

Variation of the Earth tide-seismicity compliance parameter the last 50 years for the west site of the Aegean Volcanic Arc, Greece

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Abstract: Based on the results of our studies for the tidal triggering effect on the seismicity of the Hellenic area, we consider the confidence level of earthquake occurrence - tidal period accordance as an index of tectonic stress criticality for earthquake occurrence and we check if the recent increase in the seismic activity at the west site of the Aegean Volcanic Arc indicate faulting maturity for a stronger earthquake. In this paper we present the results of this test which are positive.

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

1. Introduction

Applying the Hi(stogram)Cum(ulation) method, which was introduced recently by Cadicheanu, et al. (2007), we analyze the series of the earthquakes occurred in the last 50 years in seismic active areas of Greece, i.e. the areas (a) of the Mygdonian Basin (Contadakis et al. 2007), (b) of the Ionian Islands (Contadakis et al. 2012), (c) of the Hellenic Arc (Vergos et al. 2012) and (d) Santorini (Contadakis et al. 2013,Contadakis et al. 2014). The result of the analysis for all the areas indicate that the monthly variation of the frequencies of earthquake occurrence is in accordance with the period of the tidal lunar monthly and semi-monthly (Mm and Mf) variations and the same happens with the corresponding daily variations of the frequencies of earthquake occurrence with the diurnal luni-solar (K1) and semidiurnal lunar (M2) tidal variations. In addition the confidence level for the identification of such period 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. These results are in favor of a tidal triggering process on earthquakes when the stress in the focal area is near the critical level. Based on these results, we consider the confidence level of earthquake occurrence - tidal period accordance, p , as an index of tectonic stress criticality for earthquake occurrence and we call it” **Earth tide-seismicity compliance parameter**”. Then we check on posterior if the variation of the confidence level index, p , indicate the fault maturess in the case of the recent seismic activity at Fthiotida, and Evoikos Gulf ,Greece. In this paper we present the results of this test for the area of the west site of the Aegean Volcanic Arc on the occasion of the earthquake of $M_L=5.7$ on August 29,2014.

2. Seismicity at the west site of the Aegean Volcanic Arc

The main zone of compression with thrust faults is observed along the Hellenic arc and the western coast of Greece and is related with the subduction of the African Plate beneath the Eurasian plate. The back arc area is dominated by N-S extension and is the locus of the Aegean Volcanic Arc which is associated with the subduction (Figure 1). Along with this Arc occur the deepest earthquake in the area of Greece. On August 29 of 2014 a deep earthquake of $M_L=5.27$ occurred in the area of the west site of the Aegean Volcanic Arc, followed by a poor seismic activity with shocks of magnitudes weaker than 3.0 M_L . The area present an increasing micro seismic activity since 1998 (both in shallow and deep earthquakes) which culminate in 2010 (Figure 2).

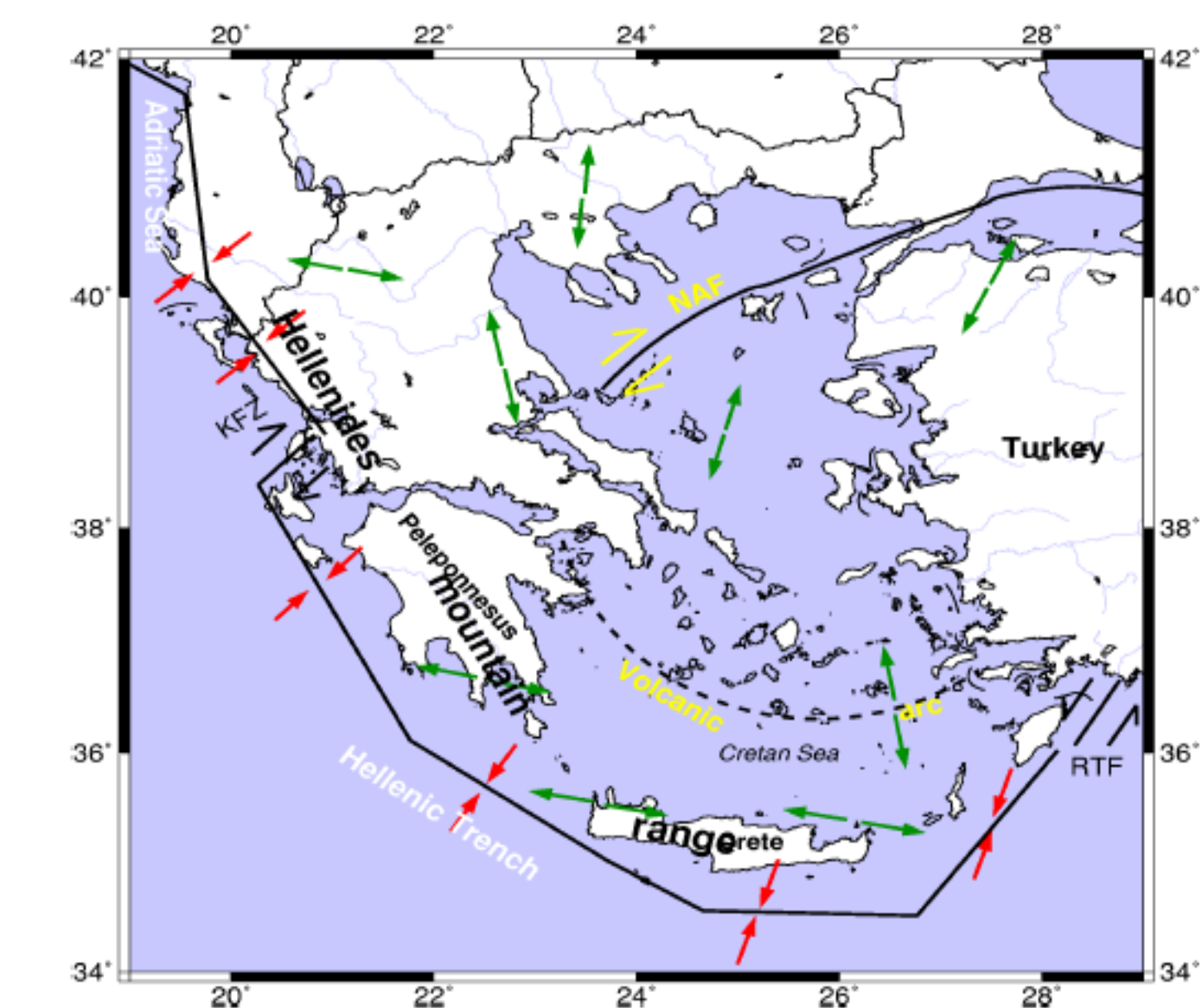


Figure 1. The compression and extension zone in the Aegean. The situation of the Aegean Volcanic Arc associated with the subduction is marked with dashed line.(quoted from the Geology and Tectonics of Aegean, Chapter 2, Forough 2005)

In the broader area 7 deep earthquakes with $5.0 < M_L < 6.3$ occurred during the last 50 years. Table 1 gives the characteristic parameters of these earthquakes.

Table 1. Earthquakes with $M_L > 5.0$ occurred within the last 50 years at the west site of the Aegean Volcanic Arc

Year	MM/DD	U.T	$\varphi(^{\circ})$	$\lambda(^{\circ})$	Depth (km)	M_L
2002	5 21	20 53 30.8	36.57	24.31	97	5.1
2004	11 4	6 22 37.4	35.86	23.23	95	5.0
2006	1 8	11 34 54.0	36.21	23.41	69	6.4
2007	2 3	13 43 22.3	35.80	22.58	99	5.0
2008	1 6	5 14 19.3	37.11	22.78	86	6.1
2014	4 4	20 8 7.4	37.20	23.73	113	5.5
2014	8 29	3 45 5.6	36.67	23.67	97	5.7

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 year 2014. In our analysis we use the seismological data of the earthquake catalogue of NOA (<http://www.gein.noa.gr>). The set of data consist of a series of 5507 earthquakes. From them 4782 are shallow, i.e. depth<50km and magnitudes ranging from 2.0 to 4.5 M_L and 725 deep earthquakes, i.e. depth>60km with M_L ranging from 2 to 6.4. These earthquakes occurred within the time interval from January 1964 to 20 of September 2014, in an area bounded by $36.14^{\circ} \leq \varphi \leq 38.20^{\circ}$ and $23.17^{\circ} \leq \lambda \leq 24.17^{\circ}$. Figure 2 displaces the development of the seismicity in the area from 1964.

It is seen that after an one year peak on 1981 the number of shocks per year start to increase from 1998 on and reaches a peak on 2010.

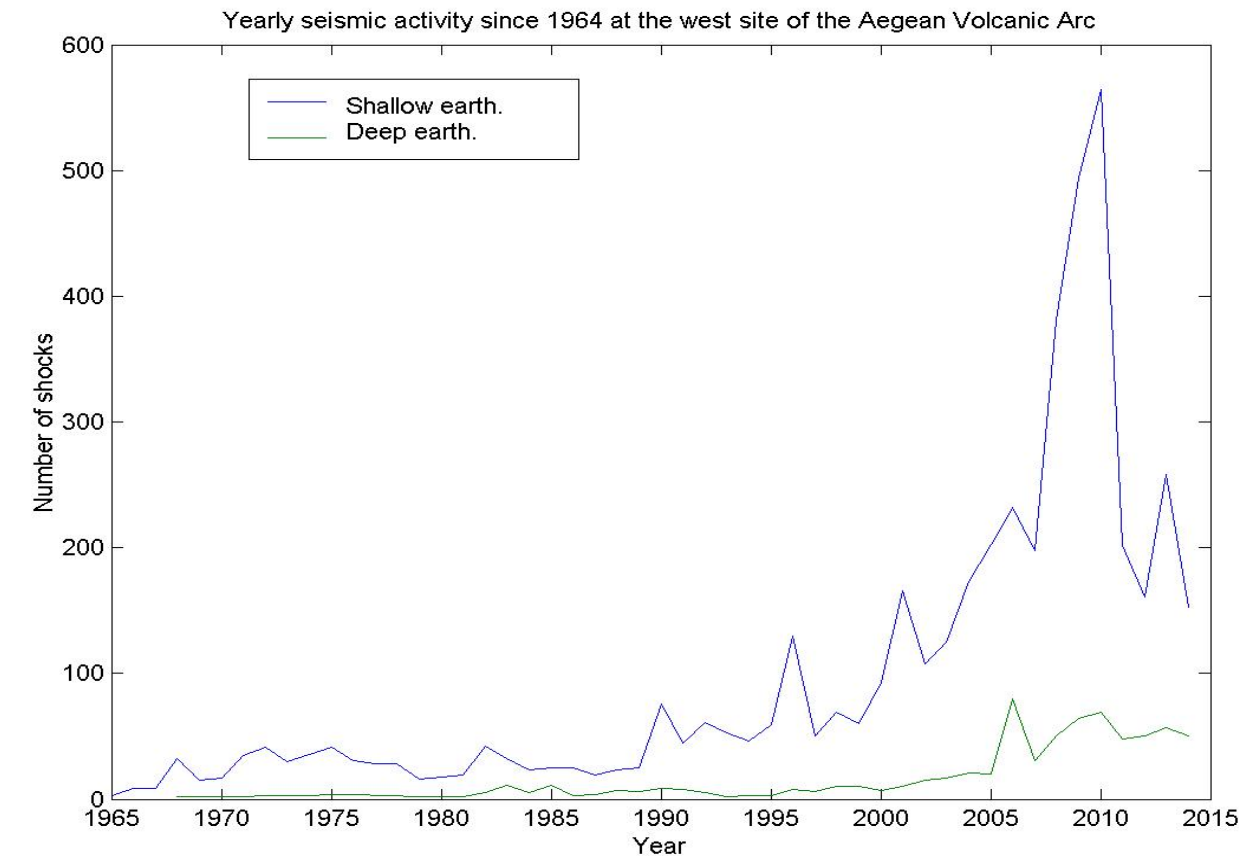


Figure 2. The development of the seismicity at the west site of the Aegean Volcanic Arc from 1964 until 2014.

3. Tidal effect

Tidal effects on a rigid Earth can be computed theoretically from the ephemerides of the Moon, the Sun and the planets. The Earth tides are the combined effect of the mentioned celestial bodies and the reaction of the solid Earth (like an elastic body) to the tidal forces. The ocean tides follow the law of hydrodynamics, with strong disturbances affecting adjacent seas, so that the ocean loading effect has to be taken into account. Earth tides are discussed extensively in Melchior (1983), Baker (1984), Wilhelm et al. (1997), Torge (2001).

The constituents of the Earth tides for the area of Thessaloniki were determined gravimetrically by Arabelos (2002). Table 1 displays the strongest components of the Earth tides for Thessaloniki. Although the amplitude of the lunar tidal component M1 is equal 27.091 nms⁻² (see Arabelos, 2002, Table 3), i.e. it is much weaker than the listed components, we consider in addition the possible effect of this constituent by means of the lunar synodic month (i.e. period from new moon to new moon which is 29^d.530589) as well as by lunar anomalistic month (i.e. time period between two successive passages of the moon from perigee which is 27^d.554551).

Table 3 displays the actual ocean corrected tidal parameters of O1 and M2 for Sofia, Istanbul and Thessaloniki, and the corresponding values from the model of Wahr-Dehant-Zschau (Dehant 1987; Dehant and Zschau, 1989), expressing the dependency of the tidal parameters on the latitude. As it is shown from the table the amplitude factors of the principal O1 and M2 tidal constituents agree within their error of estimation with the model.

Table 3. The strongest components of Earth tides in Thessaloniki

Symbol	Period T(min)	Signal/noise	Amplitude (nms ⁻²)	Origin
K1	1436	525.1	487.840	Lunar & Solar declination wave
O1	1549	379.7	352.816	Lunar principal wave
M2	745	1208.5	510.350	Lunar principal wave
S2	720	564.5	238.393	Solar principal wave

For the latitude of 38° which is the mean latitude of the area under consideration, the extrapolated model amplitude factors for O1 and M2 are equal to 1.156 and 1.158 respectively. Consequently, the amplitudes of O1 and M2 might be changed to about 408 and 591 nms⁻² respectively, which are very close to the amplitudes observed in the tidal station of Thessaloniki. However, this estimation does not take into account the actual elastic properties of the lithosphere in the Ionian zone.

Table4. Ocean corrected parameters of O1 and M2 in 3 neighboring stations

	Sofia (latitude=42.71°)		Istanbul (latitude=41.07°)		Thessaloniki (latitude=40.63°)	
	Ampli- tude factor	Phase degree	Ampli- tude factor	Phase degree	Ampli- tude nm factor	Phase degree
O1	1.1493± 0.0014	-1590± 060	1.1564± 0.0035	-281± 0.174	1.1536± 0.003	-201± 0.151
Model	1.1540	-0.2	1.1542	-0.2	1.1543	-0.2
M2	1.1541± 0.0005	-207± 0.026	1.1587± 0.0011	-039± 0.026	1.1639± 0.001	-195± 0.001
Model	1.1541	-0.2	1.1583	-0.2	1.1583	-0.2

4. 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:

$$\phi_i = [(t_i - t_0) / T_d] \times 360 - \text{int}([(t_i - t_0) / T_d] \times 360) \quad (1)$$

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_0 = the epoch we have chosen in MJD,

T_d = the period of the particular tidal component in

Julian Days.

We choose as epoch t_0 , i.e. as reference date, the time of the upper culmination in Thessaloniki of the new moon of January 7, 1989 which has 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_0 is January 14, 1989 which has MJD = 47541.28492.

We separate the whole period in 12 bins of 30° 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 \tilde{a}_i . The vectorial sum D is defined as:

$$D^2 = \left(\sum_{i=1}^N \cos \alpha_i \right)^2 + \left(\sum_{i=1}^N \sin \alpha_i \right)^2 \quad (2)$$

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:

$$p = \exp\left(-\frac{D^2}{N}\right) \quad (3)$$

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 means that the smaller the p is the greater the confidence level of the results of the Cumulative Histograms is.

5. Results

Figures 3 to 8 display the Cumulative Histogram for all the 173 earthquakes which occurred in the time interval from January 1st, 2014 to 20th of September, 2014, and correspond to the tidal periods of Anomalistic Monthly period(i.e. time period between two successive passages of the moon from perigee which is 27^d.554551) (Figure 3), Synodic Monthly period (i.e. period from new moon to new moon which is 29^d.530589) (Figure 4), Diurnal luni-solar constituents K1 (Figure 5), Diurnal luni-solar constituent O1 (Figure 6), Semi-diurnal solar constituents S2 (Figure 7), and Semi-diurnal lunar constituent (Figures 8), for the last year of the 50-year analyzed data, i.e. 2014. It is obvious that there is not a perfect compliance of tidal and earthquake frequency distribution for all the Tidal constituent except that of Monthly Synodic and partly for periods Diurnal luni-solar O1 as well as the Diurnal luni-solar K1. This is also shown in Table 5. This table displays the corresponding confidence levels for all six tidal components for 2014 together with the same quantities for a year of low tectonic activity, i.e. 1994 and the mean confidence levels for the 50 years. It appears that in general 2014 is a rather quiet year despite the two deep earthquakes with magnitudes $M_L > 5.0$.

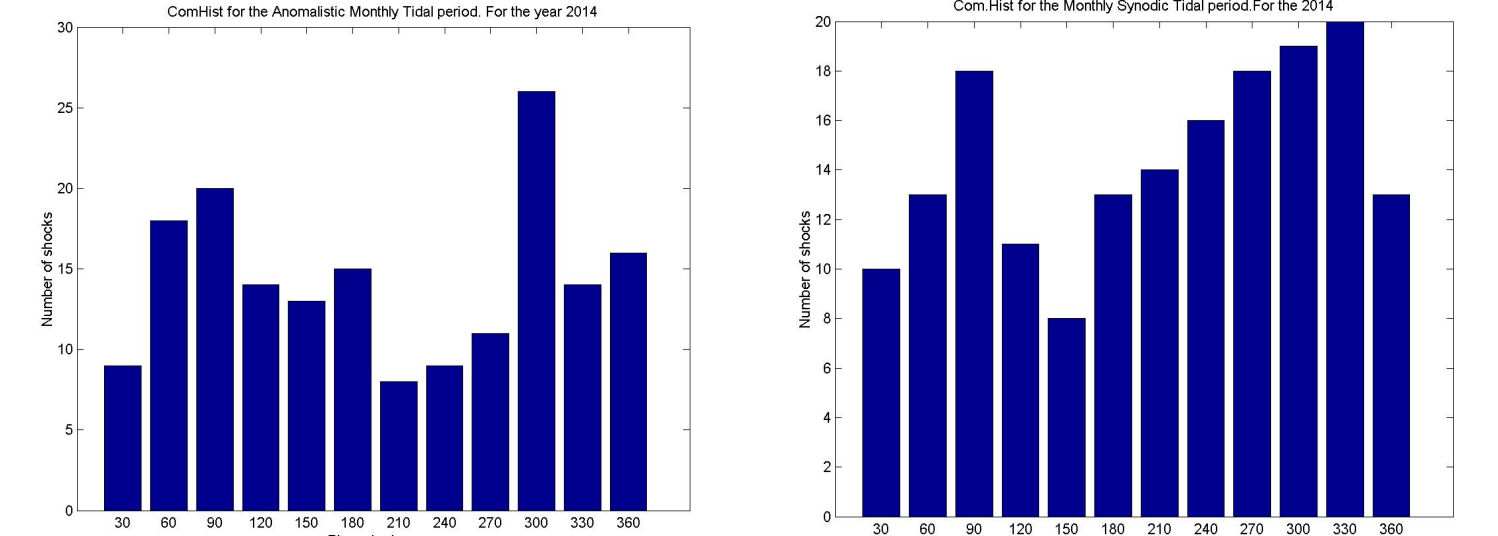


Figure 3. Cumulation Histogram for the Anomalistic Monthly period for 2014

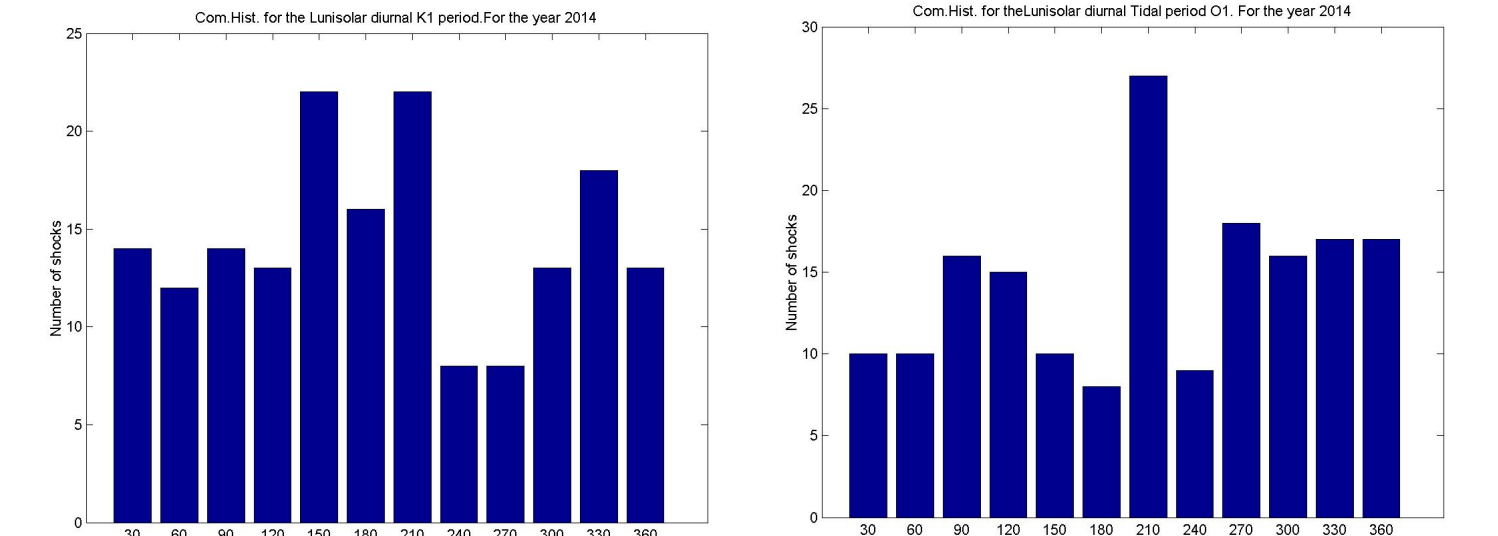


Figure 5. Cumulation Histogram for the Luni-Solar K1 period for 2014

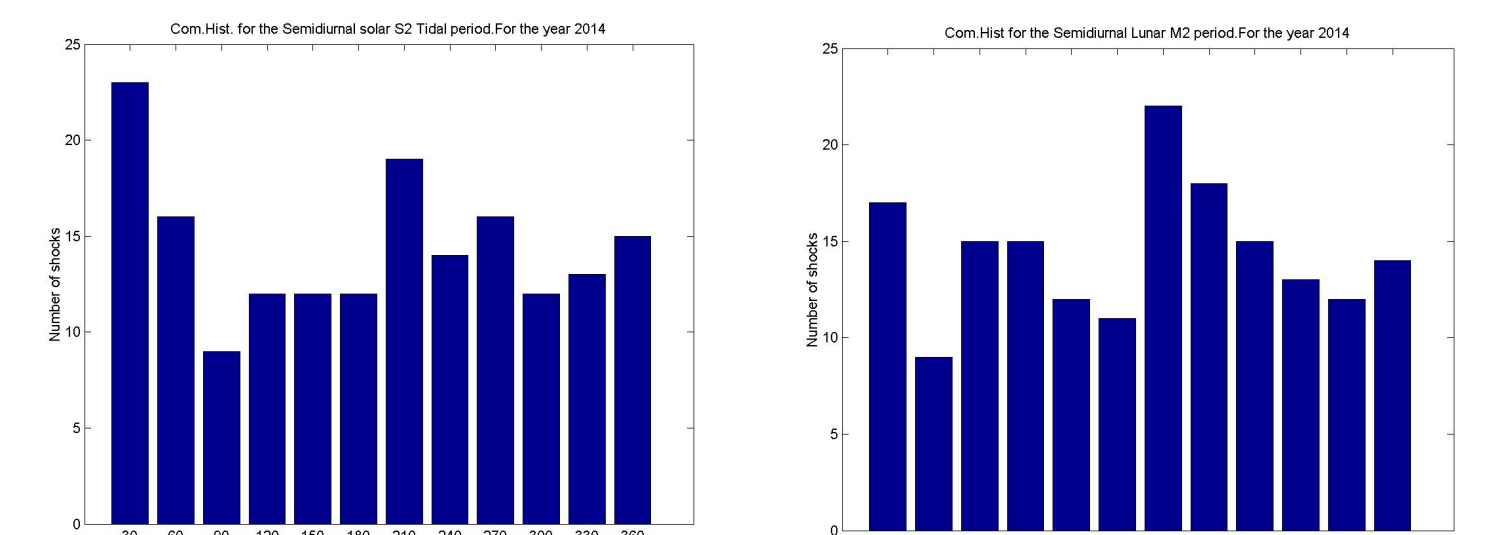


Figure 7. Cumulation Histogram for the semi diurnal Solar S2 period for 2014

Table 5 indicates also that the confidence level of the Tidal-Earthquake frequency period compliance is very sensitive to the seismicity of the area. This is shown also in figures 9 to 14. These figures display the variation of the confidence level parameter in the time period 1964 to 2014 together with the earthquakes frequency for each year for all six periods. Arrows indicate the occurrence of strong earthquakes ($M_L > 5.0$) while double earthquakes are marked with one arrow. The high compliance for the monthly tidal components, despite their small intensity may indicate that they provide in general favorable conditions for the action of the much stronger tidal components K1 and M2. In this point we may refer to the fact that the monthly tidal barometric variations are quite sensitive to the seismic activity (Arabelos et al. 2008). Perhaps this peculiar coincidence merits further investigation.

Table 5. The confidence level of earthquake-Earth tide correlation for all the earthquakes of Evoikos area for 2014 in comparison with Mean and those of 1994

	M Anom.	M Synod.	K1	O1	S2	M2
Mean	0.3823	0.3730	0.3858	0.4143	0.4178	0.4073
1994	0.8223	0.4362	0.0179	0.4156	0.7588	0.3947
2014	0.4443	0.0961	0.2289	0.2946	0.5208	0.9302

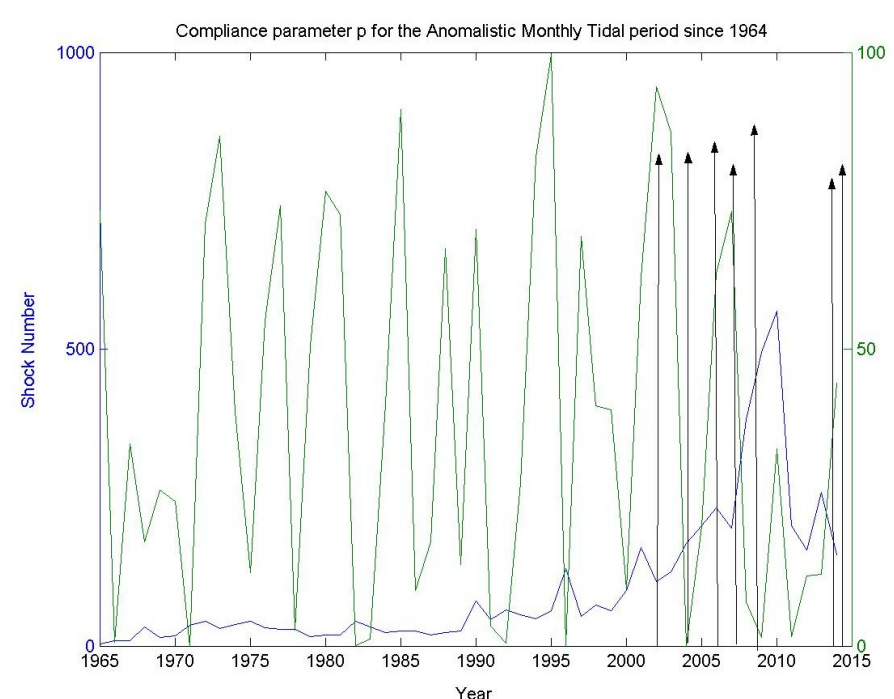


Figure 9. The confidence level parameter p between Seismicity and Tidal Anomalistic Monthly period. Arrows indicate the earthquakes with $M_L > 5.0$ at the west site of the Aegean Arc since 1964.

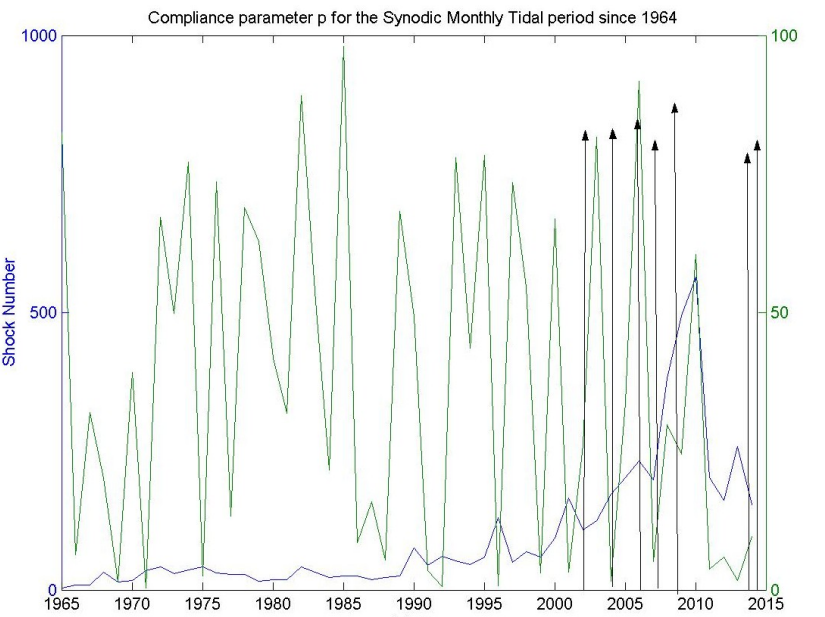


Figure 10. The confidence level parameter p between Seismicity and Tidal Synodic Monthly period. Arrows indicate the earthquakes with $M_L > 5.0$ at the west site of the Aegean Volcanic Arc since 1964.

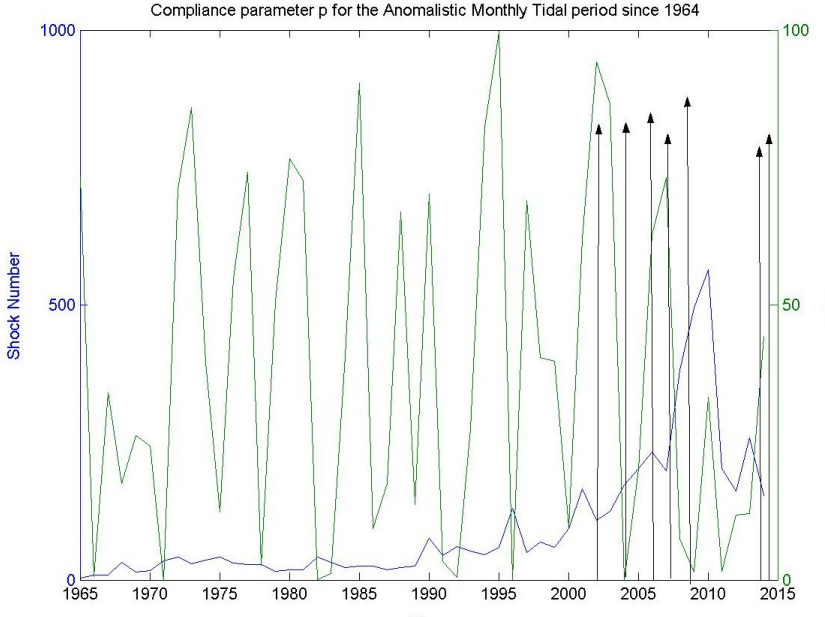


Figure 11. The confidence level parameter p between Seismicity and diurnal Tidal Luni-Solar K1 period. Arrows indicate the earthquakes with $M_L > 5.0$ at the west site of the Aegean Volcanic Arc since 1964.

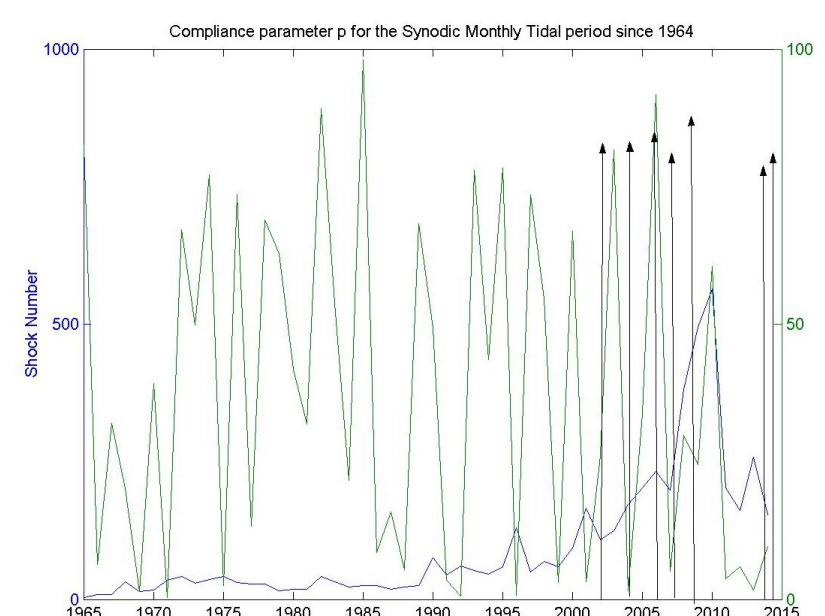


Figure 12. The confidence level parameter p between Seismicity and Tidal diurnal Luni-Solar O1 period. Arrows indicate the earthquakes with $M_L > 5.0$ at the west site of the Aegean Volcanic Arc since 1964.

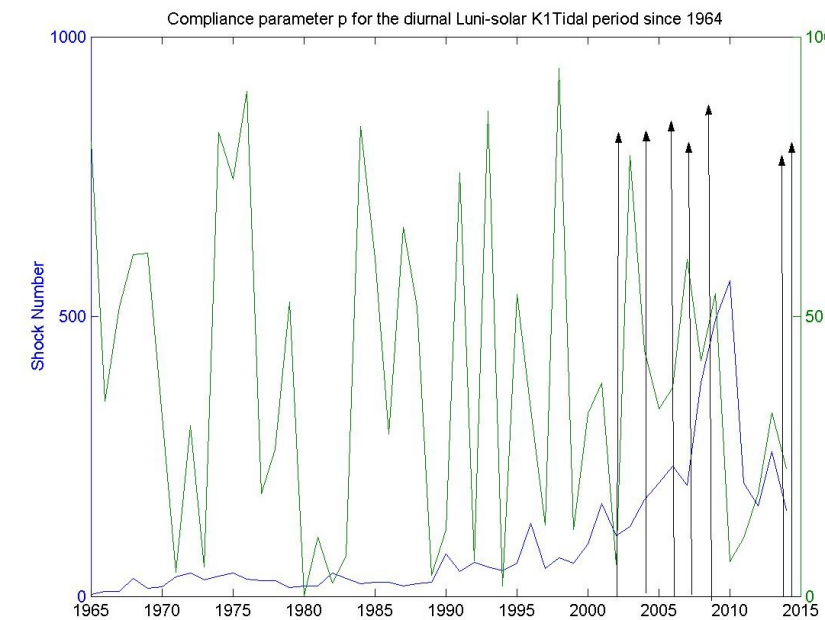


Figure 13. The confidence level parameter p between Seismicity and Tidal semi diurnal Solar S2 period. Arrows indicate the earthquakes with $M_L > 5.0$ at the west site of the Aegean Volcanic Arc since 1964.

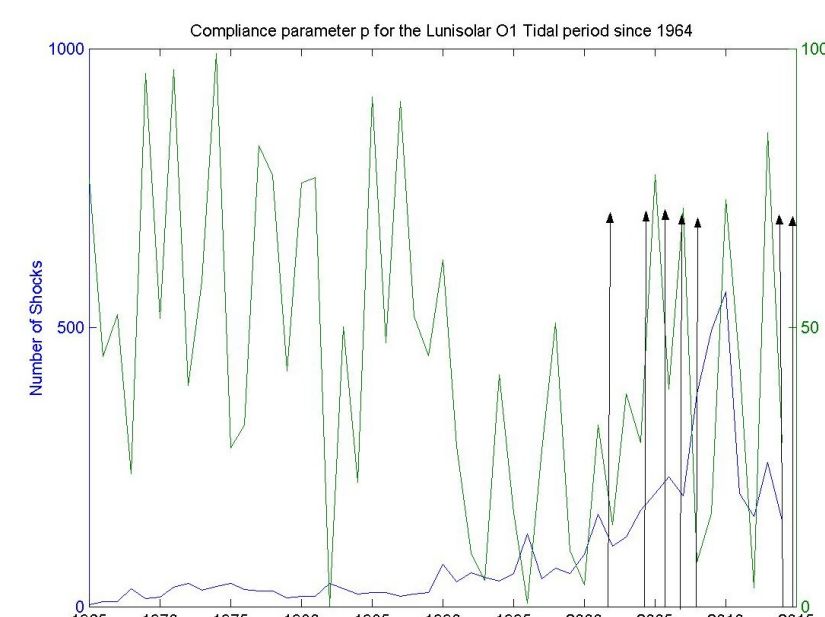


Figure 14. The confidence level parameter p between Seismicity and Tidal semi diurnal Lunar M2 period. Arrows indicate the earthquakes with $M_L > 5.0$ at the west site of the Aegean Volcanic Arc since 1964.

6. Conclusions

In this paper we investigate the tidal triggering evidence on the earthquakes of the area of the west site of the Aegean Volcanic Arc, 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 moderate meaning that the area is not seismically exited.

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