

Testing the recent Santorini seismic activity for possible tidal triggering effect

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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 Santorini island complex indicate that the faults Kameni and Columbo (to which the seismicity is clustered) (Chouliaras et al. 2013) are mature for a stronger earthquake. In this paper we present the results of this test.

Key words: Santorini volcanic complex · Luni-solar Tides · Seismicity

1. Introduction

Applying the Hi(stogram)Cum(ulation) method, which was introduced recently by Cadicheanu, van Ruymbecke and Zhu (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) and (c) of the Hellenic Arc (Vergos et al. 2012). 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 as an index of tectonic stress criticality for earthquake occurrence and we check if the recent increase in the seismic activity at the Santorini island complex indicate that the faults Kameni and Columbo (to which the seismicity is clustered) (Chouliaras et al. 2013) are mature for a stronger earthquake. In this paper we present the results of this test.

2. Recent micro-seismicity in Santorini

Santorini is the most active volcanic complex in the southern Aegean volcanic arc. Figure 1, quoted from Chouliaras et al. 2013, present the Tectonic map of Santorini' s volcanic island complex after Heiken and McCoy, 1984
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).

Since the formation of the caldera thirteen eruptions are known to have occurred in: 197 B.C., 19 A.C, 46, 726, 1457, 1508, 1573, 1650, 1707, 1866, 1925, 1939 and 1950 (Chouliaras et al. 2013). The historical seismicity record of Santorini includes 3 strong main shocks: in 1650 with M=6.0, in 1866 with M=6.1 and in 1919 with M=6.0 (Papazachos and Papazachou, 2003).

After the seismic activity of 1996, in order to improve the detection of the local seismicity the Institute of Geodynamics of the National Observatory of Athens (NOA) installed it's first permanent seismological station on Santorini in 1997 and also two permanent seismological stations in the nearby volcanic island of Milos in 2010 and 2011. By the end of 2010, when a new increase of the micro-seismic activity in the area started, a complementary portable network of 4 seismological station installed by the Institute of Geodynamics of the National Observatory of Athens (NOA) in order to closer follow up the development of this new seismic activity.

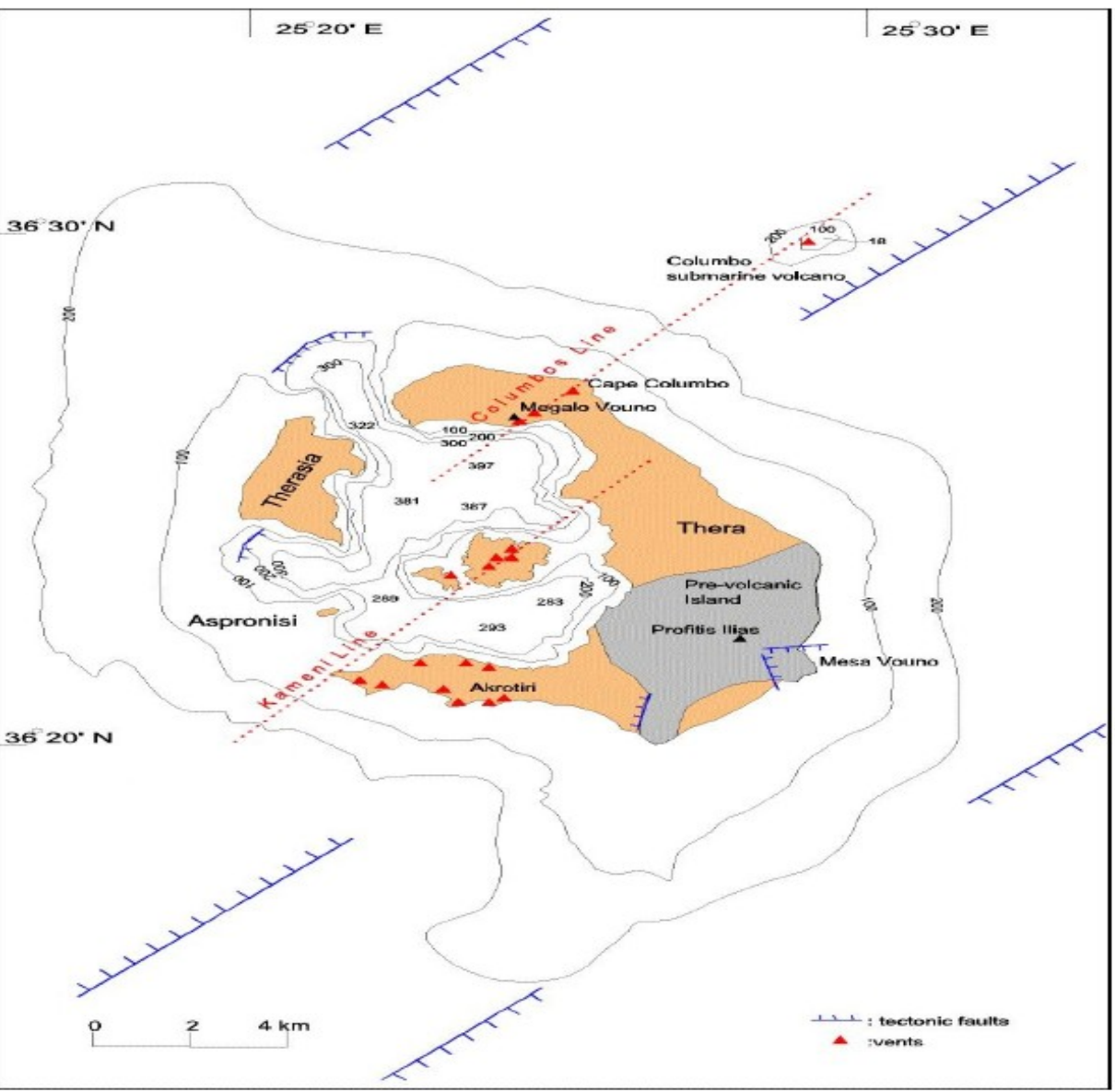


Figure 1. Tectonic map of Santorini' s volcanic island complex (after Heiken and McCoy, 1984). (Quoted from Chouliaras et al. 2013)

In their recent paper Chouliaras et al., 2013, analyzing the seismic activity of the area from 1965 till 2011 concluded that the microseismic shock rate has been increased by more than 100%. They find that the rate increase mainly exist in the Kameni and Columbo faults and in a NNE-SSW direction parallel to the active faults and perpendicular to the NNW-SSE extensional stress direction. Figure 2, quoted from Chouliaras et al. 2013, shows the seismicity of the Santorini region from 1966 to 2012 from the catalogue of the National Observatory of Athens.

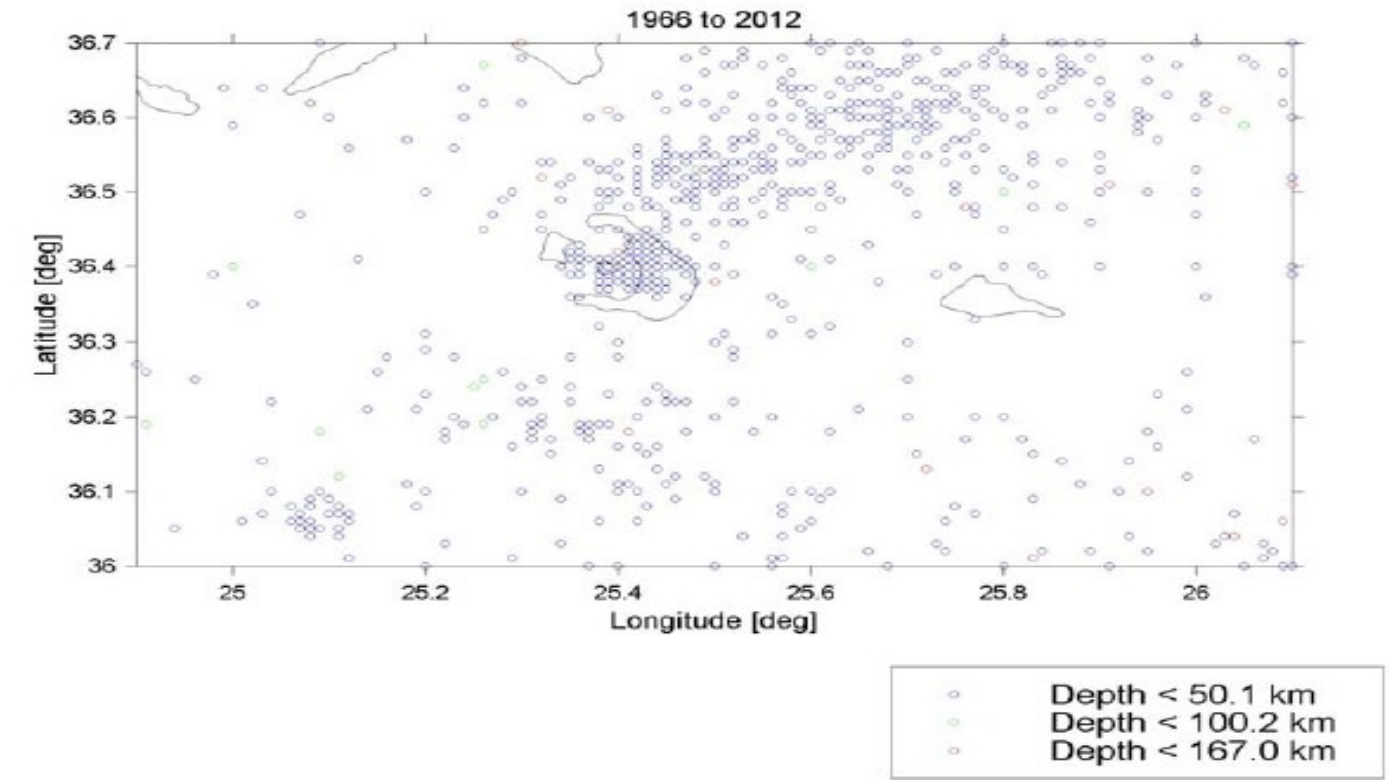


Figure 2. Seismicity of the Santorini region from 1966 to 2012 from the catalogue of the National Observatory of Athens, quoted from Chouliaras et al. 2013

For this area and for this time period 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. In our analysis we use the seismological data of the earthquake catalogue of NOA (<http://www.gein.noa.gr>). Figure 3 displaces the development of the seismicity in the area from 1968. The set of data consist of a series of 750 shallow and of intermediate depth earthquakes. Specifically, 734 shallow earthquakes with M_L ranging from 1.0 to 5.0 and 16 deep earthquakes with M_L ranging from 2.1 to 4.2 . These shocks occurred within the time interval from January 1968 to February 2012, in an area bounded by 36° 10' ≤ ϕ ≤ 36° 40' and 25° 10' ≤ λ ≤ 28° 40'. The great majority of the shocks have M_L < 3.5.

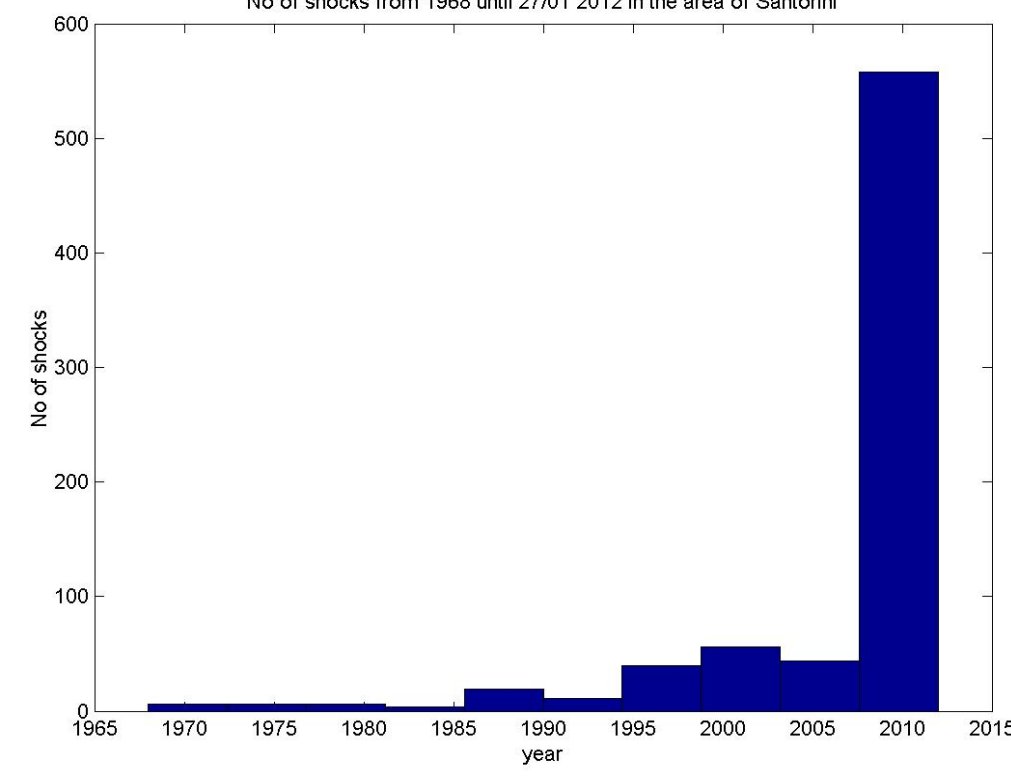


Figure 3. The seismicity in the area of Santorini

2. 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 2 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 1. 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.

Table2. Ocean corrected parameters of O1 and M2 in 3 neighboring stations

	Sofia (latitude=42.71°)		Istanbul (latitude=41.07°)		Thessaloniki (latitude=40.63°)	
	Amplitude factor	Phase (degree)	Amplitude factor	Phase (degree)	Amplitude 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

3. 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:

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

where f_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 \hat{a}_i . The vectorial sum D is defined as:

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

where N is the number of earthquakes. When a_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.

4. Results

Figures 4 to 9 display the Cumulative Histogram for all the 262 earthquakes which occurred in the time interval from January, 1968 to December 2010, and correspond to the tidal periods of: (1) diurnal luni-solar constituents K1 (Figure 4) and Semi-diurnal solar constituents S2 (Figure 5), (2) diurnal lunar constituent O1 (Figure 6) and semi-diurnal lunar constituent (Figures 7), (3) synodic month (i.e. period from new moon to new moon which is 29^d.530589) (Figure 8) and anomalistic (i.e. time period between two successive passages of the moon from perigee which is 27^d.554551) (Figure 9). Figures 10 to 15 display the corresponded Cumulative Histogram for all the 488 earthquakes which occurred in the time interval from January, 2011 to February 2012. Table 3 displays the corresponding confidence levels for all six tidal components for both sets of earthquakes.

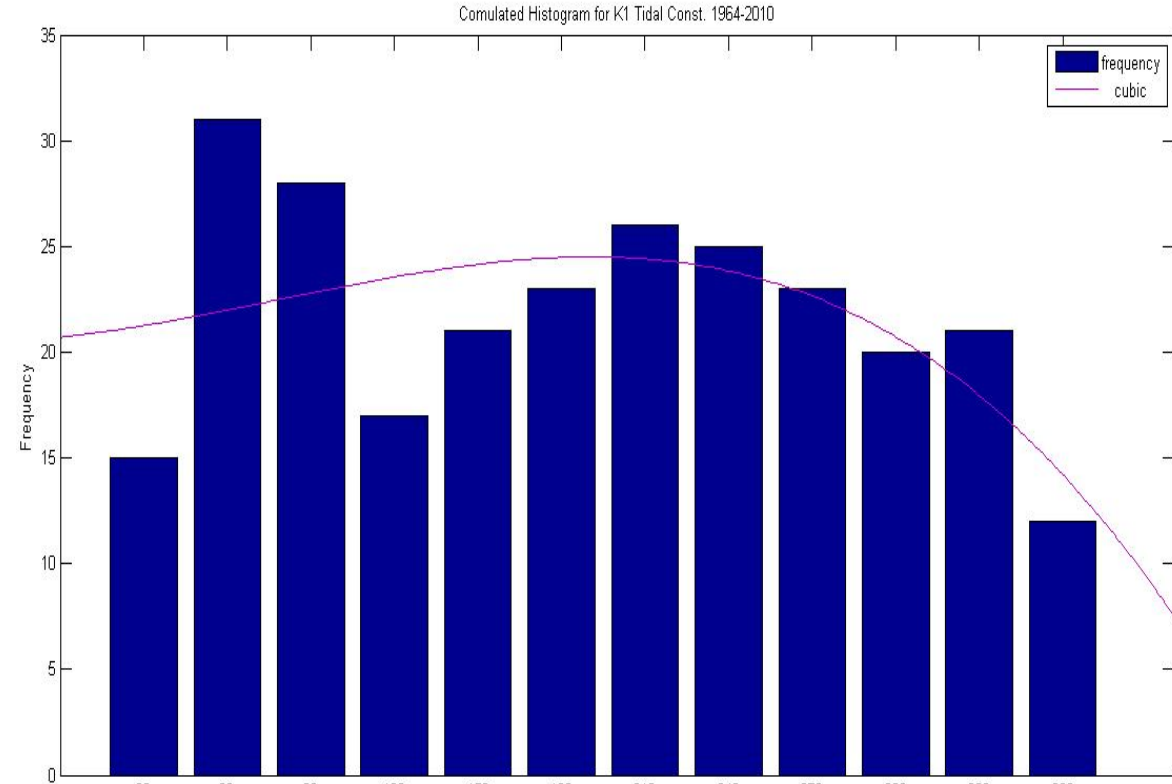


Figure 4. Cumulative Histogram corresponding to the period of K1 diurnal luni-solar Tidal component for the 26

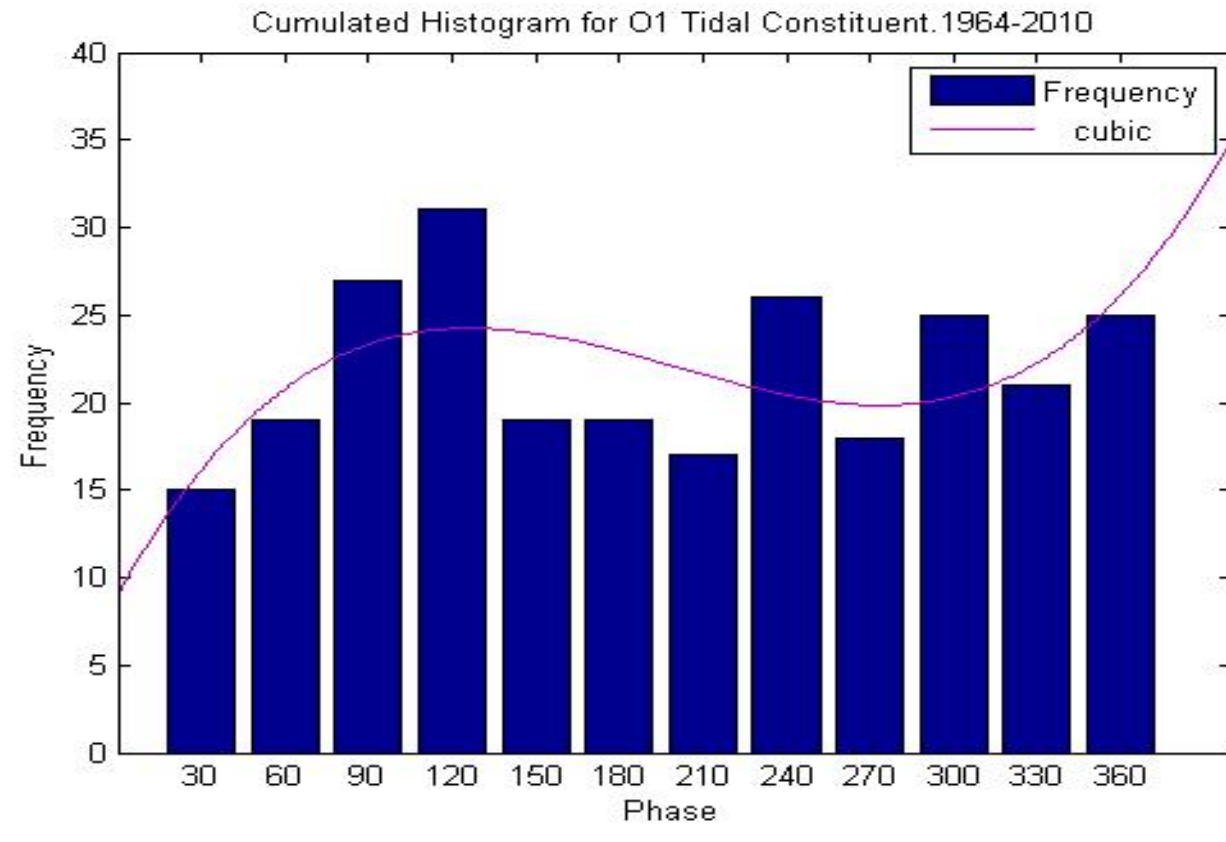


Figure 5. Cumulative Histogram corresponding to the period of O1 diurnal lunar Tidal component for the 262 shocks of the time period 1968-2010

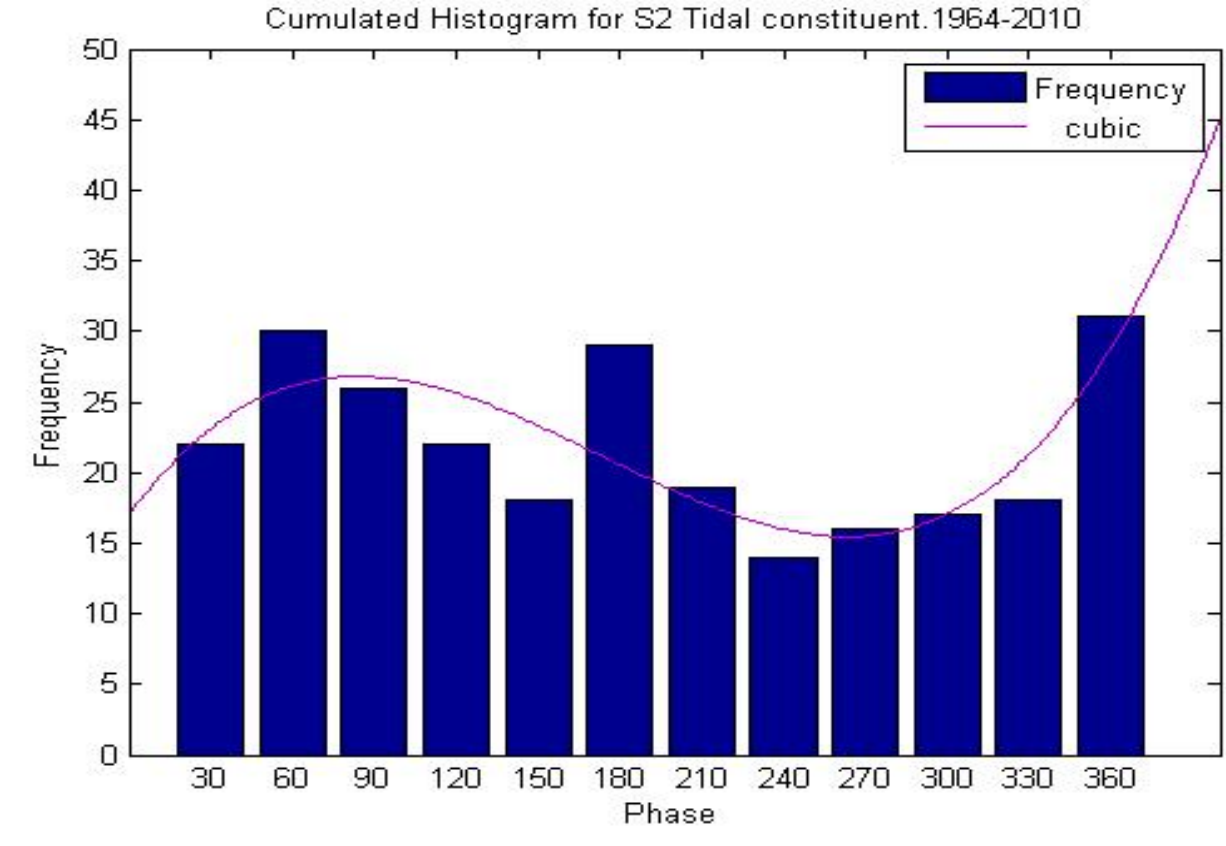


Figure 6. Cumulative Histogram corresponding to the period of S2 semi-diurnal solar Tidal component for the 262 shocks of the time period 1968-2010

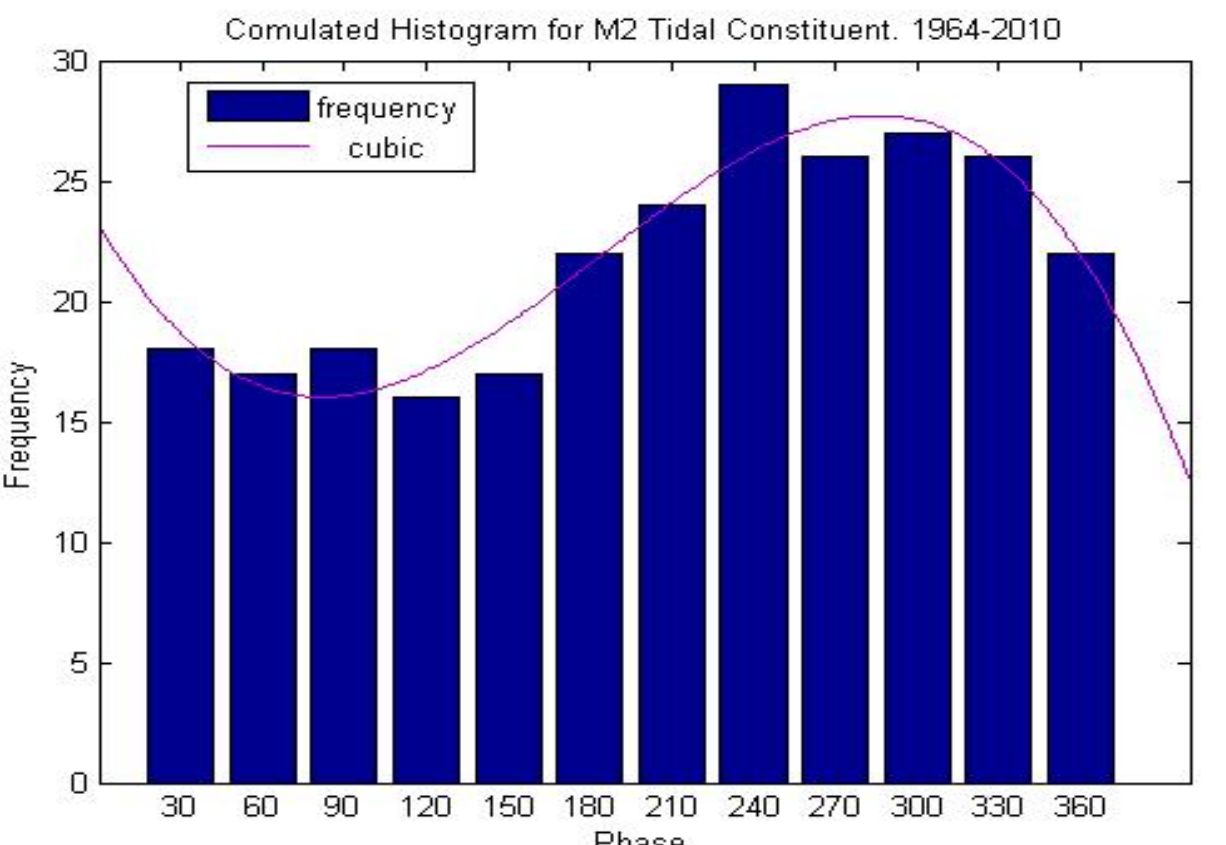


Figure 7. Cumulative Histogram corresponding to the period of M2 semi-diurnal lunar Tidal component for the 262 shocks of the time period 1968-2010

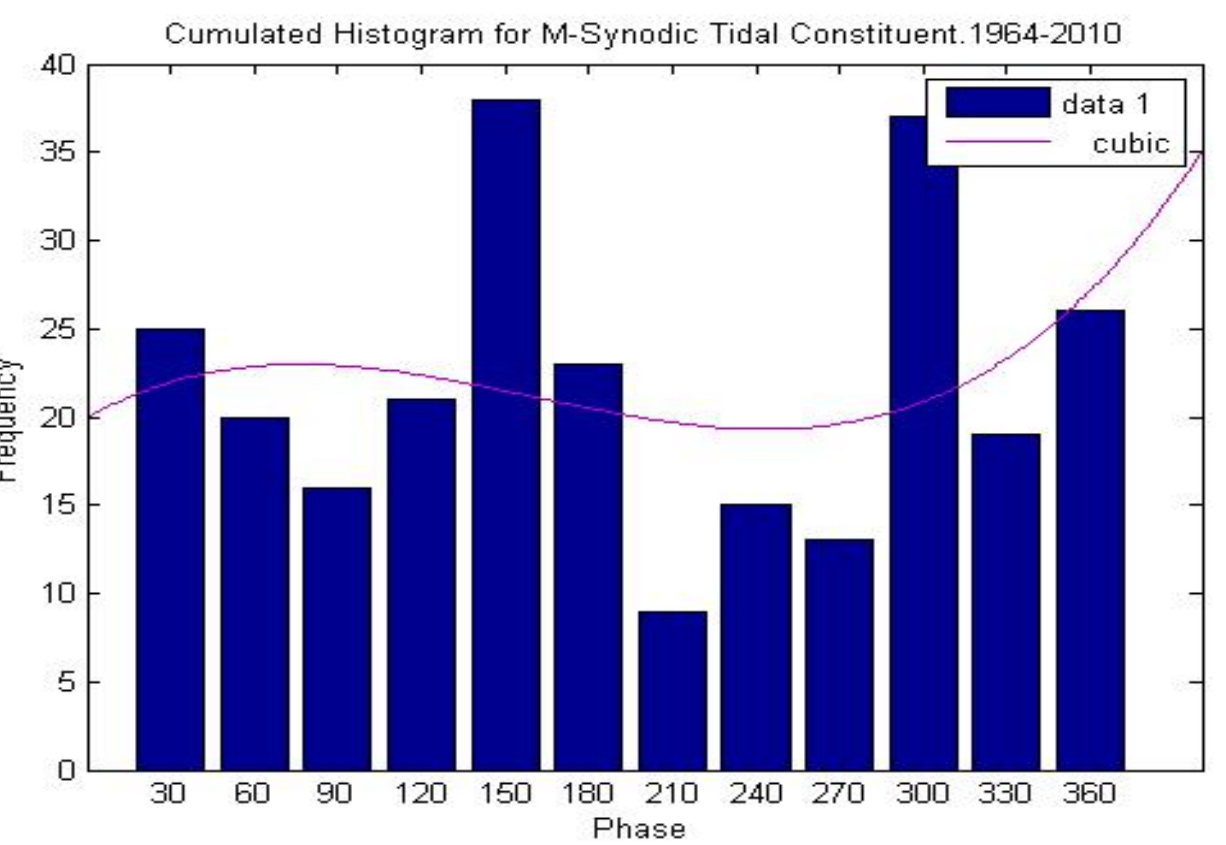


Figure 8. Cumulative Histogram corresponding to the period of the monthly M-synodic lunar Tidal component for the 262 shocks of the time period 1968-2010

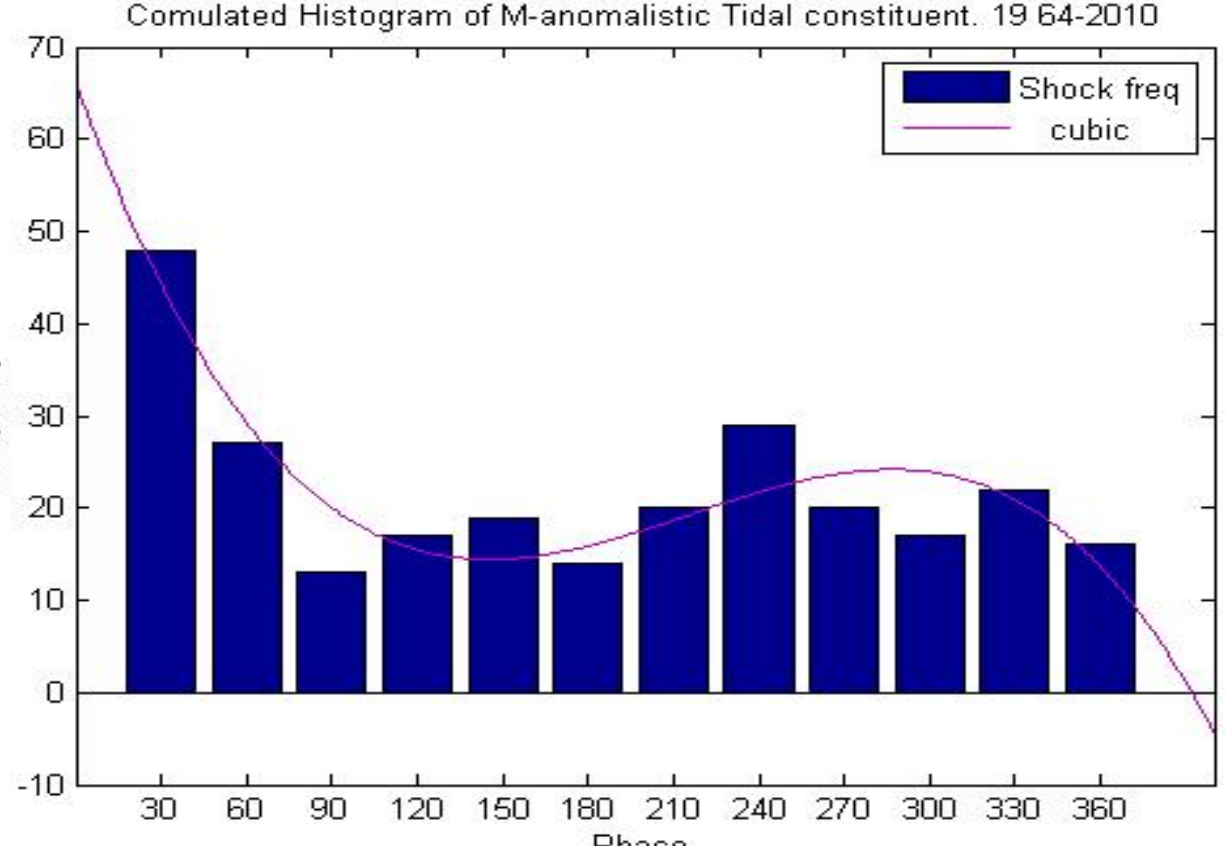


Figure 9. Cumulative Histogram corresponding to the period of the monthly M-anomalistic lunar Tidal component for the 262 shocks of the time period 1968-2010

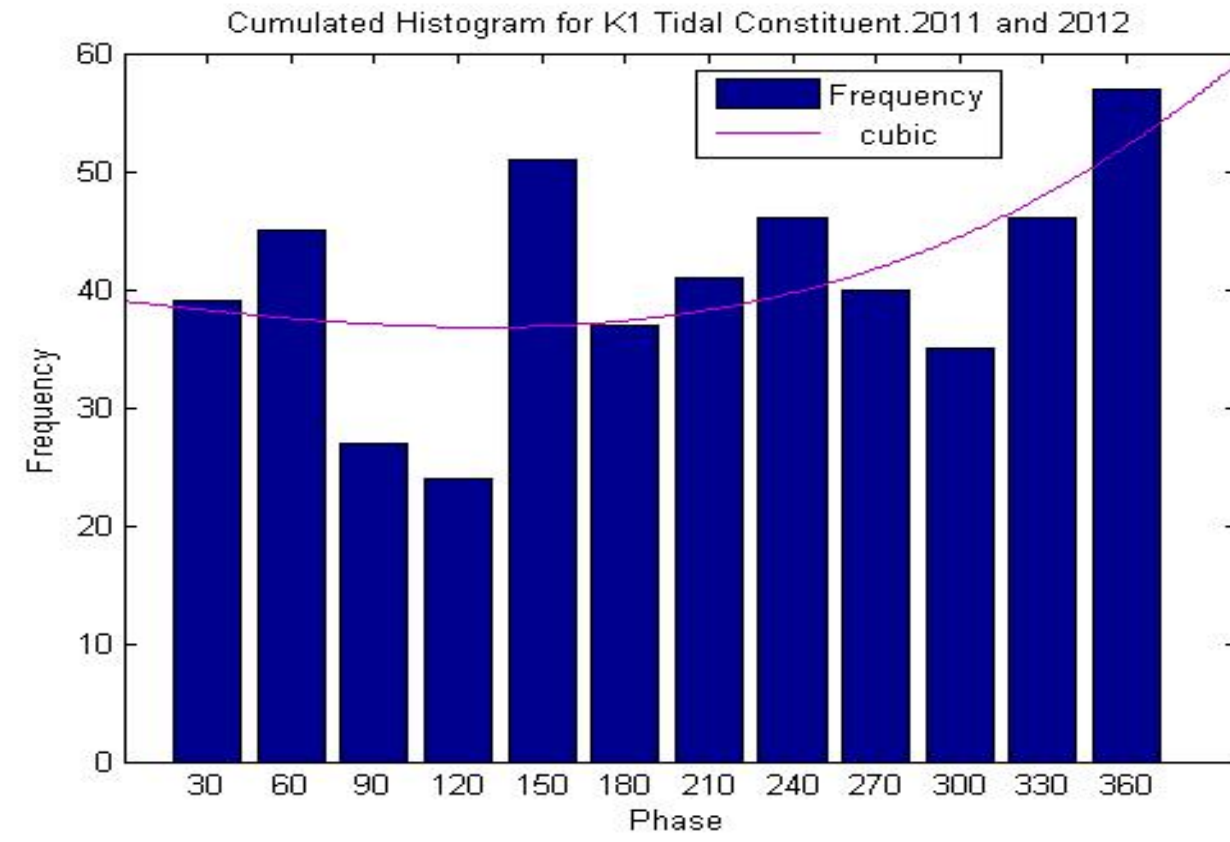


Figure 10. Cumulative Histogram corresponding to the period of K1 diurnal luni-solar Tidal component for the 488 shocks of the time period 2011-January, 2012

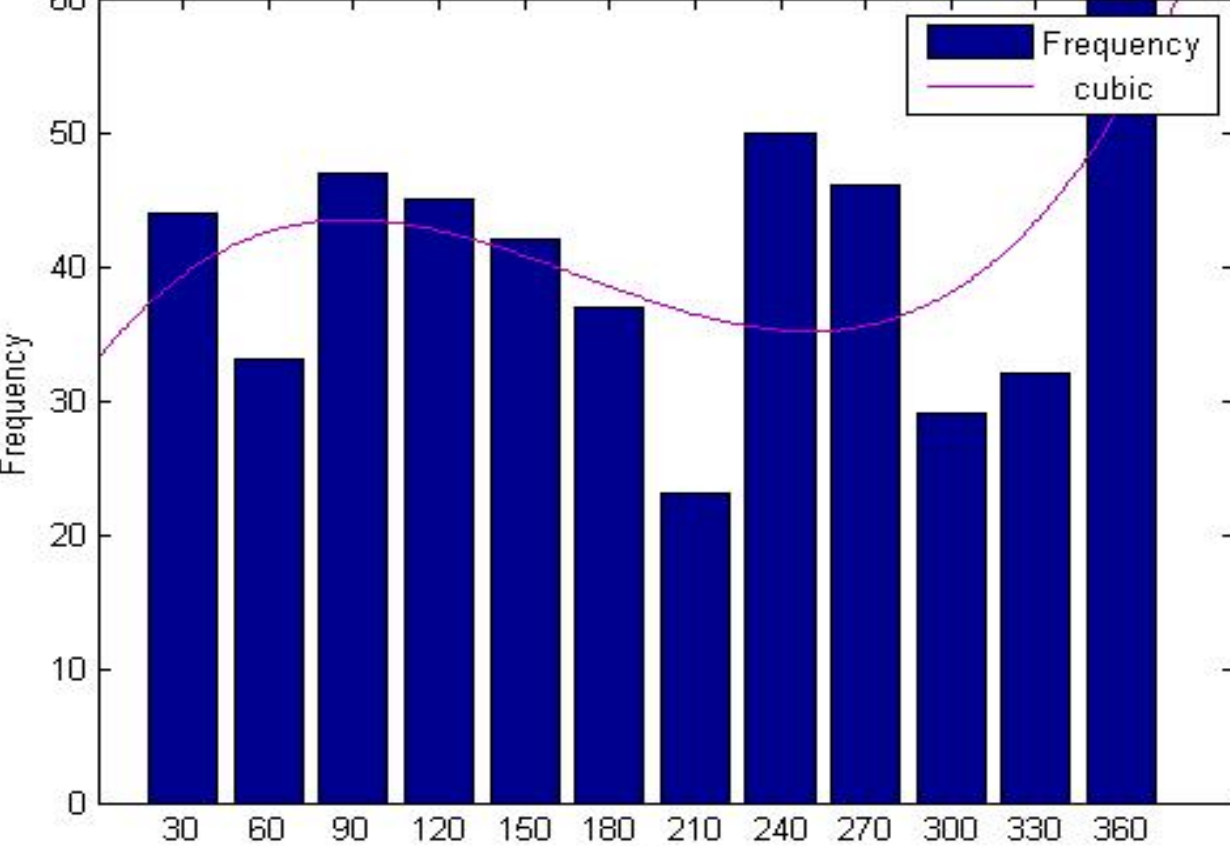


Figure 11. Cumulative Histogram corresponding to the period of O1 diurnal lunar Tidal component for the 488 shocks of the time period 2011-January, 2012

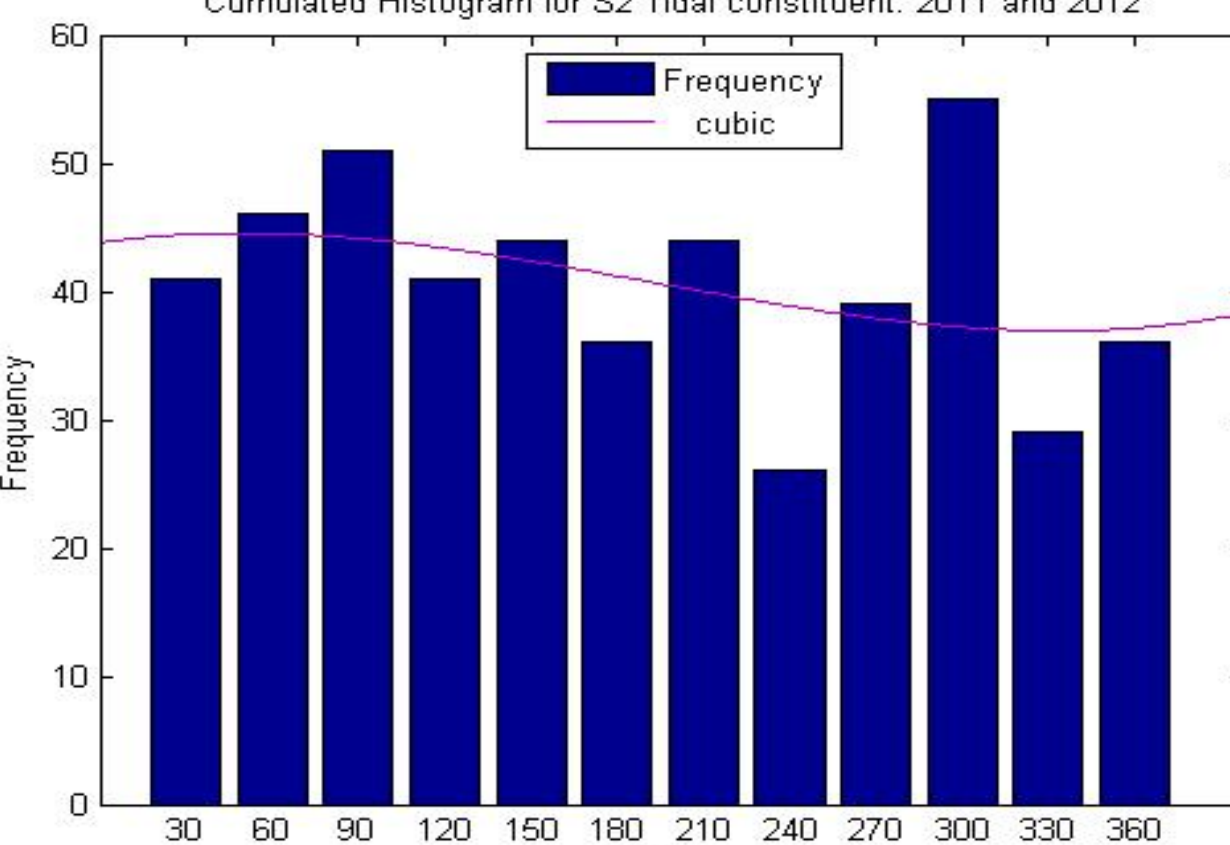


Figure 12. Cumulative Histogram corresponding to the period of S2 semi-diurnal lunar Tidal component for the 488 shocks of the time period 2011-January, 2012

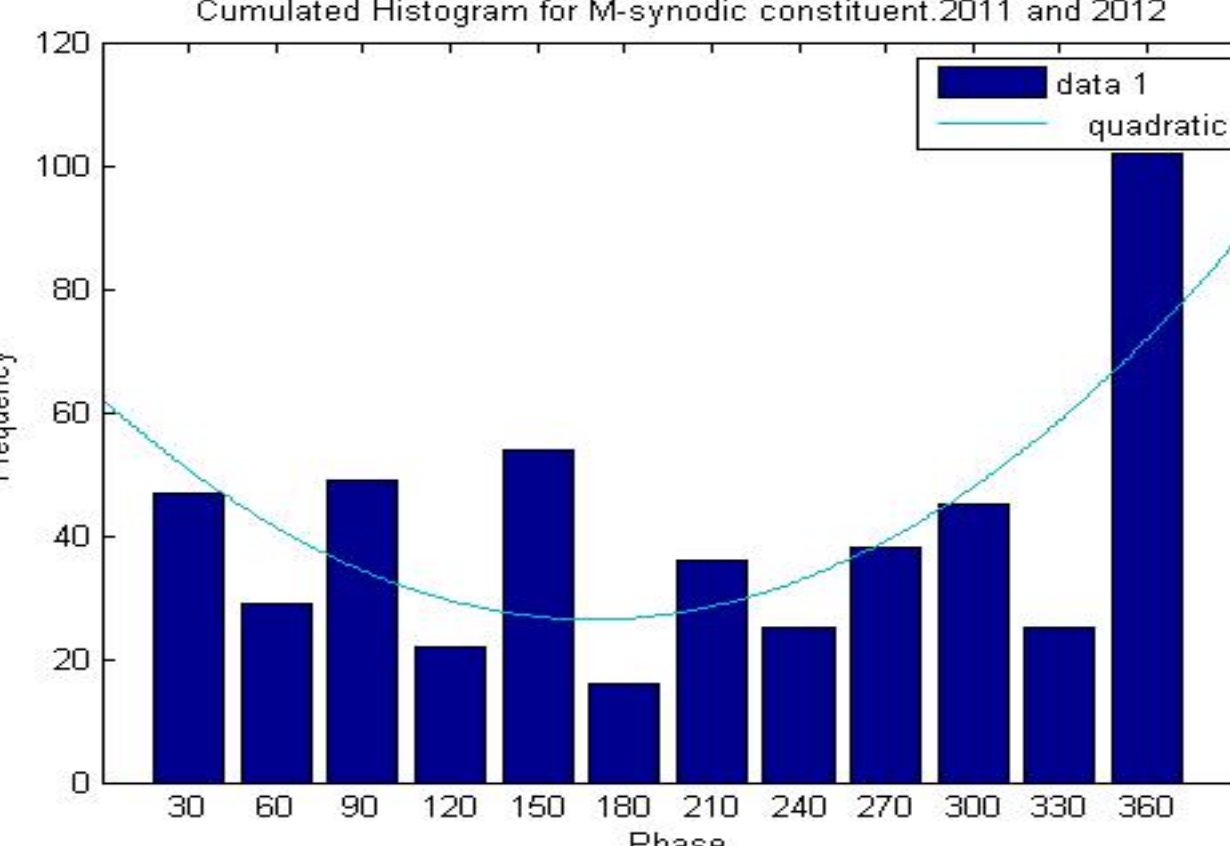


Figure 13. Cumulative Histogram corresponding to the period of the monthly M-synodic lunar Tidal component for the 488 shocks of the time period 2011- January, 2012

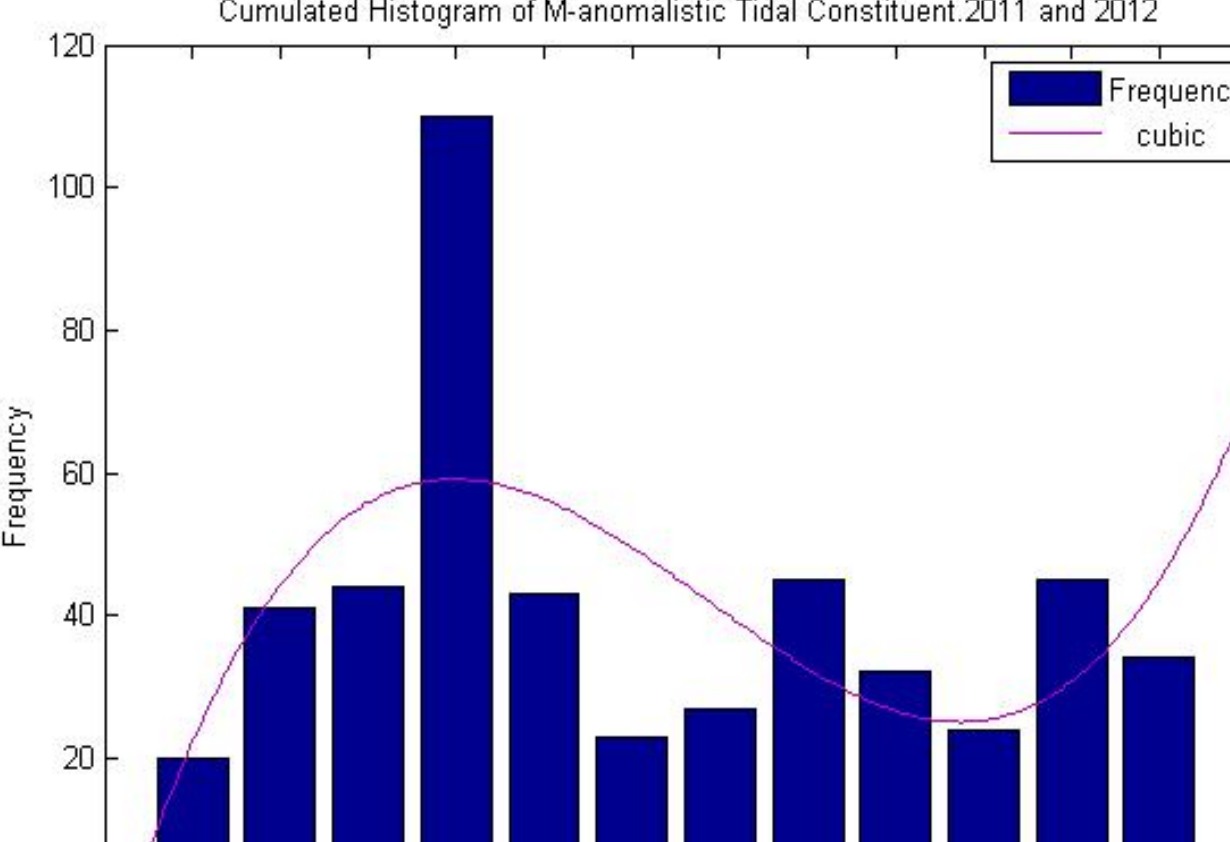


Figure 14. Cumulative Histogram corresponding to the period of the monthly M-anomalistic lunar Tidal component for the 488 shocks of the time period 2011- January, 2012

Table 3. The confidence level of earthquake-Earth tide correlation for all the earthquakes of Santorini area from 1964 to 2012

	$p(K1)$	$p(S2)$	$p(O1)$	$p(M2)$	$p(M \text{ syn})$	$p(M \text{ ano})$
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%

From Figures 4 to 9 it is obvious that the confidence level for the decision that the semi-diurnal solar S2 and semi diurnal lunar M2 components as well as the monthly lunar anomalistic component to be earthquake triggering mechanism is very high in the period 1968-2010. On the contrary the confidence level for the diurnal components and the Monthly lunar synodic are low. For the time period 2011-January 2012 the confidence level for the decision for being earthquake triggering mechanism is very high for both monthly lunar components and the lunar semi-diurnal components and has been increased for both diurnal components.

The high compliance for the monthly tidal components, despite their small intensity may indicate that they provide in general favourable 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.

5. Conclusions

In this paper we investigate the tidal triggering evidence on the earthquakes of the area of the volcanic complex of Santorini in 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 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 (1987) 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.

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