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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.

Περίληψη

Βασισμένοι στα αποτελέσματα των μελετών μας για την εκδήλωση παλιρροϊκών επιδράσεων στην σεισμικότητα του Ελληνικού Χώρου, θεωρούμε το Επίπεδο εμπιστοσύνης p της προσαρμογής της κατά φάση κατανομής του αριθμού των σεισμών και της περιοδικής μεταβολής των σεληνοηλιακών παλιρροιών ως ένα δείκτη της οριακού επιπέδου τεκτονικής τάσεως για την εκδήλωση σεισμού, και ελέγχομε αν η πρόσφατη μικροσεισμική δραστηριότητα στο Νησιώτικο Σύμπλεγμα της Σαντορίνης δείχνει ότι τα ρήγματα Καμένης και Κολούμπο (στα οποία η σεισμική δραστηριότητα εστιάζεται) είναι ώριμα για ένα ισχυρότερο σεισμό. Στην ανάλυση αυτή χρησιμοποιούμε όλους τους σεισμούς ανεξαρτήτως μεγέθους από τον κατάλογο του Γεωδυναμικού Ινστιτούτου του Εθνικού Αστεροσκοπείου Αθηνών για το χρονικό διάστημα 1968- 2012, και μελετούμε συγκριτικά το Επίπεδο εμπιστοσύνης p της προσαρμογής της κατανομής των σεισμών με τις περιόδους των παλιρροϊκών συνιστωσών, για τις χρονικές περιόδους 1968-2010 και 2011-2012 (την χρονική περίοδο της αυξημένης μικροσεισμικής δραστηριότητας). Το συμπέρασμα είναι ότι υπάρχει ένδειξης αυξημένης ευαισθησίας για εκδήλωση σεισμών την διετία 2011-2012. Πρέπει να σημειωθεί ότι Γεωδαιτικές παρατηρήσεις δείχνουν αυξημένη παραμόρφωση στην περιοχή της Σαντορίνης το 2010-2011 που πιθανόν να οφείλεται σε άνοδο μάγματος και πιθανόν συνδέεται με την αύξηση της μικροσεισμικής δραστηριότητας. Εδώ θα πρέπει να τονίσουμε ότι το μέγεθος ενός πιθανού σεισμού εξαρτάται από την τεκτονική δομή, δυναμική και ιστορία του τόπου, και δεν είναι δυνατόν

προσδιορισθεί από την απόφανση επί της ωριμότητας του ρήγματος για την εκδήλωση σεισμού.

Λέξεις Κλειδιά: *Παλιρροϊκές επιδράσεις , Μικροσεισμικότητα Σαντορίνης, Αθροιστικό κατά φάση Ιστόγραμμα, Έλεγχος Σούστερ.*

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., 2009), (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, which indicate the existence of tidal effect, 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. (Fig. 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, 1573, 1650, 1707, 1866, 1925, 1939 and 1950 (Chouliaras et al., 2013; Georgalas, 1962 and Papadopoulos, 2011). 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).

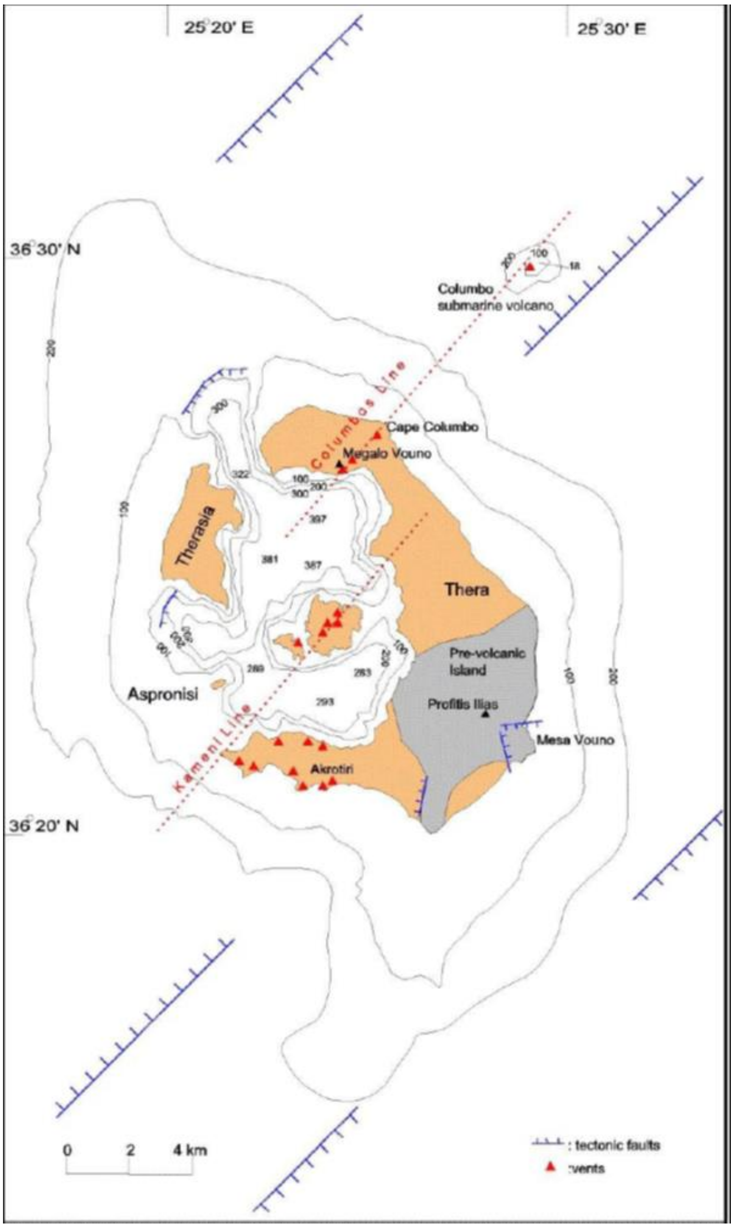

Fig. 1. Tectonic map of Santorini's volcanic island complex after (Heiken and McCoy, 1984; Quoted from Chouliaras et al., 2013).

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 its 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 stations was 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.

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. Finally, (Papazachos et al., 2012) in a multi parameter examination of the recent activity conclude that there is an excellent spatial and time correlation, with deformation accelerations signaling an increase of the earthquake activity, temperature fluctuations, etc., verifying the magmatic origin of the observed unrest. Fig. 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.

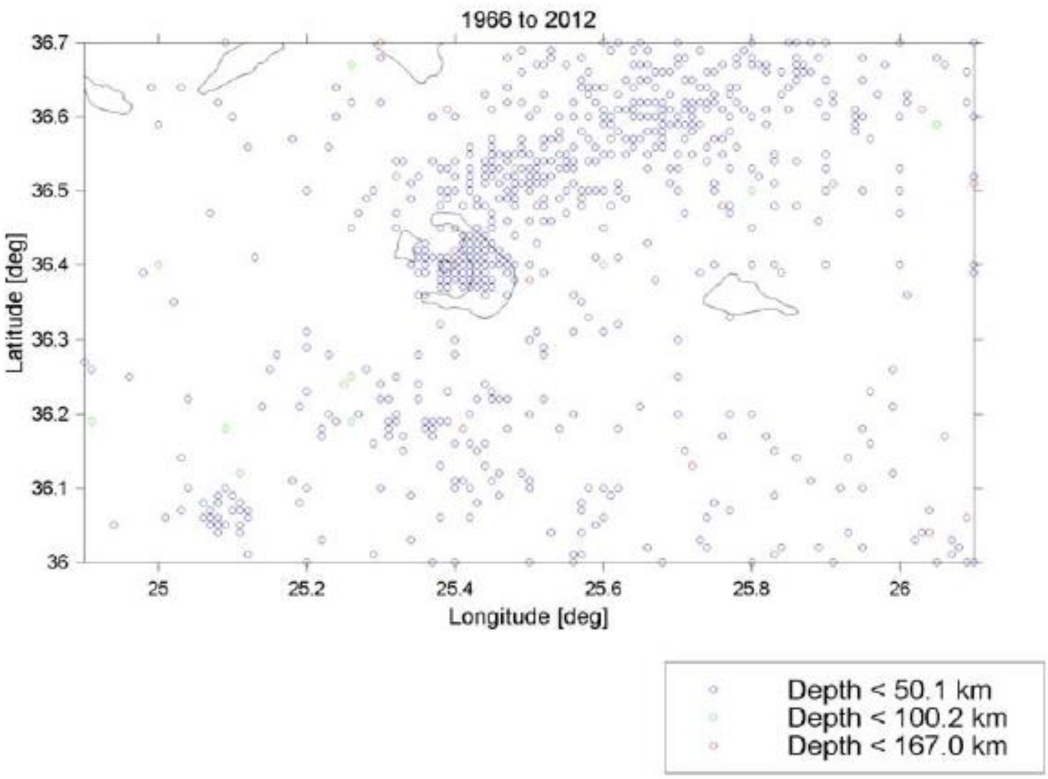

Fig. 2. Seismicity of the Santorini region from 1966 to 2012 from the catalogue of the National Observatory of Athens.

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 being 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 displays the evolution 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 $36^o\,10' \leq \varphi \leq 36^o\,40'$ and $25^o\,10' \leq \lambda \leq 28^o 40'$. The great majority of the shocks have $M_L < 3.5$.

3. Tidal effect

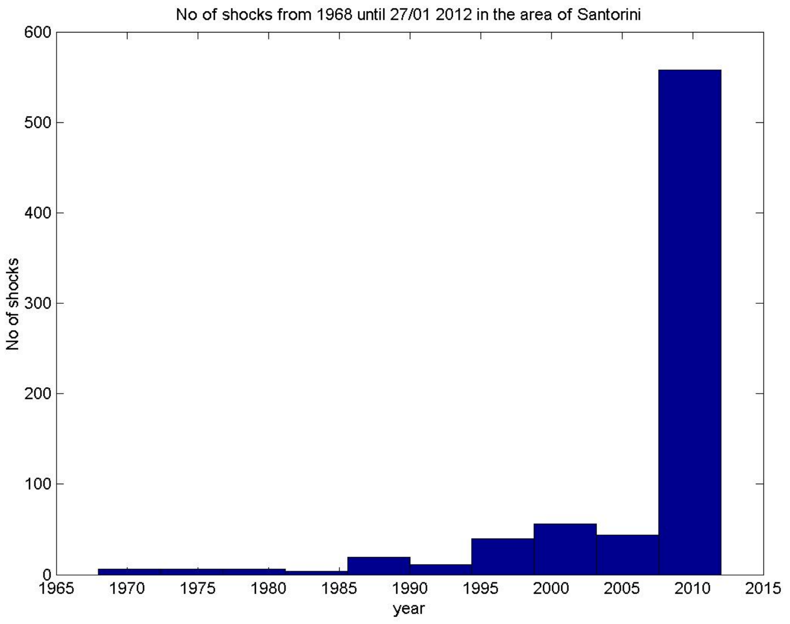

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Fig. 3. The seismicity in the area of Santorini

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 Zchau, 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.

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

Table 1. The strongest components of Earth tides in Thessaloniki

For the latitude of 38^o 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 Santorini Island complex.

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

Table 2. Ocean corrected parameters of O1 and M2 in 3 neighboring stations

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:

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

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,

T_d = the period of the particular tidal component in Julian Days.

int[…] = the integer part of the numbers into the brackets

We choose as epoch t_o, 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_o 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. We have to note that in our analysis important is the stress criticality in order to have a shock, no matters if this stress criticality is of primordial or secondary nature (ie. induced by a strong earthquake). The inclusion of all socks simply increases the statistical image of the distribution. This has been shown in (Arabelos et al., 2016) where the distribution of the whole shocks of the catalogue and the time distribution of the strong earthquakes (M > 4) was much the same (Fig.2.) of the above mentioned paper.

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; 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 ã$_{i.}$ The vectorial sum D is defined as:

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

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:

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

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 (Fig. 4.) and Semi-diurnal solar constituents S2 (Fig. 6.), (2) diurnal luni-solar constituent O1(Fig. 5.) and semi-diurnal lunar constituent (Fig.7.), (3) synodic month (i.e. period from new moon to new moon which is $29^d.530589$) (Fig. 8.) and anomalistic (i.e. time period between two successive passages of the moon from perigee which is $27^d.554551$) (Fig. 9.). It should be noted that hole histograms a cubic curve fitting by the program in order to facilitate the reader to acquire the filing of the way the distribution varies.

Figures 10 to 15 display the corresponding 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.

	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%

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

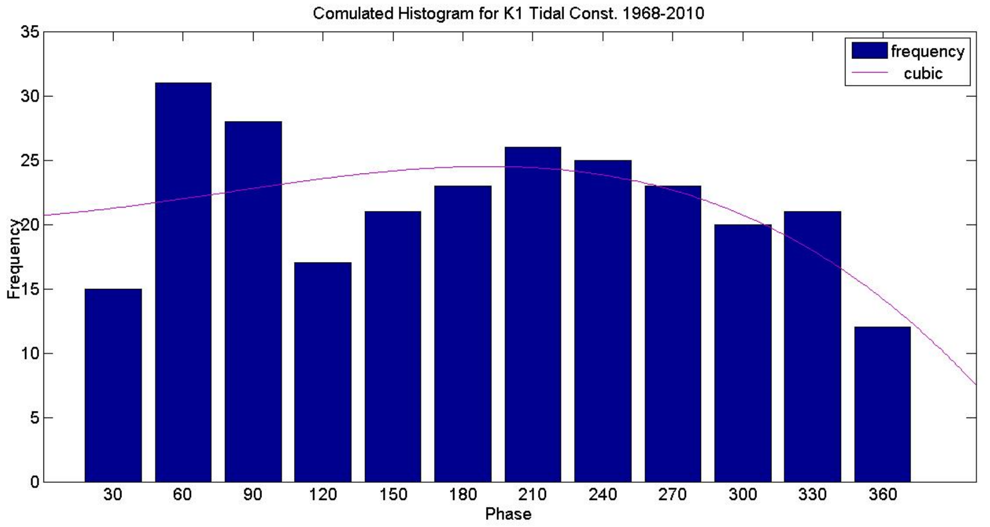

Fig. 4. Cumulative Histogram corresponding to the period of K1 diurnal luni-solar Tidal component for the 262 shocks of the time period 1968-2010

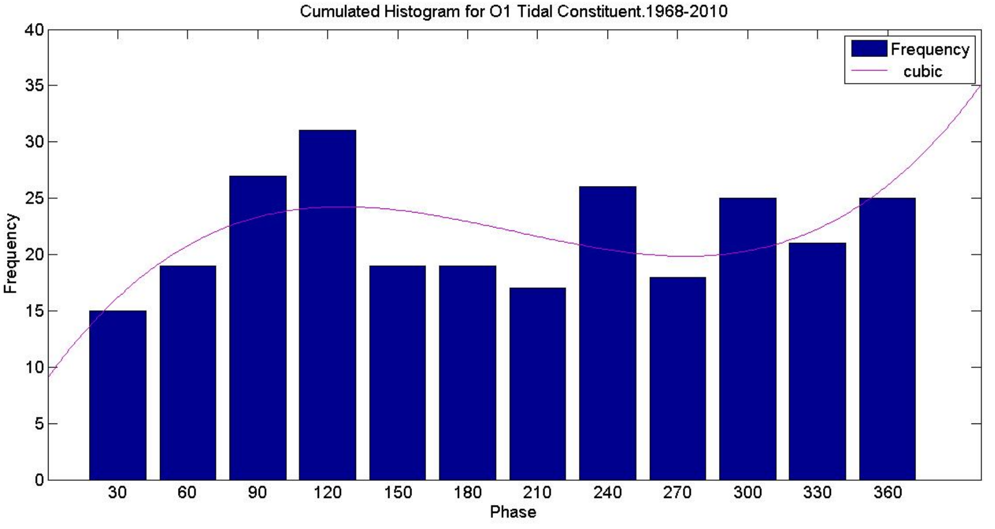

Fig. 5. Cumulative Histogram corresponding to the period of O1 diurnal lunar Tidal component for the 262 shocks of the time period 1968-2010

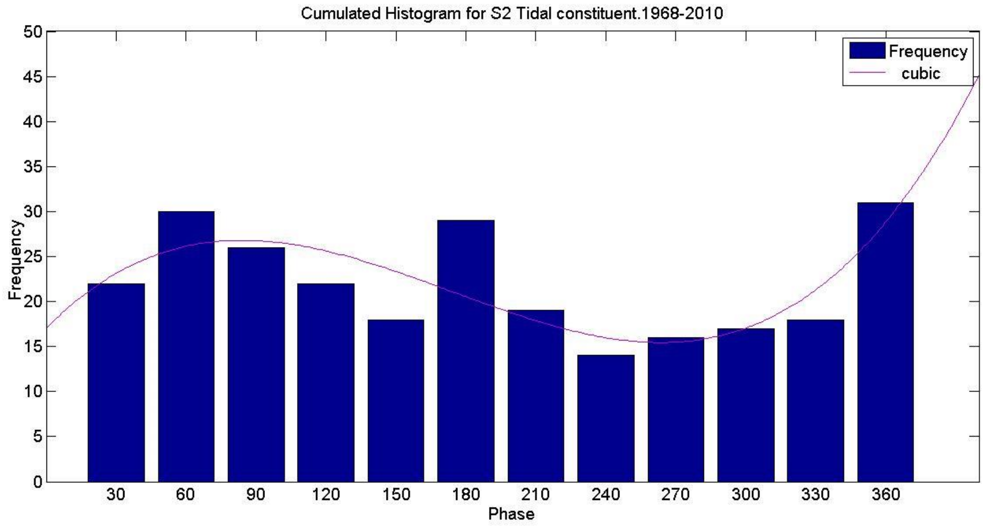

Fig. 6. Cumulative Histogram corresponding to the period of S2 semi-diurnal solar Tidal component for the 262 shocks of the time period 1968-2010

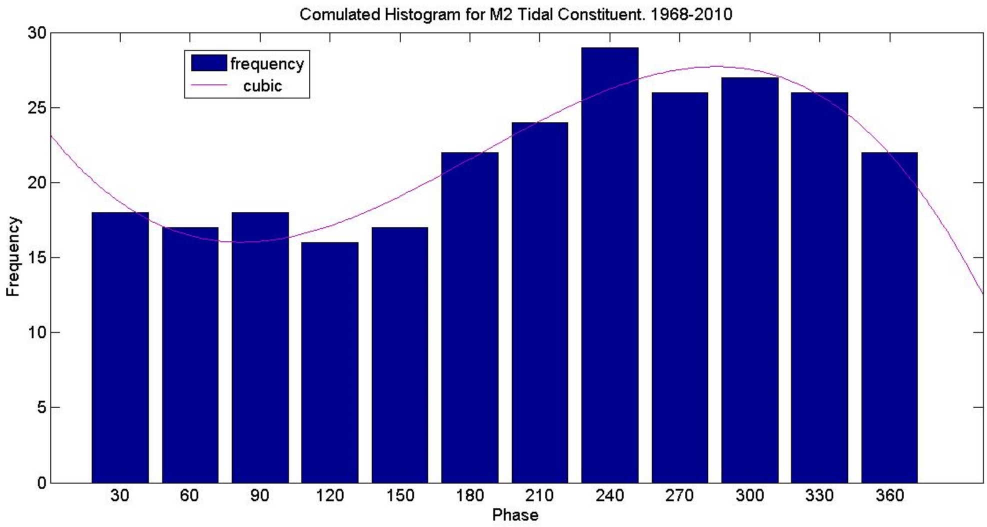

Fig. 7. Cumulative Histogram corresponding to the period of M2 semi-diurnal lunar Tidal component for the 262 shocks of the time period 1968-2010

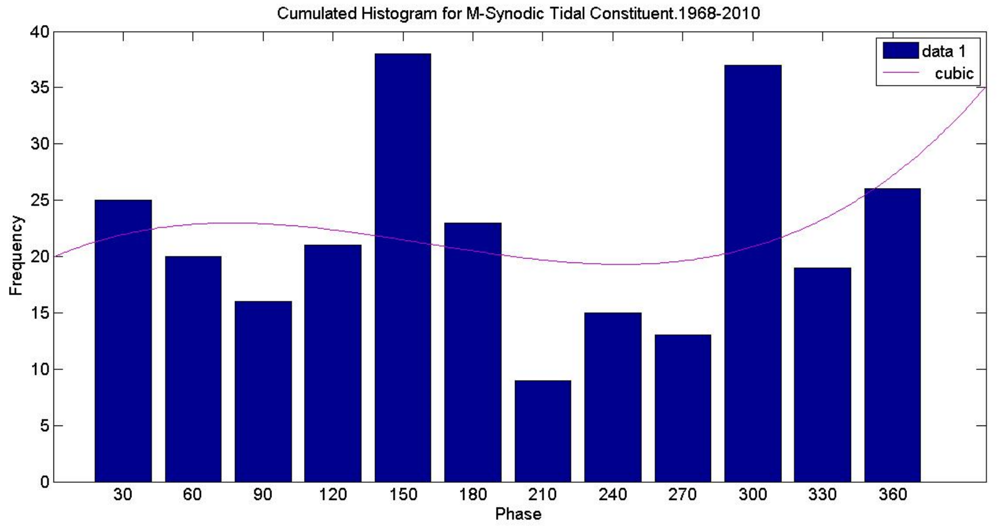

Fig. 8. Cumulative Histogram corresponding to the period of the monthly M-synodic lunar Tidal component for the 262 shocks of the time period 1968-2010

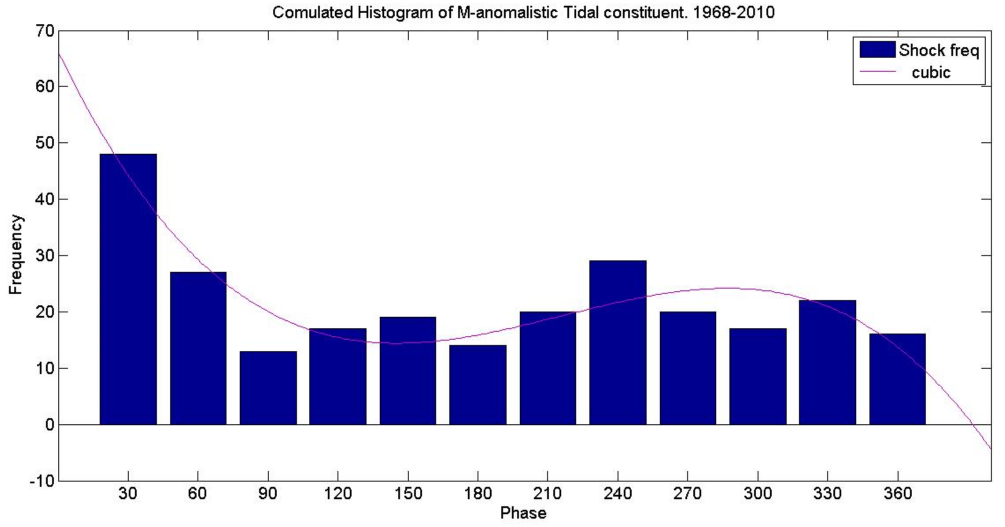

Fig. 9. Cumulative Histogram corresponding to the period of the monthly M-anomalistic lunar Tidal component for the 262 shocks of the time period 1968-2010

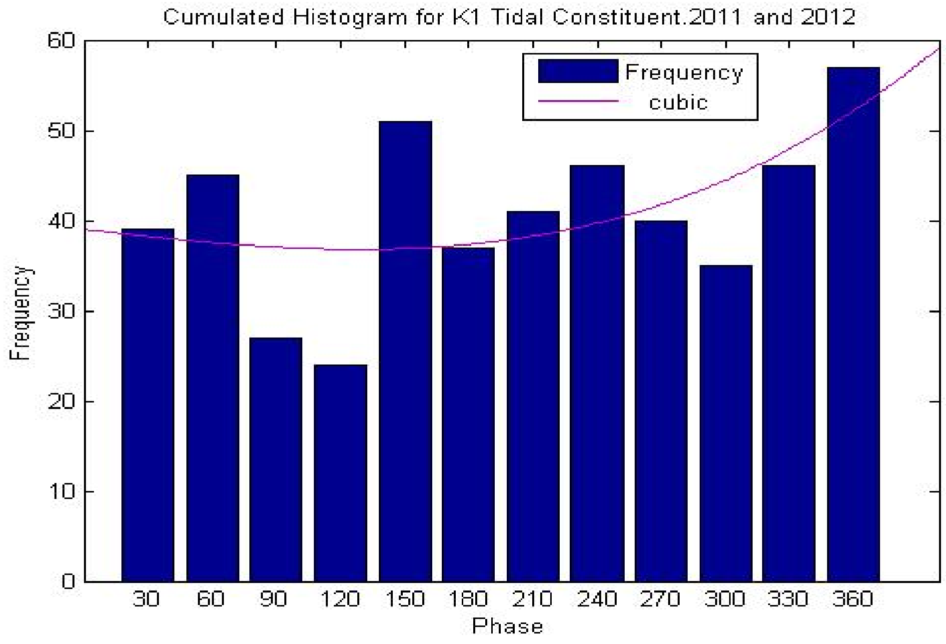

Fig.10. Cumulative Histogram corresponding to the period of K1 diurnal luni-solar Tidal component for the 488 shocks of the time period 2011-January, 2012

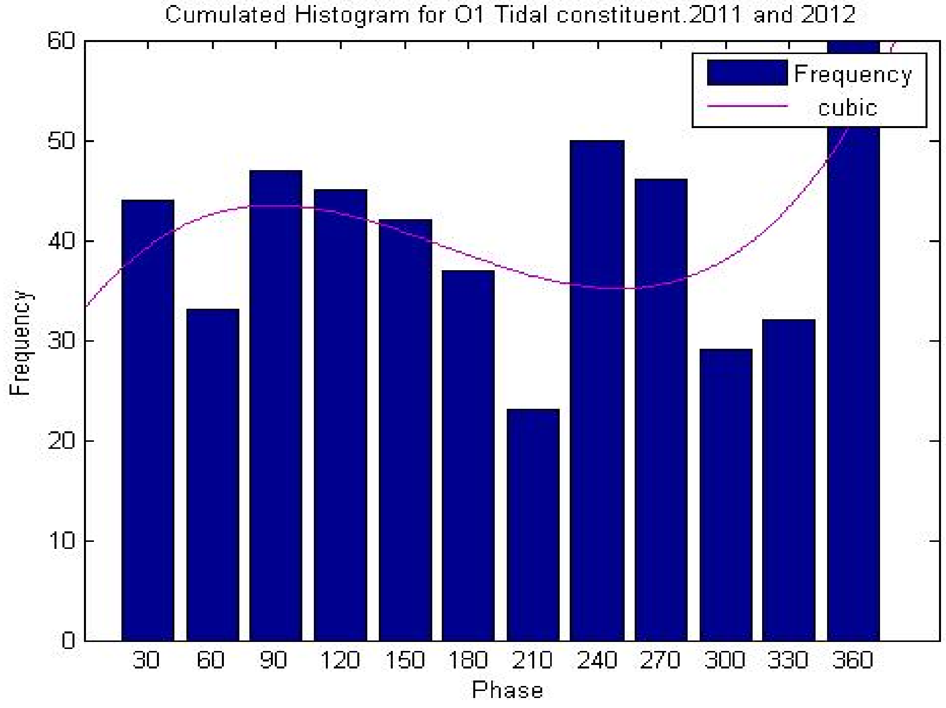

Fig. 11. Cumulative Histogram corresponding to the period of O1 diurnal luni-solar Tidal component for the 488 shocks of the time period 2011-January, 2012

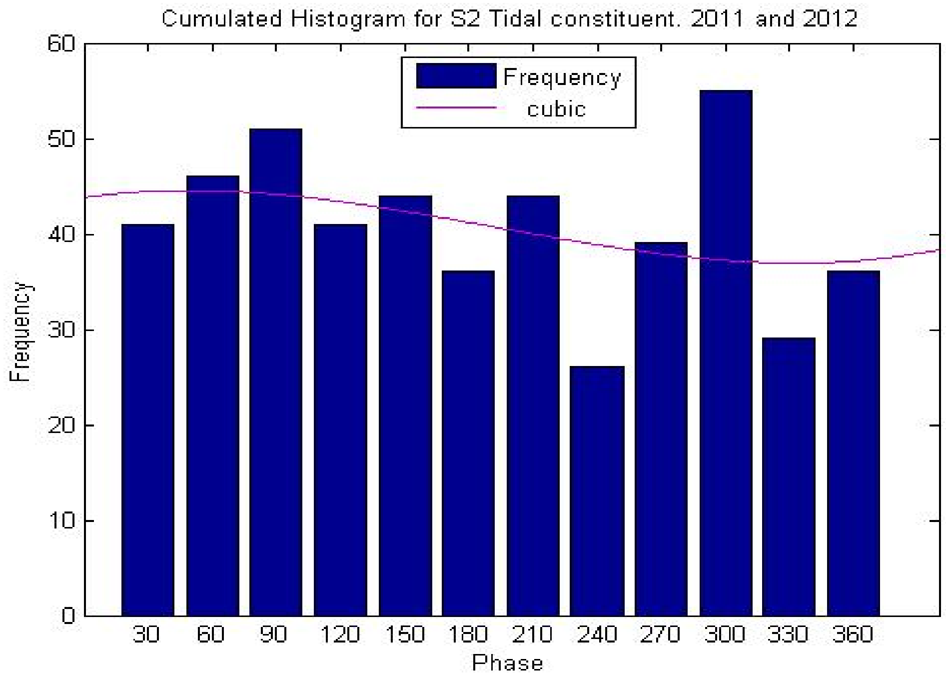

Fig. 12. Cumulative Histogram corresponding to the period of S2 semi-diurnal solar Tidal component for the 488 shocks of the time period 2011-January, 2012

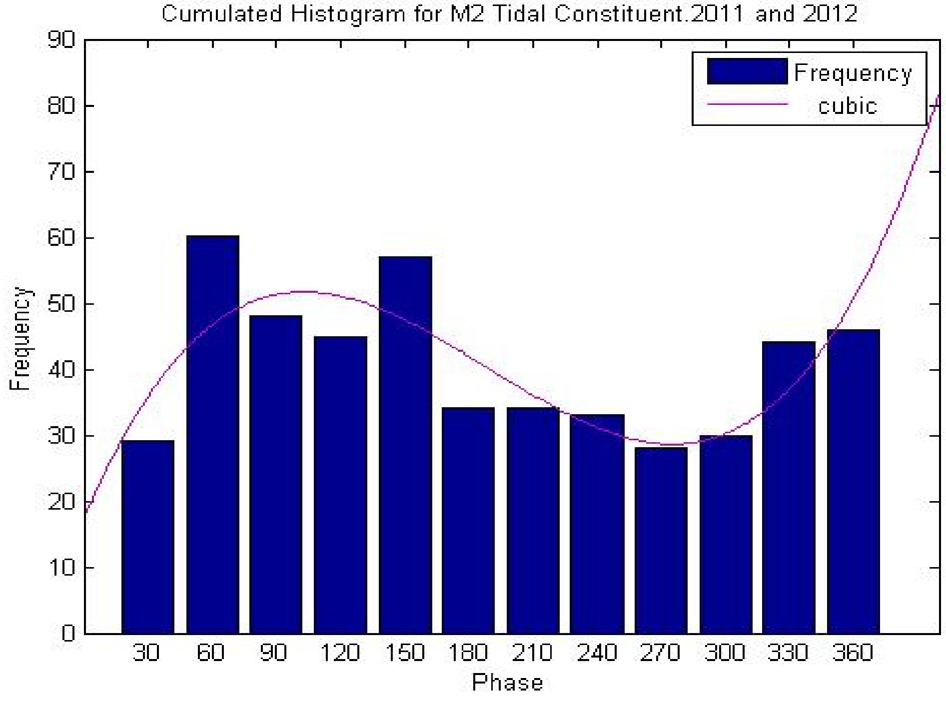

Fig. 13. Cumulative Histogram corresponding to the period of M2 semi-diurnal lunar Tidal component for the 488 shocks of the time period 2011-January, 2012

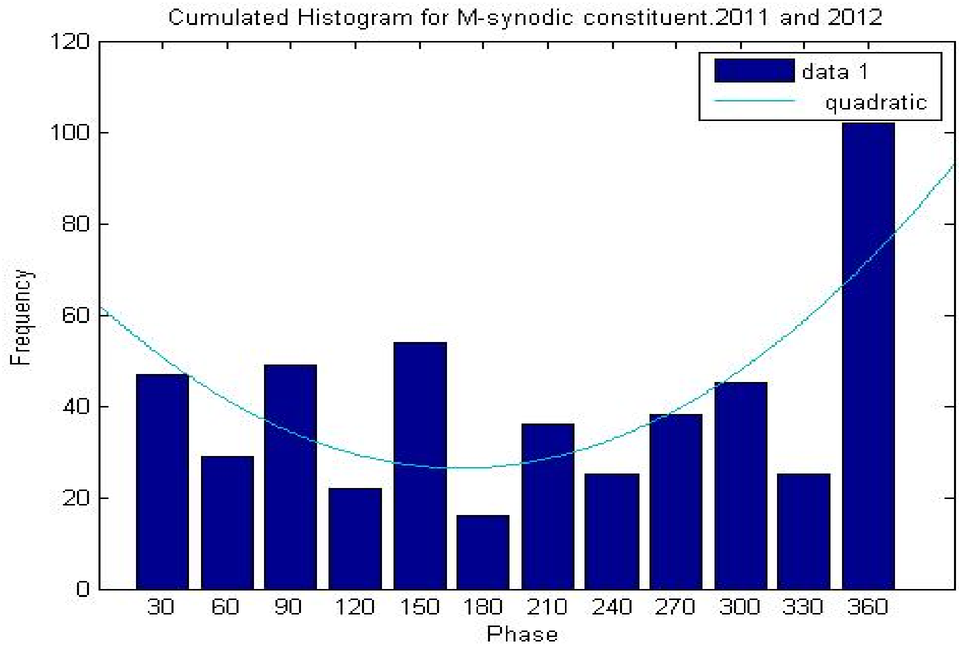

Fig. 14. Cumulative Histogram corresponding to the period of the monthly M-synodic lunar Tidal component for the 488 shocks of the time period 2011-January, 2012

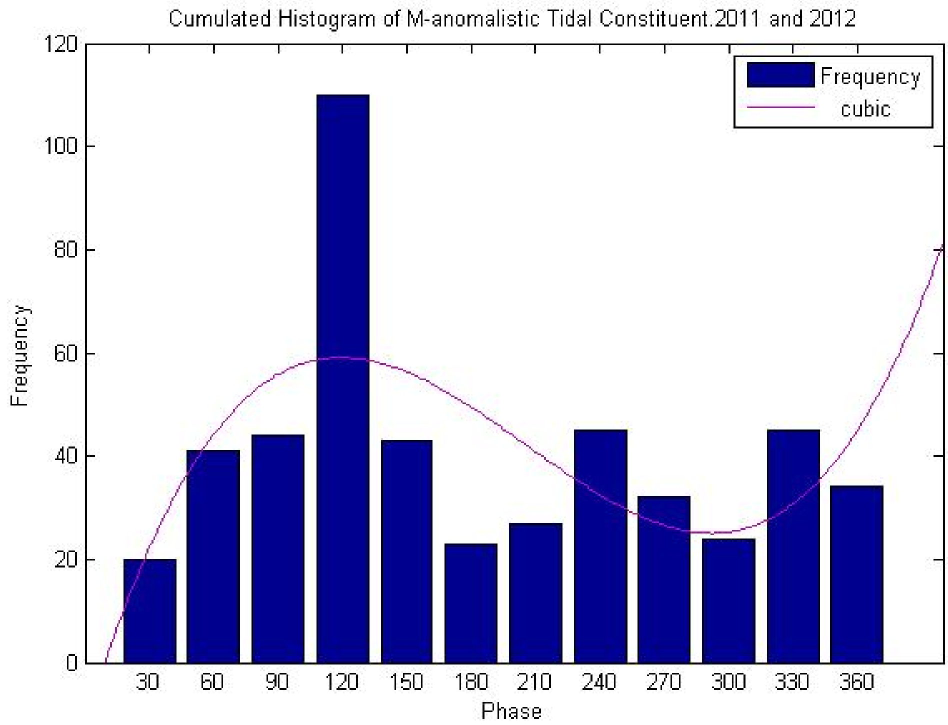

Fig.15. Cumulative Histogram corresponding to the period of the monthly M-anomalistic lunar Tidal component for the 488 shocks of the time period 2011-January, 2012

From the 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**.** We note that our results are in accordance with the results of (Dionysiou et al., 1993), and 1994 for the monthly lunar component. In particular figure 14 of our paper agree with figure 1 of (Dionysiou et al., 1993), with both presenting the earthquake distribution according to the monthly lunar tidal period. Furthermore, our figure 14 agree with the earthquake distribution to the monthly lunar tidal period for the areas of Ionian Islands (Fig. 2), Crete (Fig. 4) and Thessaloniki (Fig.10.) of (Dionysiou et al., 1994) paper, while they present a phase difference with earthquake distribution for the area of Peloponnese and Dodecanese (Fig.3 and 5). This may be due to the fault directions of the different areas. 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 earthquake occurrence for the time period 2011-2012 when an increase in the micro-seismic activity appeared in the area. It should be noticed that from geodetic data it is reported increased deformation in the Santorini area between 2010-2011, so the mechanism of earthquake occurrence may be also related to the cause of deformation i.e. magma ascent (Lagios E. et al., 2013).

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