Evidence for tidal triggering on the shallow earthquakes of the seismic area of Mygdonia Basin, North Greece

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Abstract

In this paper we investigate the tidal triggering evidence 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 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. The result of our analysis indicate that the monthly variations 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 and semidiurnal lunar and solar tidal (K1, O1, M2, S2) variations. This result is in favor of a tidal triggering process on earthquakes when the stress in the focal area is near the critical level.

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 occured. Recent

analyses have point to this fact. In these papers not only the tidal triggering for global (Tanaka et al., 2002) and local (Tanaka et al., 2006; Cadicheanu, 2007) 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. On the other hand Mygdonia Basin belong to the Servomacedonian Massif and is the locus of the catastrophic earthquake of $M_w = 6.5$ which occur on June 20, 1978. The area is under thorough study ever since from geodetic (see for instance Contadakis and Leventakis 1992, Asteriadis and Schwan 202) seismic, tectonic and geological point of view. This important work was published in a great number of significant papers which are difficult to be sited here. Thus we referred ourselves to the resent paper (Vamvakaris et al. 2006) and to the references therein.

In this paper we investigate the tidal triggering evidence on the shallow earthquakes of the seismic area of Mygdonia basin, using the Hi(stogram)Cum(ulation) method (Cadicheanu et al., 2007).

2. The data

The set of data consist of a series of 471 earthquakes with local magnitude of M > 2.5 occurred within the time interval from 1964 up to 2008 in an area of 1 square degree bounded by $40^o \leq \varphi \leq 41^o$ and $23^o \leq \lambda \leq 24^o$. The magnitudes were quoted from the Catalogue of Geodynamic Institute of the National Observatory of Athens. Figure 1, quoted from Vamvakaris et al., (2006) displays the area under study. In this picture the main faulting zones in the area together with the maximum extensional principal stress directions of the different sub-zones as they were given by a number of researchers (referred in the paper of Vamvakaris et al., (2006).

As it is seen in this figure the whole area is dominated by a N-S extensional stress and comprises a 70 km long E-W striking fault, the lake Volvi fault which is branching in three SE-NW striking faults with gradually increasing Azimouth. Starting from the easternmost branching, the 30 km Asyros-Scolari faults which is responsible for the 6.5 earthquake of 20, June of 1978 (7a in the figure), the 20 km long Liti-Agios Vasilios fault (7b in the figure) and the Asvestochori-Polichni fault (8 in the figure). Finally the Anthemountas faulting zone is located in the southern part of the area which is 40km long and is an E-W toESE-WNW strike. Figure 2 displays the space distribution of the 471 earthquakes. It is seen that the depths of the focuses of all the shocks are less than 50km and that most of them are situated along the main lake Volvi and Anthemountas fault. A number of them are situated along the North Aegean fault and quite a few are situated along the fault of Asyros-Scholari. Most of them belong to the seismic activity of 20 of June, 1978 and are the strongest of our sample. The eath-tides are due to the combined effect of the

Luni-Solar attraction upon the earth and are very well known. A detailed account on their theory and their determination is given by Melchior (1978). So they may be computed theoretically. However for the area of Thessaloniki the constituent of earth tides were determined gravimetrically by Arabelos (2002). Table 1 displays the strongest components of the earth-tides for Thessaloniki.
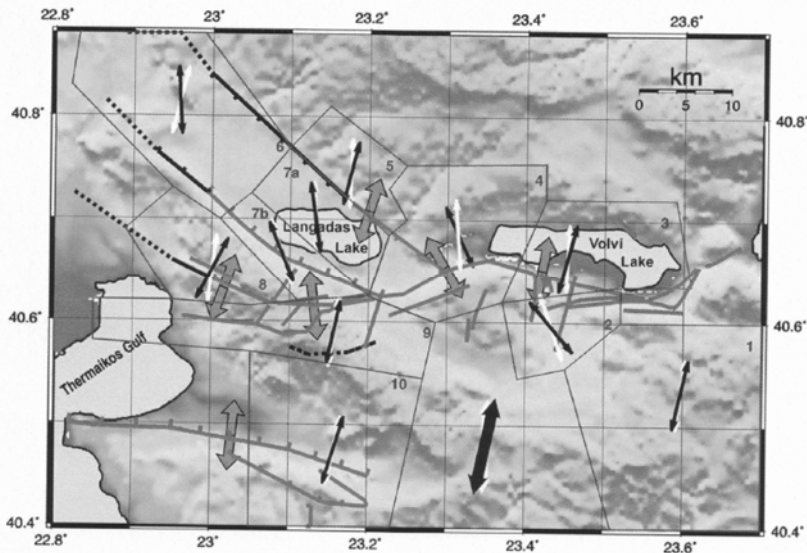
Figure 1. *The main faults of the Mygdonia Basin and the maximum extensional principal direction for the different zones (Vamvakaris et al., 2006)*

Although the monthly lunar tidal component is much weaker than the listed components we consider in addition the possible effect of this component by means of the lunar synodic month (i.e. period from new moon to new moon which is $29^d.530589$).

Table 1. *The strongest components of Earth tides in Thessaloniki*

Symbol	Period T (min)	Amplitude (nms^{-2})	Origin
K1	1436	487.840	Lunar & Solar declination wave
O1	1549	352.816	Lunar principal wave
M2	745	510.350	Lunar principal wave
S2	720	238.393	Solar principal wave

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 components are very well known and quite accurately predictable in the local coordination system, we assign for each shock a unique phase angle within the period of variation of a particular a tidal component, for which the effect of earthquake triggering is under investigation, with the simple relation:

$$phi_i = \left(\frac{(t_i - t_o)}{T_d} - \text{integer} \frac{(t_i - t_o)}{T_d} \right) \times 360 \qquad (1)$$

where ph_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 ,
t_o = the epoch we have chosen in Modified Julian Days,
T_d = the period of the particular tidal component in Julian Days.
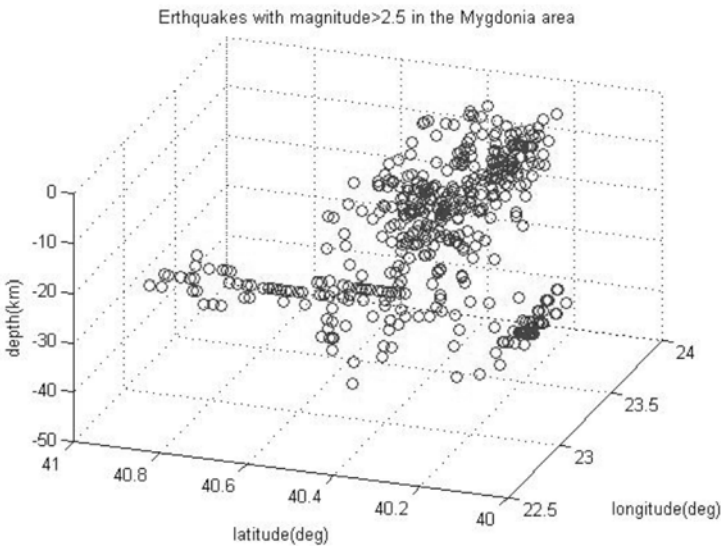
Figure 2. The space distribution of the 471 earthquakes

We choose as the epoch t_o, i.e. the reference date, the time of the upper culmination in Thessaloniki of the new moon of 7th January 1989 which has Modified Julian Date = 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). We separate the whole period in 12 bins of 30° and stack every event accord-

M. E. Contadakis, D. N. Arabelos, S. Spatalas

ing to its phase angle in the proper bin. Thus we construct a Cumulating Histogram of earthquake events for the tidal period under study. For example Figure 3 and Figure 4 display the Cumulating Histograms for all the events in the area (471) corresponding to the tidal frequencies K1 and M2. It appears that M2 affect the earthquake occurrence with a phase angle 0 degree while the K1 component affects the earthquake occurrence with a phase angle of 180 degrees. Are these decisions truth?
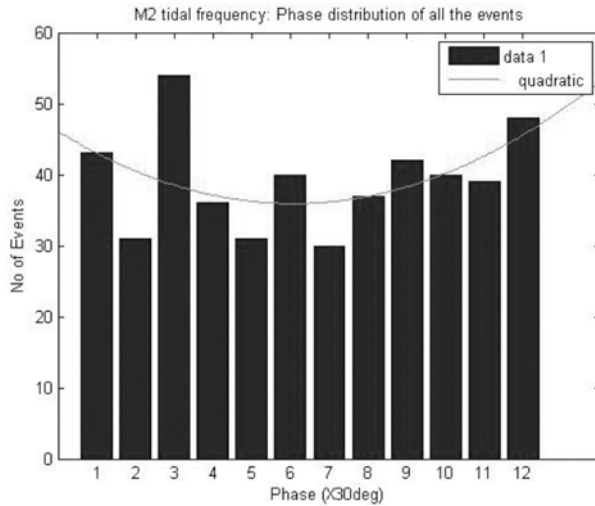
Figure 3. *Cumulating Histogram corresponding to M2 period of all the events*
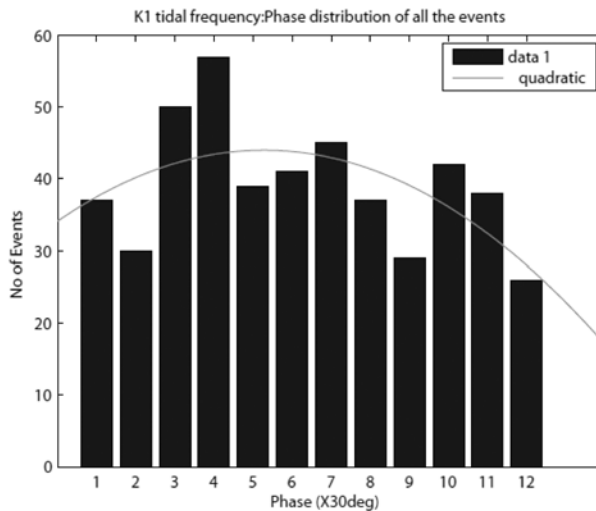
Figure 4. *Cumulating Histogram corresponding to K1 period of all the events*

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:

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

where N is the number of earthquakes.

When the α_i is distributed randomly, the probability that the length of a vectorial sum is equal or larger than D is given by the equation:

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

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 means that the smaller the p is the greater the confidence level of the results of the Cumulating Histograms is. In the above mentioned examples of Figure 3 and Figure 4 The confidence level for the K1 tidal constituent is a triggering mechanism of earthquakes in the area is very high i.e. $p(K1) = 2.49\%$ while for the M2 constituent is low i.e. $p(M2) = 24.19\%$.

4. Results

Figures 5, 6 and 7 display the Cumulating Histogram for all the 471 earthquakes with local magnitudes > 2.5 which correspond to the tidal frequencies O1,S2 and the lunar synodic month (i.e. period from new moon to new moon which is $29^d.530589$) and Table 2 the corresponding confidence levels.

Table 2. *The confidence level of earthquake-earth tide correlation for all earth-quakes 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%

It is obvious that the confidence level for the decision that Luni-Solar diurnal K1 and the Lunar synodic month components to be earthquake triggering mechanism is very high. Less probable are the effect of the Lunar diurnal O1 and Lunar

semidiurnal M2 components and quit improbable the effect of the Solar semidiurnal component S2. The phase lags are 0° for O1 and M2 and M semi-synodic and 180° for K1 and M-synodic and components. In the Cumulating Histogram (Figure 7) of the M-Synodic component the M semi-synodic component with 0° phase lag is clearly apparent.
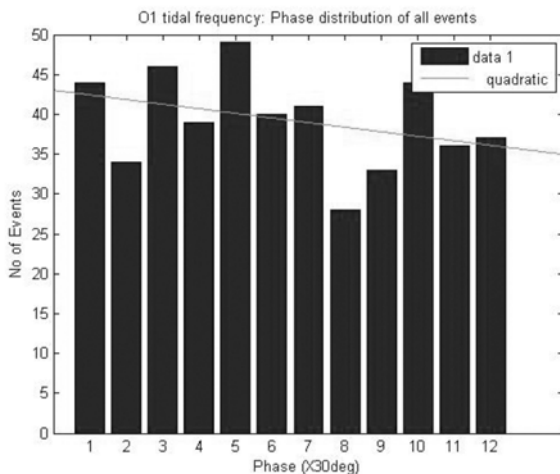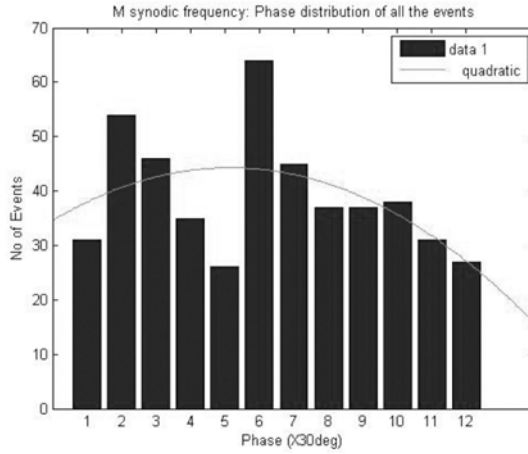

**Figure 5.** *Cumulating Histogram corresponding to O1 period of all the events*
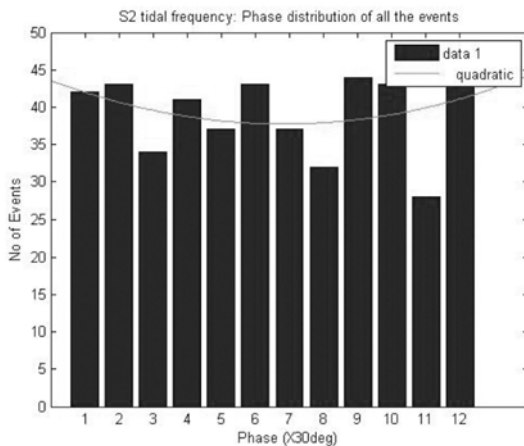
Figure 6. *Cumulating Histogram corresponding to S2 period of all the events*

From the Figure 8 it is evident that the probability p does not remain stable but it varies and comparing with Figure 9 we realize that it become smaller before and during earthquakes with magnitude greater than 4.5. This fact is in favor of the action of earth tides as a triggering mechanism for earthquake occurrence. It must be stressed out that the generation of an earthquake is a multi-parameter phenome-

Figure 7. *Cumulating Histogram corresponding to the M-Synodic month period of all the events*
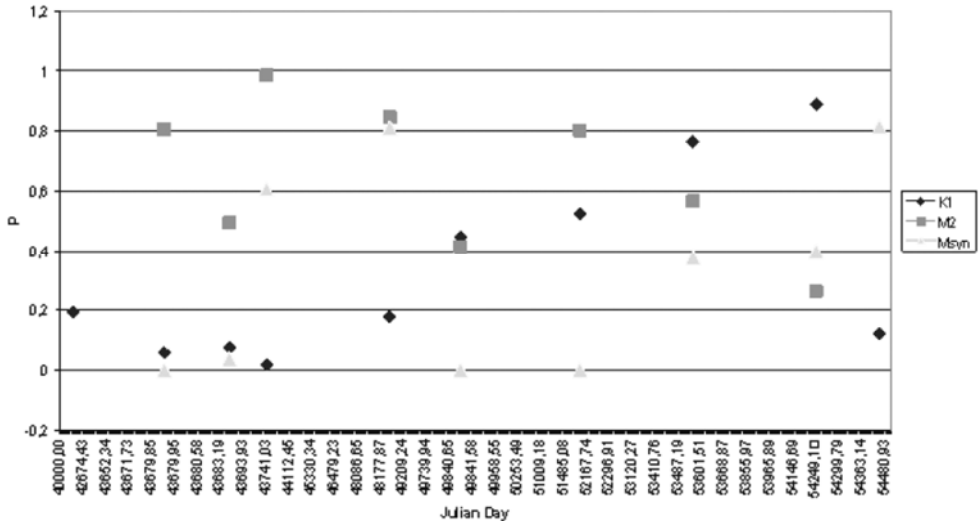
Figure 8. *Confidence level for the correlation between earth-tides and earthquake occurrence*

non. It must be expected that the triggering effect maybe different in different faults and tectonic condition. We have seen that Mygdonian basin has a complicated structure with three main faults to dominate (see Figure 1). In Figure 2 we realize that all the earthquakes focuses are found either accurately concentrated along the Assyros and the North Aegaen faults or are spread along and around the main fault of Volvi and Anthemountas. Thus the earthquakes of the two faults of Assyros and Noth Aegean are events of those two faults while the earthquakes

M. E. Contadakis, D. N. Arabelos, S. Spatalas

along the Volvi and Anthemountas faults are events of the main fault of Volvi as well as events of the Anthemountas and the many smaller faults of the area (Vamvakaris et al. 2006). Table 3 displays the probability p for the compliance of earthquakes phase distribution and the tidal frequency and figures 10, 11 and 12 displays, as an example the corresponding to the three faults Cumulating Histograms for the tidal frequency K1.

Table 3. *The confidence level for the faults Assyros, Volvi and North Aegean*

| Faults	$p(K1)$	$p(M2)$	$p(\text{M-synodic})$
Assyros	0%	0%	0.07%
Volvi	28.21%	34.08%	9.48%
North Aegean	0%	0%	0%
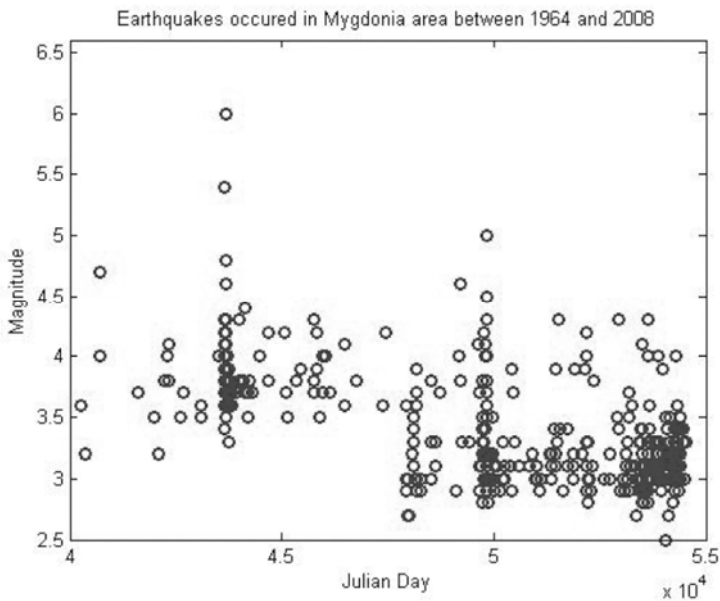
Figure 9. *Earthquakes with local magnitude >2.5 occurred in Mygdonia area in the time interval from 1964 up to 2008*

It is very interesting that the probability for Assyros, North Aegean and Volvi Assyros fault are progressively higher as we proceed from Assyros to Nort Aegean and then to Volvi – Anthemountas area. Reaching to the certainty for Assyros fault which is the locus of the catastrophic earthquake of magnitude 6.5 in 1978, become higher for the concentrated seismicity in the fault of North Aegean, where the maximum magnitude was 4.5, and even higher for the seismicity in the area of
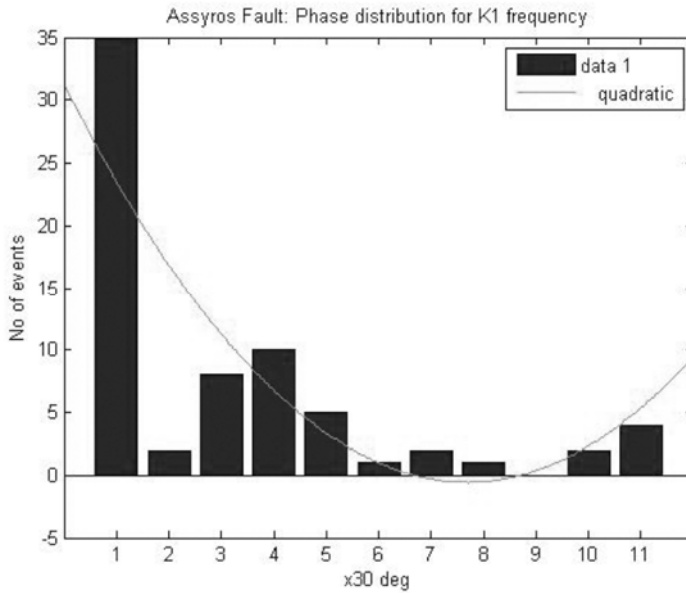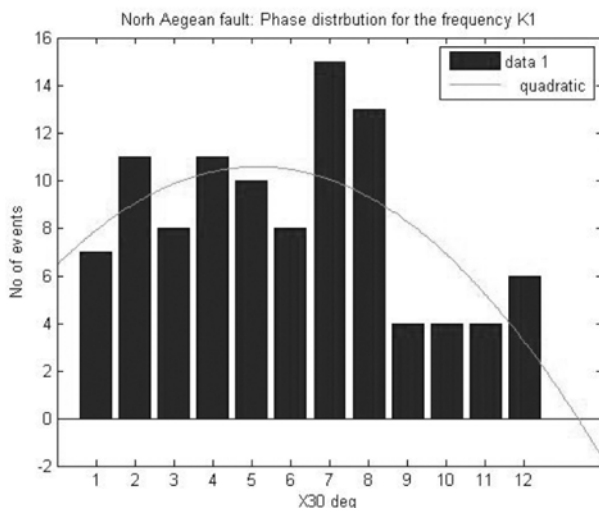
Figure 10. *Cumulating Histogram corresponding to K1 period for the Assyros Fault*
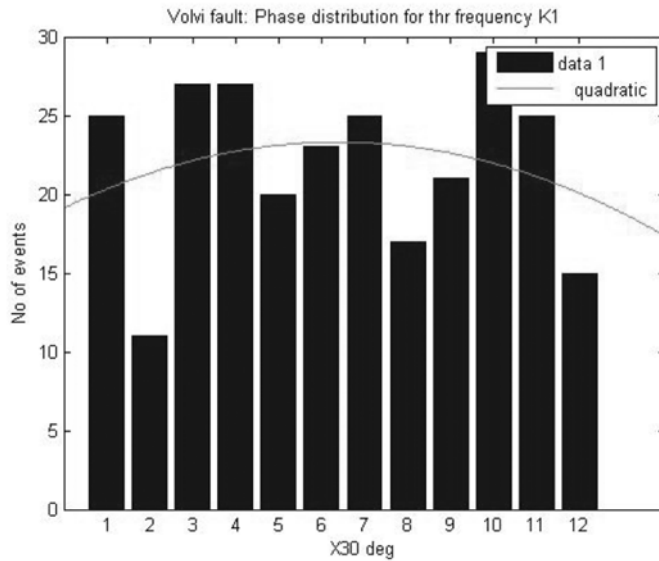
Figure 11. *umulating Histogram corresponding to K1 period for the Volvi Anthemountas Faults*

Volvi – Anthemountas.That is the triggering mechanism of earth-tides is declared with high confidence level for a seismic activity which is concentrated in a particular fault while the confidence level for the faults of the Volvi area renders a degree

M. E. Contadakis, D. N. Arabelos, S. Spatalas

of uncertainty to the correlation of earth tides and earthquake occurrence. It should be noted that the confidence level also become larger as the magnitude of the main shock of the seismic activity is larger.

Figure 12. *Cumulating Histogram corresponding to K1 period for the North Aegean Fault*

5. Conclusion

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.

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