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Evidence for tidal triggering for the earthquakes of the Ionian geological zone, Greece

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ABSTRACT

We here investigate the evidence for tidal triggering of the earthquakes of the seismic area of the Ionian geological zone in Greece, using the cumulative histogram method that was introduced recently by Cadicheanu et al. (*Nat. Hazards Earth Syst. Sci.*, 2007, 7, 733-740). We analyzed the series of earthquakes that occurred in the area bounded by $19^{\circ}\text{E} \leq \varphi \leq 22^{\circ}\text{E}$ and $36^{\circ}\text{N} \leq \lambda \leq 40^{\circ}\text{N}$ from 1964 to 2006. Over this time, there were 19,916 shallow and intermediate depth earthquakes with magnitudes ranging between 2.5 and 6.2. The great majority of these earthquakes, including those with $M \geq 5.0$, were shallow. The results of our analysis indicate that the monthly variations in the frequencies of the earthquake occurrence are in agreement with the period of the tidal lunar monthly variations. The same is true for the corresponding daily variations of the frequencies of earthquake occurrence and the diurnal lunisolar (K1) and semidiurnal lunar (M2) tidal variations. In addition, the confidence levels for the identification of such periodical agreement between the frequency of earthquake occurrence and the tidal periods varies according to the seismic activity; i.e. the higher confidence levels correspond to the periods with stronger seismic activity. These results are in favor of a tidal triggering process of earthquakes when the stress in the focal area is near the critical level.

1. Introduction

The question of possible connections between the Earth tides and earthquake occurrence is a very old one, and it has been tackled in a number of studies since more than 100 years ago. The results have been contradictory, with most of the outcomes not able to prove the possibility of any correlations between earthquake occurrence and the Earth tides [see for instance: Schuster 1897, Knopoff 1964, Simpson 1967, Shudde and Barr 1977, Rydelek et al. 1992, Vidale et al. 1998, and many others]. On the other hand, the outcomes of a considerable number of relatively recent studies have been 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 variations, the tidal stress rate is comparable or much higher than the tectonic stress accumulation in a fault. Thus, unless the earthquake event is the result of sudden stress accumulation on a fault [Vidale et al. 1998], it has to be concluded that the Earth tides can act as a triggering mechanism for a mature fault; i.e. a fault for which the stress accumulation is approaching the critical point for rupture occurrence. Recent analyses indicate that this is so [Tanaka et al. 2002, 2006, Cadicheanu 2007]. In these previous studies, not only was tidal triggering at the global [Tanaka et al. 2002] and local [Tanaka et al. 2006, Cadicheanu 2007] scales found, but in addition, in the last two studies, an increase in the reliability of the tidal-earthquake occurrence correlation was shown to be a precursory phenomenon for strong earthquakes.

In the present study, we statistically analyzed a sample of 19,916 shallow- and intermediate-depth earthquakes with magnitudes ranging from 2.5 to 6.2 that occurred in the Ionian Sea, with the purpose of investigating potential tidal triggering effects on earthquake occurrence.

2. The data

The dataset consists of a series of 19,916 earthquakes with local magnitude of $M > 2.5$ that occurred within the time interval from January 1964 to December 2006, in an area bounded by $19^{\circ}\text{E} \leq \varphi \leq 22^{\circ}\text{E}$ and $36^{\circ}\text{N} \leq \lambda \leq 40^{\circ}\text{N}$. The magnitudes were obtained from the Catalogue of the Geodynamic Institute of the National Observatory of Athens, Greece (<http://www.gein.noa.gr/services/cat.html>) Figure 1 is reproduced from Papazachos et al. [1998] and it shows the main morphotectonic characteristics, while Figure 2 is reproduced from Papazachos et al. [1999] and it shows the main faulting zones and faulting types in this area of Greece. The area under study lies along the western part of the Hellenic Trench. The faults in the area were directed parallel to the Hellenic Trench and represent thrust

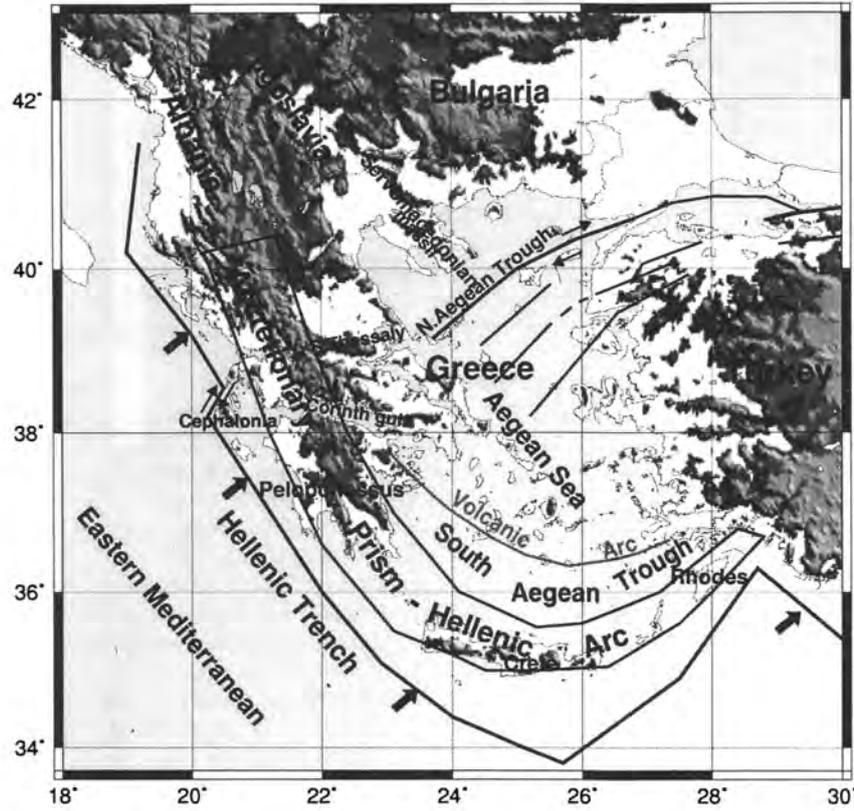


Figure 1. The main morphotectonic characteristics of the broader area of Greece [after Papazacos et al. 1998].

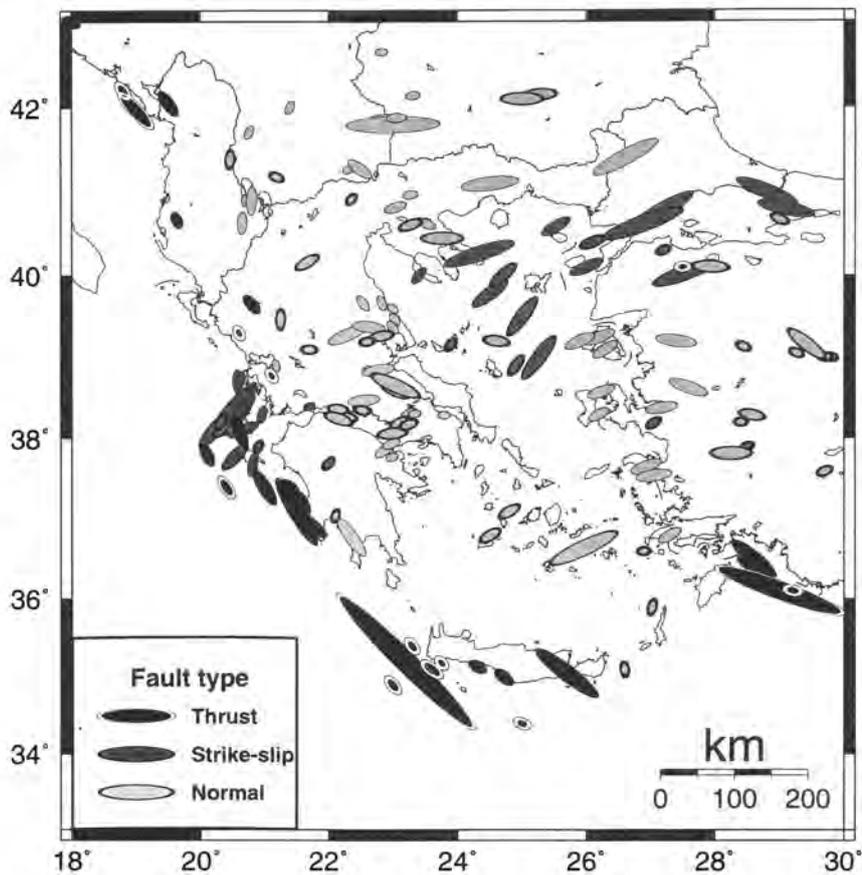


Figure 2. The rupture zones in the area of Greece [after Papazachos et al. 1999].

faulting, whereas north of Cephalonia, there is a zone of faults with dextral strike-slip faulting.

Figure 3 shows the space distribution of 278 earthquakes with magnitudes ≥ 4.5 that occurred between January 1964 and December 2006. It can be seen that the focal depths of all of these shocks were < 50 km, and that most of them were situated along the Hellenic Trench.

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 effects of these celestial bodies and the reactions of the solid Earth (like an elastic body) to the tidal forces. The ocean tides follow the law of hydrodynamics, with strong disturbances affecting

Symbol	Period T (min)	Signal/ noise	Amplitude (nms^{-2})	Origin
K1	1436	525.1	487.840	Lunar and 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 the Earth tides in Thessaloniki.

adjacent seas, so that the ocean-loading effects have to be taken into account. Earth tides are discussed extensively in Melchior [1983], Baker [1984], Wilhelm et al. [1997], and Torge [2001].

The components of the Earth tides for the area of Thessaloniki were determined gravimetrically by Arabelos [2002]. Table 1 shows the strongest components of the Earth tides for Thessaloniki. Although the amplitude of the lunar tidal component M1 is 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 effects of this component by means of the lunar synodic month (i.e. the period from new moon to new moon, which is 29.530589 days) and the lunar anomalistic month (i.e. the time period between two successive passes of the moon from perigee, which is 27.554551 days).

Table 2 shows the actual ocean corrected tidal parameters of O1 and M2 for Sofia, Instabul and Thessaloniki, and the corresponding values from the model of Wahr-Dehant-Zschau [Dehant 1987, Dehant and Zchau 1989], which expresses the dependency of the tidal parameters on latitude. As is shown from Table 2, the

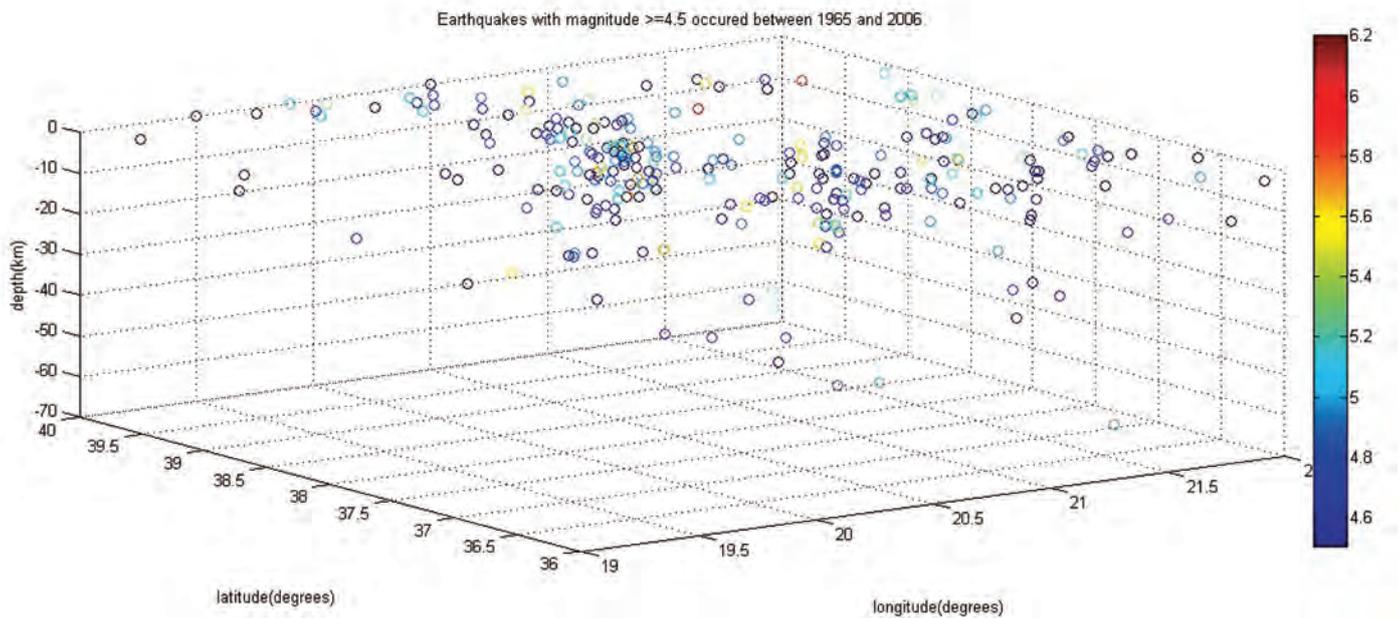


Figure 3. The space distribution of 278 earthquakes with magnitude ≥ 4.5 that occurred in the period from January 1964 to December 2006.

Parameter	Sofia (latitude 42.71°)		Istanbul (latitude 41.07°)		Thessaloniki (latitude 40.63°)	
	Amplitude factor	Phase degree	Amplitude factor	Phase degree	Amplitude nm factor	Phase degree
O1	-1.1493±0.0014	-0.1590±0.60	1.1564±0.0035	-0.281±0.174	1.1536±0.003	-0.201±0.151
Model	1.1540	-0.2	1.1542	-0.2	1.1543	-0.2
M2	1.1541±0.0005	-0.207±0.026	1.1587±0.0011	-0.039±0.026	1.1639±0.001	-0.195±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 the three neighboring stations.

amplitude factors of the principal O1 and M2 tidal components agree with the model, within their errors of estimation. For the latitude of 38°N, which is the mean latitude of the area under consideration, the extrapolated model amplitude factors for O1 and M2 are 1.1545 and 1.1587, respectively. Consequently, the amplitudes of O1 and M2 might be changed to about 354 nms⁻² and 501 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.

3. Method of analysis

To investigate the possible correlations between Earth tides and earthquake occurrence, we determined the time of occurrence of each earthquake in relation to the sinusoidal variation of the Earth tides, and investigated any possible correlations of the time distributions of these earthquake events with the Earth tide variations. Since the periods of the Earth tides component are very well known and relatively

accurately predictable in the local coordination system, we assigned 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 relationship:

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

where ϕ is the phase angle of the time occurrence of the i earthquake in degrees, t_i is the time of occurrence of the i earthquake in modified Julian days (MJD), t_0 is the period that we chose in MJD, and T_d is the period of the particular tidal component in MJD.

We chose as epoch t_0 , i.e. the reference date, the time of the upper culmination in Thessaloniki of the new moon of January 7, 1989, which was MJD 47533.8947453704. Thus the calculated phase angle for all of the periods under study has 0 phase angle at the maximum of the corresponding tidal component (M2 and S2 have an upper culmination maximum every two cycles). As far as the monthly anomalistic moon was

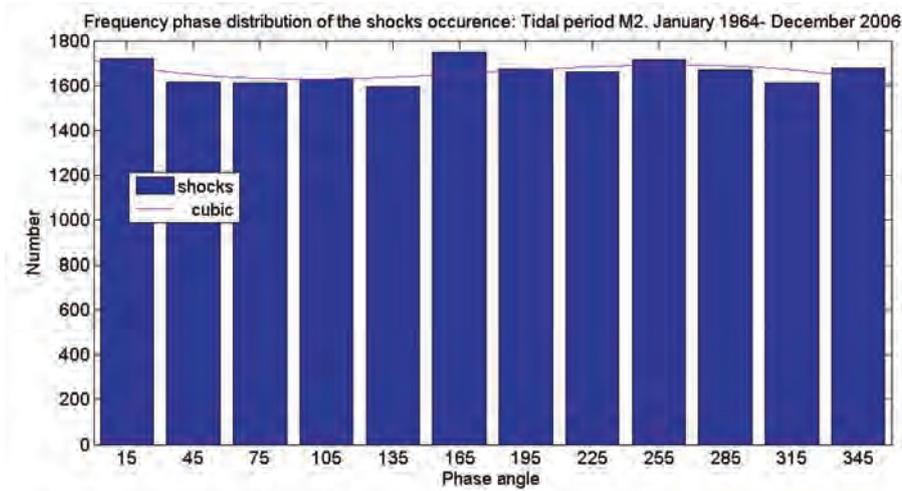


Figure 4. Cumulative histogram corresponding to the M2 period, of all of the 19.916 events.

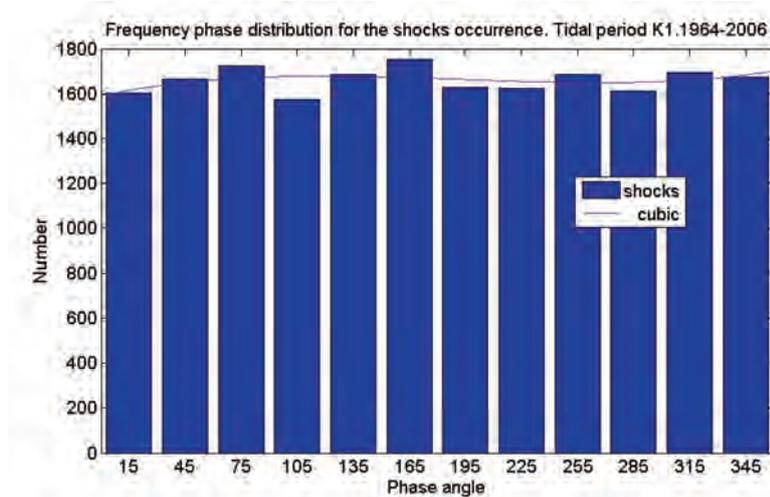


Figure 5. Cumulative histogram corresponding to K1 period, of all of the 19.916 events.

concerned, the corresponding epoch t_0 was January 14, 1989, which was MJD 47541.28492.

We separated the whole period into 12 bins of 30° and stacked every event into the correct bin according to its phase angle. Thus, we constructed cumulative histograms of the earthquake events for the tidal period under study. For example, Figures 4 and 5 show the cumulative histograms for all of the 19.916 events in the area corresponding to the tidal frequencies of K1 and M2.

It appears that M2 affected the earthquake occurrence, with a phase lag of -90 and 0 degrees, while the K1 component affected the earthquake occurrence with a phase angle of $+90$ degrees. Are these data truth? A crucial point of this analysis is the use of a correct statistical test which will provide us with arguments upon which we can decide whether such a result is correct or not; i.e. will provide us with the correct confidence level for our decision. To this end, we used the well known Schuster's test [Schuster 1897, see also Tanaka et al. 2002, 2006, Cadicheanu et al. 2007]. In Schuster'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:

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

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

$$p = \exp(-D^2/N). \quad (3)$$

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. For instance, from the above-presented examples of Figures 4 and 5, it is apparent that the confidence level for the K1 tidal constituent to be a triggering mechanism of earthquakes in the area is very low; i.e. $p(K1) = 82.21\%$ while for the M2 constituent it is remarkably higher i.e. $p(M2) = 25.64\%$.

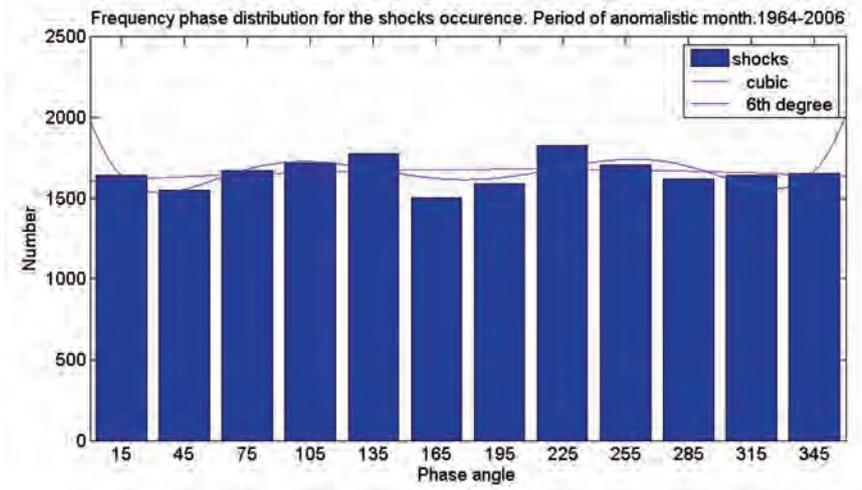


Figure 6. Cumulative histogram corresponding to the anomalistic month period, of all of the 19.916 events.

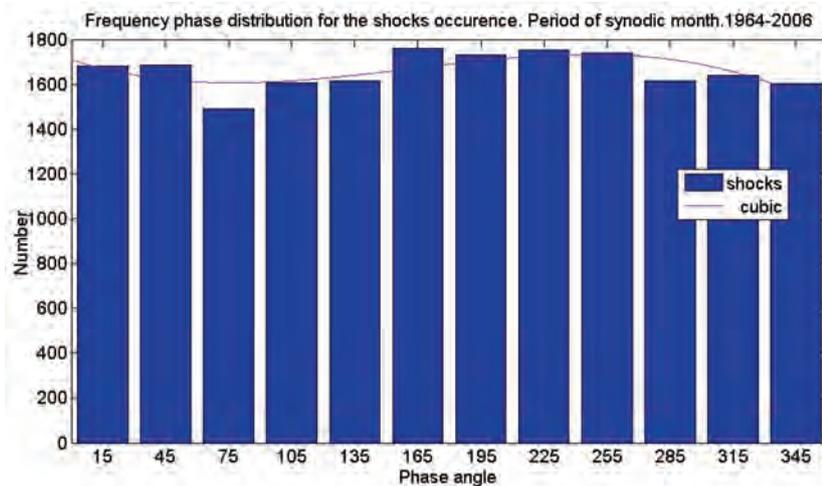


Figure 7. Cumulative histogram corresponding to the monthly synodic period, of all of the 19.916 events.

4. Results

Figures 6 and 7 show the cumulative histograms for all of the 19,916 earthquakes with local magnitudes >2.5, which corresponds to the tidal periods of the lunar anomalistic (Figure 6; i.e. the period between two successive passages of the moon from perigee, which is 27.554551 days) and synodic (Figure 7; i.e. the period from new moon to new moon, which is 29.530589 days) month. Table 3 shows the corresponding confidence levels for all of the four tidal components.

$p(K1)$	$p(M2)$	$p(M \text{ anomalistic})$	$p(M \text{ synodic})$
82.21%	25.64%	34.07%	0.02%

Table 3. The confidence levels of the earthquake–Earth tide correlations for all the earthquakes in the present study.

It can be seen that the confidence levels for the lunar synodic month component to be responsible for the earthquake triggering mechanism is very high. The effects of the Lunar anomalistic month and Lunar semidiurnal M2 components are less probable, and the effects of the diurnal lunisolar component K1 are relatively improbable. Taking into account the low accuracy in the phase determination, due to the relatively large extent of the stacking bins (i.e. 30°), we can read the phase lags of the maximum seismic activity from Figures 6 and 7, which are +90° and +270° for the anomalistic month, and +30° and +210° for the synodic month. Both of these follow the periodic variations of the maximal tidal forces, with different phase lags, but with a confidence level for a possible correlation between seismic activity and monthly tidal variation, which is much higher for the synodic month.

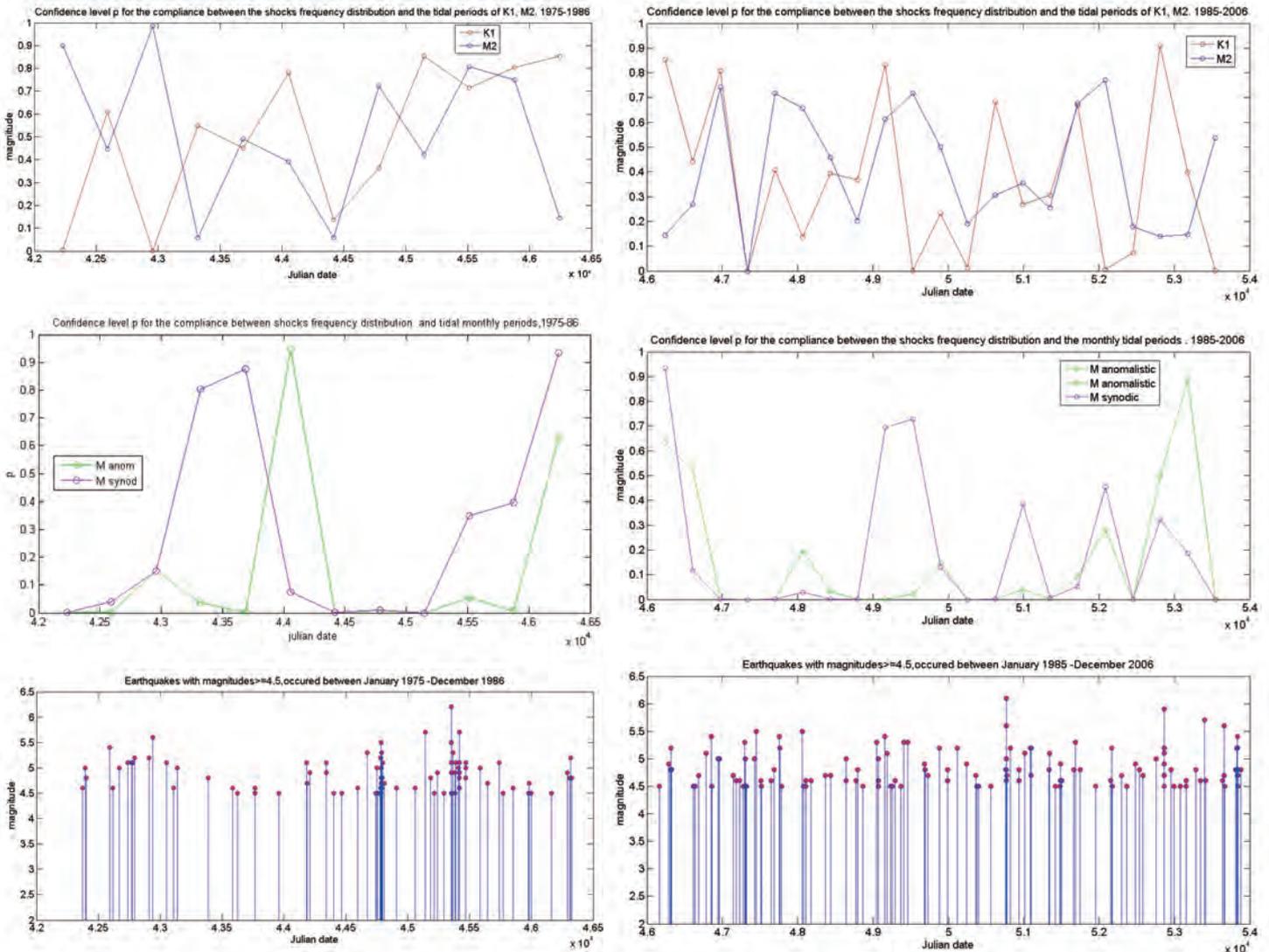


Figure 8 (left). Confidence levels for compliance between the frequency distribution of the shock occurrence and (a) K1, M2 tidal periods. (b) M-anomalistic and M-synodic periods. (c) Earthquakes with magnitudes ≥ 4.5 for the time from January 1975 to December 1986.

Figure 9 (right). Confidence levels for compliance between the frequency distribution of the shock occurrence and (a) K1, M2 tidal periods. (b) M-anomalistic and M-synodic periods. (c) Earthquakes with magnitudes ≥ 4.5 for the time from January 1985 to December 2006.

However the confidence level p for the compliance of the frequency distribution for the shock occurrence with

the tidal periods is not stable. It varies over the time, and it is smaller in periods of high seismic activity. This means that the confidence for the compliance of the frequency distribution for the shocks occurrence with the tidal periods is higher in the periods with increased seismic activity. This can be seen from Figures 8 and 9, where the yearly variations of p together with the earthquakes with magnitudes >4.5 in the same period are shown, and it is more clearly evident from Figure 10, where the monthly variations of p during the time period of increased seismic activity in the area of Zakynthos from January 1981 to December 1983 is shown.

From Figures 11, 12, 13 and 14, in conjunction with Table 4, it is apparent that there is good compliance of the frequency phase distribution of the shock occurrence with the K1, lunisolar tidal period, with medium compliance with the M2, semi-diurnal lunar period, and perfect compliance with M1, the monthly lunar anomalistic, and the synodic periods. The phase lags of all four of the frequency distributions are much the same as that of the total sample (see Figures 4, 5, 6 and 7), however, they are much more clearly seen. In particular, the phase lag for K1 is about -90° , which is the phase of the maximum rate of change of the K1 tidal component, and about $+90^\circ$ and 0° for M2, while the phase lags of the monthly M1 are $+30^\circ$ for the synodic, and -90° for the anomalistic. These result are in favour with the possibility that the combined gravitational tidal stress is an additional stress that triggers the earthquake event. The high compliance for the monthly tidal components despite their small intensities might indicate that in general they provide favourable conditions for the action of the much stronger tidal components K1 and M2. On this point, we can refer to the monthly tidal barometric variations that are quite sensitive to the seismic activity [Arabelos et al. 2008]. Perhaps this peculiar coincidence merits further investigation. Finally, we draw the attention to the confidence level p for the

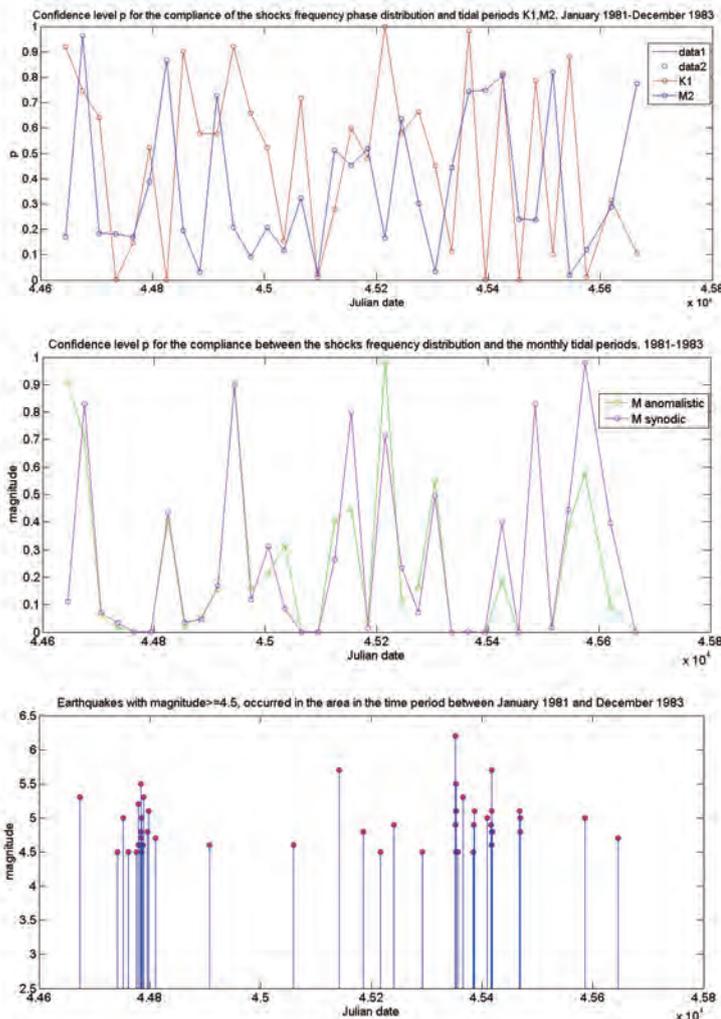


Figure 10. Confidence levels for compliance between the frequency distribution of the shock occurrence and (a) K1, M2 tidal periods. (b) M-anomalistic and M-synodic periods. (c) Earthquakes with magnitudes ≥ 4.5 for the time from January 1981 to December 1983.

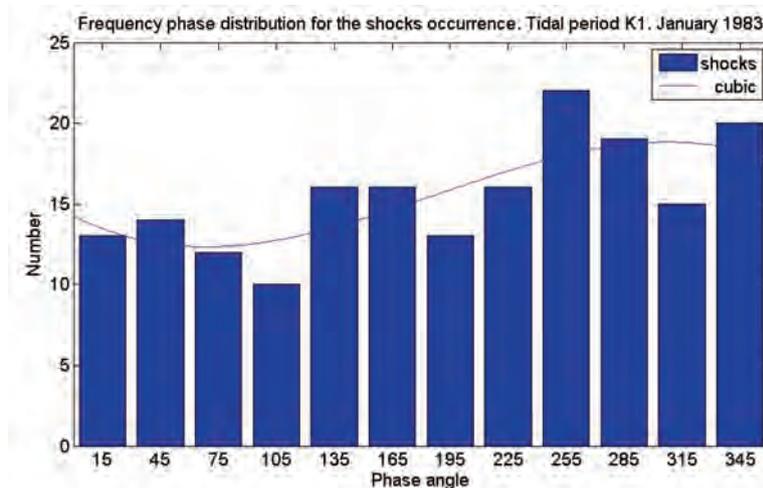


Figure 11. Cumulative histogram corresponding to the tidal period K1 of the 186 events that occurred during January 1983 in the area of Zakynthos.

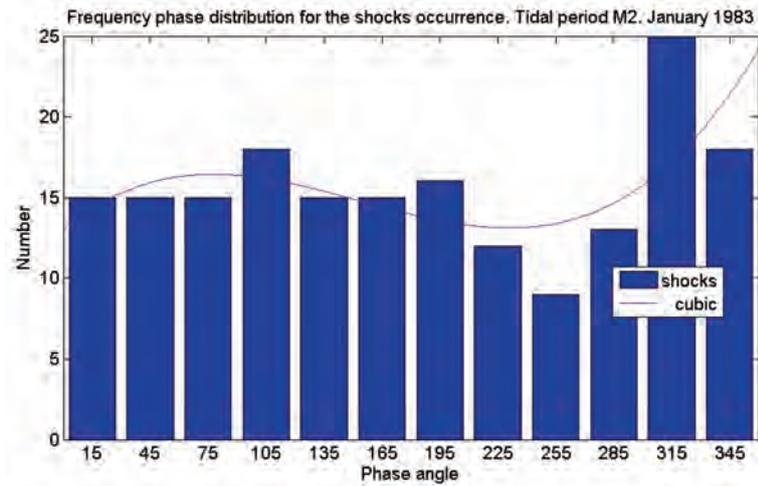


Figure 12. Cumulative histogram corresponding to the tidal period M2 of the 186 events that occurred during January 1983 in the area of Zakynthos.

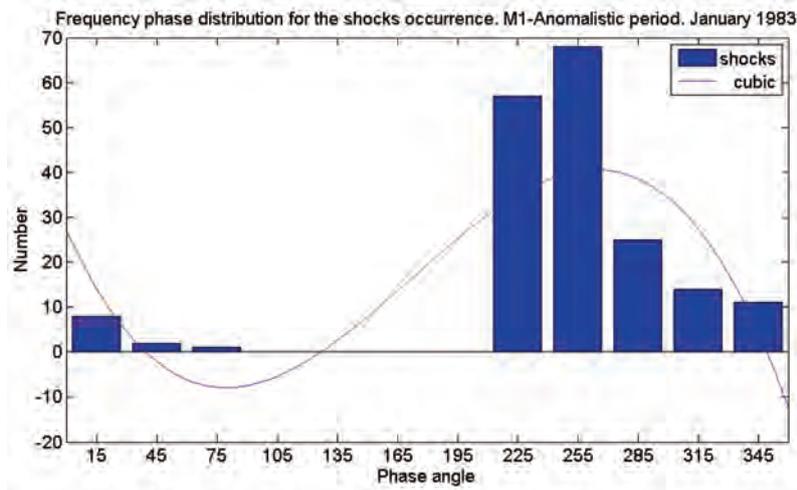


Figure 13. Cumulative histogram corresponding to the tidal period M1 anomalistic of the 186 events that occurred during January 1983 in the area of Zakynthos.

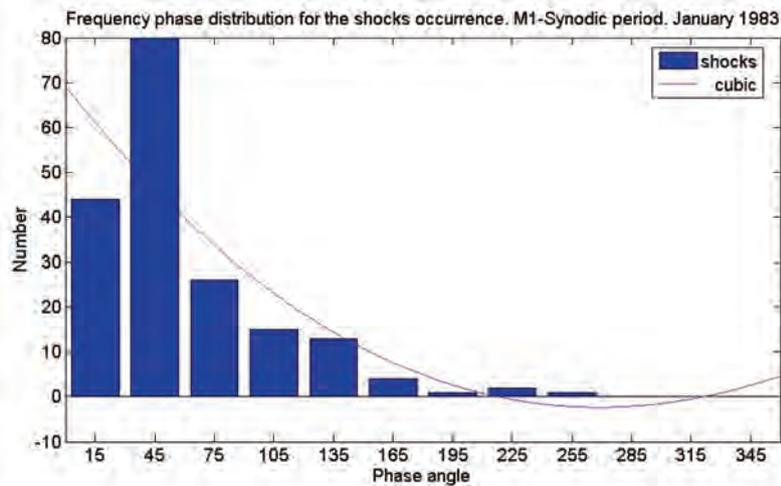


Figure 14. Cumulative histogram corresponding to the tidal period M1 synodic of the 186 events that occurred during January 1983 in the area of Zakynthos.

$p(K1)$	$p(M2)$	$p(M1\text{-anomalistic})$	$p(M\text{-synodic})$
11.27%	44.38%	0.00%	0.00%

Table 4. The confidence levels of the earthquake–earth tide correlation for the 186 earthquakes events that occurred during January 1983 in the area of Zakynthos.

compliance of the frequency phase distribution of the shock occurrence, which increases around the time of high seismic activity. This indicates that the parameter p , which is a measure of this compliance, can be used as an additional earthquake precursory index.

5. Conclusions

In the present study we investigated the tidal triggering evidence for the earthquakes of the seismic area of the Ionian geological zone in Greece. The results of our analysis using the cumulative histogram method indicate that the monthly variations in the frequencies of earthquake occurrence are in agreement 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.

The statistical test of Schuster [1987] indicates very high probability for the monthly component Mm to act as a trigger mechanism for earthquake occurrence, and a small probability for the diurnal lunisolar K1 and semidiurnal lunar M2 components, although the variation amplitudes of both (K1, M2) are about 18 times greater than that of Mm. It appears that the revolution of the moon on its elliptical trajectory around the earth creates periodically favorable conditions for the triggering effect of the strong diurnal and semidiurnal components.

In addition, the confidence levels for the identification of such periodical agreement between earthquake occurrence frequencies and tidal periods varies with the seismic activity; i.e. the higher confidence levels correspond to periods with stronger seismic activity. These results are in favor of a tidal triggering process for earthquakes when the stress in the focal area is near the critical level. This indicates also that the parameter p , which is a measure of the confidence level, can be used as an additional earthquake precursory index.

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