table 1. *The confidence level of earthquake-earth tide correlation for all earthquakes of our sample*

p(K1)	p(O1)	p(M2)	p(S2)	p(M synodic)	p(M semi-synodic)
2.49%	33.43%	22.19%	85.74%	0.77%	0%

Table 2. *The confidence level for the faults Assyros, Volvi and North Aegean*

Faults	p(K1)	p(M2)	p(M-synodic)
Assyros	0%	0%	0.07%
Volvi	28.21%	34.08%	9.48%
North Aegean	0%	0%	0%

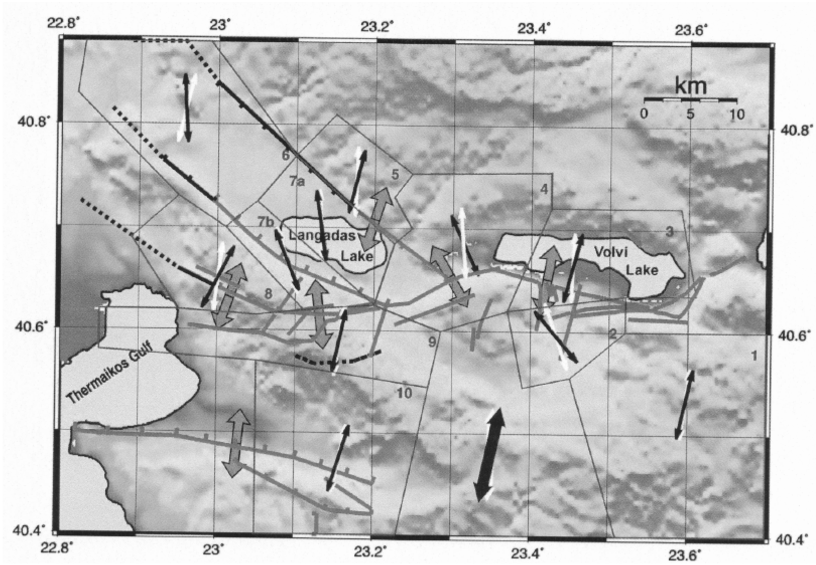


Figure 5. *The main faults of the Mygdonia Basin and the maximum extensional principal direction for the different zones (Vamvakaris et al. 2006)*

In concluding we may say that the correlation between earth tides and earthquake occurrence is a space time dependent fact. The probability of being real this correlation, increases drastically and become certainty when we deal with the seismicity of a particular fault in the period of the fault activity. This is in favor of the explanation according which earth tides act as a triggering mechanism in the case where tectonic stresses have reached a critical point. On the other hand the parameter for the confidence level of this correlation p is casually connected with the criticality of the fault and may be used as a precursory parameter.

4.1 Ionian geological zone

In the investigation for the tidal triggering evidence on the earthquakes of the seismic area of the Ionian geological zone in Greece we analyze the series of the earthquakes which occurred in the area bounded by $19^{o} \leq \varphi \leq 22^{o}$ E $36^{o} \leq \lambda \leq 40^{o}$ N in the time period from 1964 to 2006. In this time period 19,916 shallow and intermediate depth earthquakes with magnitudes ranging between 2.5 and 6.2 occurred.

Figure 1, quoted from Papazachos B.C. et al. (1998) displays the main morphotectonic characteristics and **Figure 2**, quoted from Papazachos B.C. et al. (1999) display the main faulting zones and faulting type in the area of Greece (Contadakis et al. 2009b, Contadakis et al. 2012).

The area under study is the one along the western part of the Hellenic Trench. The faults in the area are parallel to the Hellenic Trench and present a thrust faulting, whereas north of Cephalonia there is a zone of faults with dextral strike slip faulting.

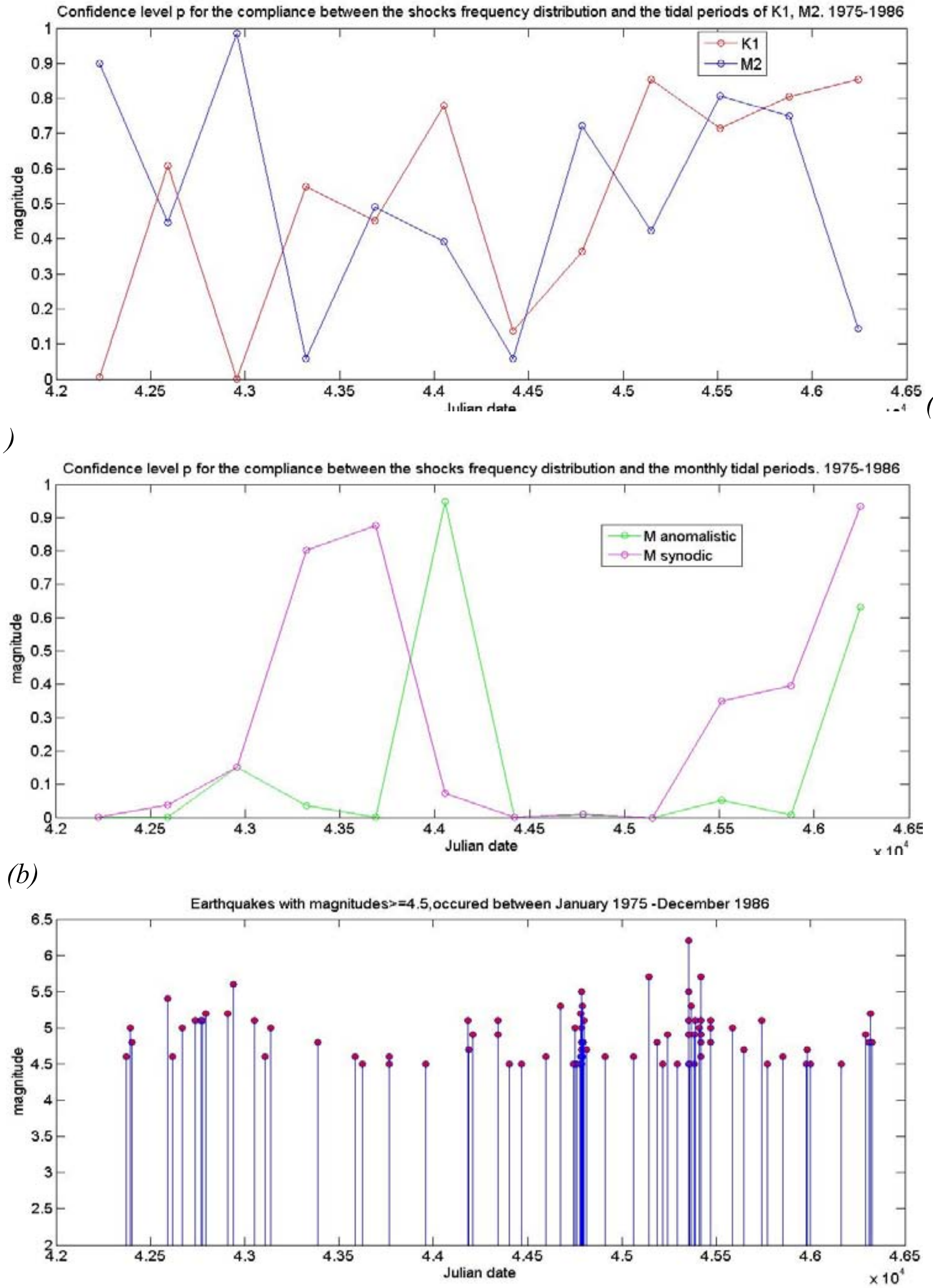
The great majority of the earthquakes, including those with M ≥5.0, are shallow earthquakes. The result of our analysis indicates that the monthly variation of the frequencies of earthquake occurrence is in accordance with the period of the tidal lunar monthly (Mm) variations. The same happens with the corresponding daily variations of the frequencies of earthquake occurrence with the diurnal lunisolar (K1) and semidiurnal lunar (M2) tidal variations. In addition, the confidence level for the identification of such periodical accordance between earthquakes occurrence frequency and tidal periods varies with seismic activity, i.e. the higher confidence level corresponds to periods with stronger seismic activity, (see **Figure 6**). These results are in favor of a tidal triggering process on earthquakes when the stress in the focal area is near the critical level.

4.3 Helenic Arc

In the investigation for the tidal triggering evidence on the earthquakes of the seismic area of the Hellenic Arc ,we analyze the series of the earthquakes occurred in the area which is confined by the longitudes 22^o and 28^o E and latitudes 34^o and 36^o N in the time period from 1964 up to 2012. In this time period 16,137 shallow and of intermediate depth earthquakes with M_L up to 6.0 and 1,482 deep earthquakes with M_L up to 6.2 occurred. **Figure 1**, quoted from Papazachos et al. (1998) displays the main morphotectonic characteristics and **Figure 2**, quoted from Papazachos et al. (1999) displays the main faulting zones and faulting type in the area of Greece. The area under study is the one along the south-western, south and south-eastern parts of the Hellenic Trench Arc (Vergos et al. 2012). The faults in the area are directed parallel to the Hellenic Trench and present a thrust faulting, whereas spurious minor faults with normal faulting exist. **Table 3** summarize the results of our analysis.

Table 3. *The confidence level of earthquake-Earth tide correlation for all the earthquakes of our sample*

	p(K1)	*p(S2)*	*p*(O1)	*p*(M2)	*p*(M syn)	*p*(M ano)
Shallow	0.18%	0.00%	65.89%	68.46%	10.83%	58.10%
Deep	0.37%	0.14%	69.88%	93.09%	41.04%	10.64%



(a)

(b)

(c)

Figure 6. *Confidence level for the compliance between frequency distribution of the shocks occurrence and (a) K1,M2 tidal periods,(b) M-anomalistic and M-synodic periods.(c) Earthquakes with magnitudes>=4.5 for the time period: January 1975 to December 1986.*

In accordance with our previous studies, the result of the present analysis indicate that the monthly variation of the frequencies of earthquake occurrence is in accordance with the period of the tidal lunar monthly variations and the same happens with the corresponding daily variations of the frequencies of earthquake occurrence with the diurnal luni-solar (K1) and semidiurnal solar (S2) tidal variations. These results are in favor of a tidal triggering process on earthquakes when the stress in the focal area is near the critical level.

4.4 Santorini volcanic complex

Santorini is the most active volcanic complex in the southern Aegean volcanic arc. **Figure 7**, quoted from Chouliaras et al.(2013), present the Tectonic map of Santorini' s volcanic island complex after Heiken and McCoy, 1984 (Contadakis et al. 2013).

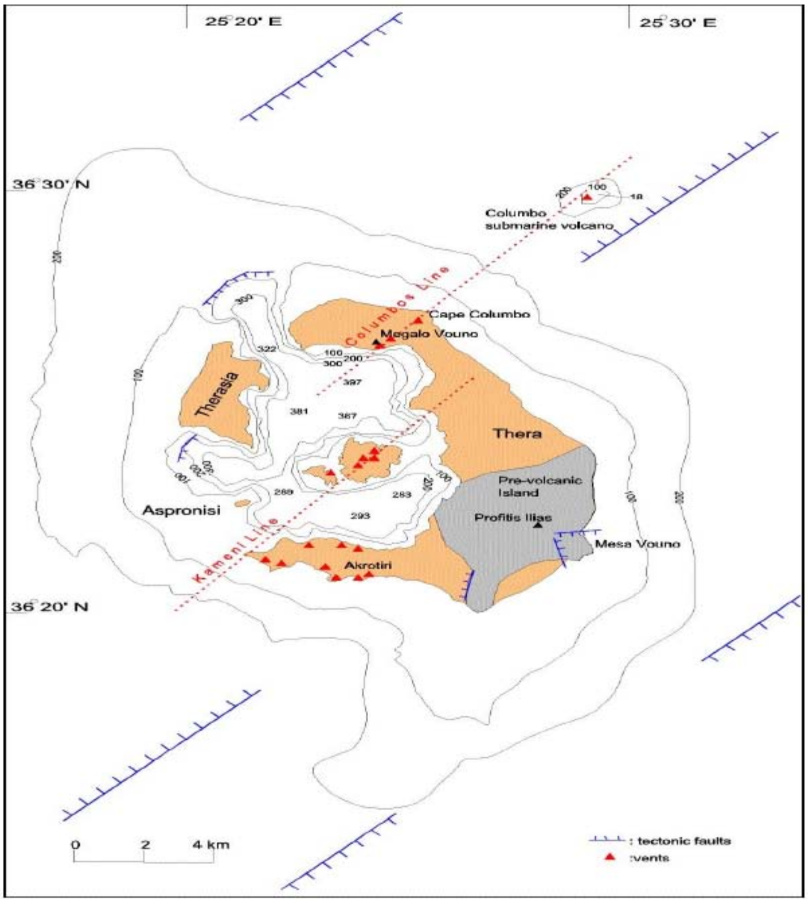


Figure 7. *Tectonic map of Santorini' s volcanic island complex (after Heiken and McCoy, 1984). (Quoted from Chouliaras et al. 2013)*

As it is seen this complex comprises five islands: Thera, Therasia, Aspronisi, Palea Kameni and Nea Kameni which constitute the compound volcano caldera formed in 1640 B.C. (Fytikas et al., 1984).

Table 4 summarizes the results. It is seen that the monthly variation of the frequencies of earthquake occurrence is in accordance with the period of the tidal lunar monthly (Mm) variations. The same happens with the corresponding semi-diurnal variations of the frequencies of earthquake occurrence with the semi-diurnal solar (S2) and semidiurnal lunar (M2) tidal variations. The Statistical test of Shuster (1897) indicate higher probability for all but S2 components to act as a trigger mechanism for earthquakes occurrence for the time period 2011-2012 when an increase in the micro-seismic activity appeared in the area.

Table 4. *The confidence level of earthquake-Earth tide correlation for all the earthquakes of Santorini area from 1964 to 2012*

	p(K1)	*p(S2)*	*p*(O1)	*p*(M2)	*p*(M syn)	*p*(M ano)
1964-2010	36.9%	2.34%	86.54%	0.82%	40.12%	4.91%
2011&2012	17.96%	33.07%	35.8%	0.06%	0.00%	0.00%

4.4 Fthiotida Central Greece

On August 7nth of 2013 a 5.2 M_L earthquake occurred in Fthiotida area followed by a seismic activity with shocks of magnitudes greater than 4.0 M_L which is continued until today. The area is a known tectonically active area in Greece. **Figure 8**

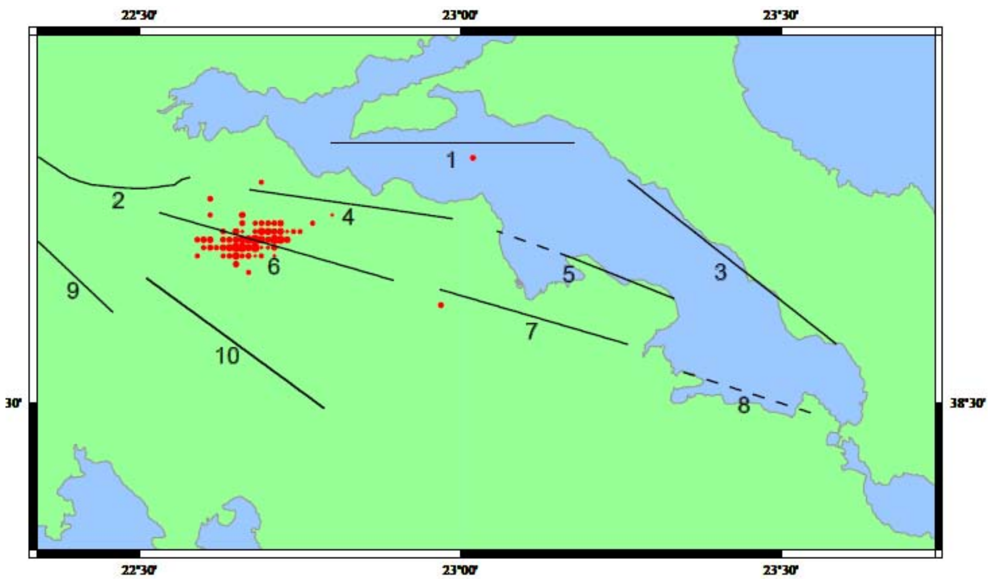


Figure 8. *The seismic activity of 2013 in Fthiotida.(Shematic fault of the area (Ganas et al. 2006)).(1) Edipsos, (2) Sperchios, (3) Kadilli, (4,5) Kamena Vourla, (6) Kallidromon, (7,8) Atalanti, (9,10) Tithorea.*

displays the area and the shocks with magnitudes greater than 3.5 M_L which occurred within 2013. In this figure the main faults of the area, as it is quoted by Ganas et al.(2006), were drown. It is seen that the seismic activity of 2013 occurred in Kallidromon fault. It should be noted that the main faults of the area are normal

For this area we apply the Hi(stogram)Cum(ulation) method , in order to see if Tidal triggering effect is been detected and if this effect is better traced in the period of the increased microseismicity i.e. the years 2011-February of 2012 (Contadakis et al. 2013).

The set of data consist of a series of 33281 shallow and 769 of intermediate depth earthquakes with M_L ranging from 0.2 to 6.3, occurred within the time interval from January1964 to December 2013, in an area bounded by $38^o \leq \varphi \leq 39^o$ and $25^o 10' \leq \lambda \leq 28^o 40'$. **Figure 9** summarizes the results of this work. As an example this Figure displaces the variation of the confidence level parameter p between Seismicity and Tidal Anomalistic Monthly period and the seismicity.

It is seen that the confidence level parameter p decreases as the seismicity increases and vice versa.

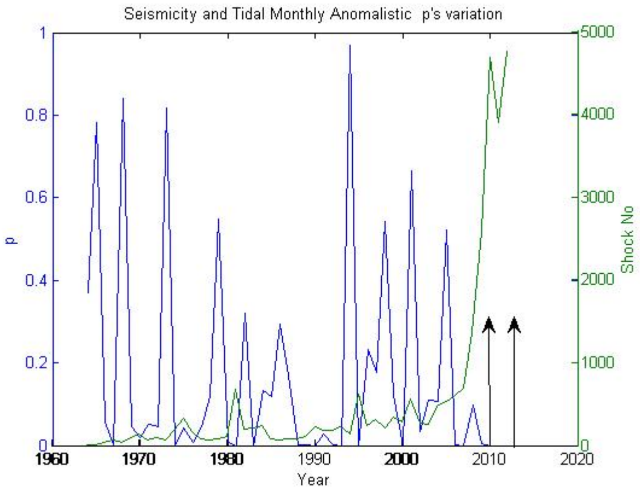


Figure 9. *The confidence level parameter p between Seismicity and Tidal Anomalistic Monthly period. Arrows indicate the 5.2 M_L earthquakes at Aegion on 2010 and Fthiotida on 2013*

6. Conclusions

The result of our analysis using the HiCum method, indicate that the monthly variation of the frequencies of earthquake occurrence is in accordance with the period of the tidal lunar monthly (Mm) variations. The same happens with the corresponding diurnal and semi-diurnal variations of the frequencies of earthquake occurrence with the diurnal (K1), (O1) and semi-diurnal solar (S2) and semidiurnal lunar (M2) tidal variations. The confidence level of the Tidal-Earthquake frequency period compliance is very sensitive to the seismicity of the area and we call it Tidal -Earthquake frequency compliance parameter. This results are in favor of the existence of Tidal triggering effect on Earthquake occurrence. Furthermore, we suggest that this parameter may be used in earthquake risk evaluation.

References

Cadicheanu, N., van Ruymbeke, M and Zhu P., 2007: Tidal triggering evidence of intermediate depth earthquakes in Vrancea zone(Romania), *NHESS 7, 733-740*

Contadakis, M. E., Arabelos, D. N., Spatalas, S., 2009a, Evidence for tidal triggering on the shallow earthquakes of the seismic area of Mygdonia basin, North Greece, in Terrestrial and Stellar Environment, eds. D. Arabelos, M.E. Contadakis, C. Kaltsikis, I. Tziavos, Ziti Press Thessaloniki, Greece, pp 223-235.

Contadakis, M. E.; Arabelos, D. N.; Spatalas, S. D.,2009b, Evidence for Tidal triggering on the earthquakes of the Ionian geological zone, Greece, AnGeoAbstr., 11,4115

Contadakis, M. E.,Arabelos, D.N., Spatalas, S.D., 2012, Evidence for tidal triggering for the earthquakes of the Ionian geological zone, Greece, *Annals of Geophysics*, Vol. 55, No. 1, p. 73-81

Contadakis, Michael E.; Arabelos, Dimitrios N.; Vergos, George, 2013,Testing the recent Santorini seismic activity for possible tidal triggering effect, GA . EGU2013-8358

Contadakis, M. E.; Aarabelos, D.; Vergos, G.; Spatalas, S., 2014, Variation of the Earth tide-seismicity compliance parameter during the recent seismic activity of Fthiotida, Greece, AnGeoAbstr., AnGeoAbstr., 16,1121

Chouliaras, Dracatos G., Makropoulos, K. and N.S. Melis, 2013, Recent seismicity detection increase in Santorini volcanic island complex, *NHESS*, 12, 859-866

Enescu, D., and Enescu, B., D.: Possible cause-effect relationships between Vrancea (Romania) earthquakes and some global geophysical phenomena, Natural Hazards, Kluwwer Academic Publishers, 19, 233-245, 1999.

Fytikas, M., Innocenti, F., Manetti, P., Mazzuoli, R., Peccerillo, A., Villari, L., 1984 Tertiary to Quaternary evolution of volcanism in the Aegean region, Geol. Soc. London, Spec. Publ., 17, 687-699

Ganas A., Sokos E., Agalos A., Leontakianakos G., Pavlides S., 2006, Coulomb stress triggering of earthquakes along the Atalanti Fault, central Greece: Two April 1894 M6+ events and stress change patterns, Tectonophysics, 420, 357–369

Heiken, G. and McCoy, F., 2002, Precursory activity to the Minoan Eruption, Thera, in Kagan, Y. Y., Edrs. Seismic moment distribution revisited: I. Statistical results, Geophys. J. Int. 148, 520–-541

Knopoff, L.: Earth tides as a triggering mechanism of earthquakes, Bull. Seismol.Soc.Am. 54, 1865-1870, 1964.

Papazachos C., Kiratzi A. and Kontopoulou D. (1998). Active Tectonics in Aegean and surrounding area, in Basic results of the seismologic in Greece, in Honorem Prof. B.C. Papazachos, Ziti Publication, Thessaloniki,49-74 Greece(in Greek).

Papazachos B.C., Papaioannou C.A., Papazachos C.B., Savvaidis A.S. (1999). Rupture zones in the Aegean region, Tectonophysics, 308, 205-221.

Rydelek, P. A., Sacks, I. S., and Scarpa, R.: On tidal triggering of earthquakes at Campi Flegrei, Italy. Geophys. J. Int., Int., 109, 125-137, 1992.

Schuster, A.: On lunar and solar periodicities of earthquakes, Proc. R.Soc. Lond., 61, 455-465, 1897.

Shudde, R.,H. and Barr, D.R.: An analysis of earthquake frequency data. Bull. Seismol. Soc. Am., 67, 1379-1386, 1977.

Simpson, J., F.: Earth tides as a triggering mechanism for earthquakes. Earth Planet Sci. Lett., 2, 473-478, 1967.

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

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

Tanaka, S., Sato, Matsumura, S., and H., Ohtake, M.: Tidal triggering of earthquakes in the subducting Philipine Sea plate beneath the locked zone of the plate interface in Tokai region, Japan. Tectonopysics, 417, 69-80, 2006.

Vamvakaris, D.A., Papazachos, C.B., Karagianni, E.E., Scordilis, E.M., Hatzidimitriou , P.M.: Small- Scal spatial variation of the stress field in the back-arc Aegeanarea: Results from the seismotectonic study of the broader area of Mygdonia basin (N.Greece). Tectonophysics, 417, 249-267, 2006.

Vergos, G., Arabelos, D. N., Contadakis, M. E., 2012, Evidence for Tidal triggering on the earthquakes of the Hellenic Arc, Greece., Geoph. Res. Abs, Vol 14,2325

Vidale, J. E., Agnew, D. C., Johnston, M. J. S., Oppenheimer, D. H.: Absence of earthquake correlation with earth tides: an indication of high preseismic fault stress rate. J. Geophys. Res., 103, 24567-24572, 1998.