EARTHQUAKE SEASONALITY IN THE AREA OF GREECE

Buckthought,K.* and Polimenakos,L.C.**

* Earthquake Forecasts, Inc., 30 Concourse Gate, Unit 35, Nepean, Ontario, K2E 7V7, Canada.
** Esperou 19, P. Phaliro, GR 17561, Greece.

ABSTRACT

The existence of a seasonal trend in earthquake occurrence in the area of Greece is examined for main, M≥5.2 shallow, and M≥6.0 intermediate depth shocks, for the time interval 1911-1985. The Sun's longitude was also analyzed for any seasonal trend. A highly significant spring trend is found for shallow events of the areas of Thessaly, Northern Aegean Sea and the coast of central Western Turkey. Intermediate depth events of South Aegean Sea exhibit a significant summer trend. The Sun's longitude for events of the above zones is located between 340° and 30° (around vernal equinox).

ΕΠΟΧΙΑΚΟΤΗΤΑ ΤΗΣ ΕΜΦΑΝΙΣΗΣ ΤΩΝ ΣΕΙΣΜΩΝ ΣΤΟΝ ΕΛΛΗΝΙΚΟ ΧΩΡΟ.

Buckthought,K. και Πολυμενάκος,Λ.Χ.

ΠΕΡΙΛΗΨΗ

Στην παρούσα εργασία διερευνάται η ύπαρξη εποχιακότητας της εμφάνιση των σεισμών στον ελληνικό χώρο. Μελετήθηκαν κύριοι, επιφανειακοί με M≥5.2 και ενδιάμεσου βάθους σεισμοί με M≥6.0 για το χρονικό διάστημα 1911-1985. Βρέθηκε μια πολύ σημαντική τάση εμφάνισης σεισμών κατά την άνοιξη για επιφανειακούς σεισμούς από τις περιοχές της Θεσσαλίας, του Βορείου Αιγαίου και της ακτής της κεντρικής Δυτικής Τουρκίας και κατά το καλοκαίρι για σεισμούς ενδιάμεσου βάθους από την περιοχή του Νοτίου Αιγαίου. Το γεωγραφικό μήκος του ήλιου για τους σεισμούς των ανωτέρω περιοχών βρίσκεται μεταξύ 340° και 30° (κοντά στην εαρινή ισημερία).

INTRODUCTION

Studies of earthquake seasonality, have only been attempted very recently. McClellan (1984) observed that shallow Californian earthquakes tend to occur in spring before the large, 1906, San Francisco earthquake. The above trend was found to be statistically significant, exceeding seasonal frequencies expected from random variation in the earthquake occurrence rate. For the area of Greece, Tamrazyan (1970), using M≥6.5 shallow as well as intermediate depth shocks for the interval 1900- 1957 showed that all strong events (M: 7.2-8.3) tend to occur in summer and moreover that they are "timed to the daily rotation change curve on its descending part". However, a careful inspection of Tamrazyan's fig.10 reveals that the 'strong events' are mainly intermediate depth events which occur particularly in the summer, while shallow events appear to be more uniformly distributed throughout the year. Papazachos and Papadimitriou (1984) noted that an earthquake sequence in the North Aegean Sea (1954-1970, M:6.6-7.1) occurred between February and May. Galanopoulos (1985), using data with M≥5.5 from the entire Aegean and surrounding area and for the time interval 1902-1980, found out that the monthly number of earthquakes tends to be relatively higher in March while the amount of the seismic energy released was found to be relatively higher in August, where also the largest shallow shocks tend to occur. However, Galanopoulos (1985) arrived at the above result considering also aftershocks while he did not discriminate between different depth ranges. Most recently, Polimenakos (1992) detected a pronounced summer trend in the occurrence of main, intermediate depth earthquakes from the Hellenic Arc (M≥6.0) while he observed no trend at all for main shallow events from the same area.

The above results provide evidence for a significant seasonal effect in the occurrence of earthquakes. In the present work, we will try, by utilizing only main shocks, to provide an integrated approach to the investigation of a possible seasonal trend in Greece and the surrounding area.

DATA

The selection of earthquake data for the area of Greece is based on the separation of Greece and the surrounding area into seismic zones after Papazachos (1980). The examined zones are the eighteen shallow seismicity zones (SHZ 1-18) and the intermediate depth seismicity zone (IDZ). The location of the aforementioned regions is presented in Figure 1. Datasets including only main instrumental shocks (no foreshocks or aftershocks) with M≥5.2 and M≥6.0 were evaluated for all the shallow zones (1-18), while a set with M≥6.0 events was evaluated for the intermediate depth zone. The data come from the catalogue by Comninakis and Papazachos (1986). Shallow events with M≥6.0 and M≥5.2 are considered as being complete for the time intervals 1901-1985 and 1911-1985 respectively (Comninakis and Papazachos, 1986). Intermediate depth events with M≥6.0 are considered as being complete for the time interval 1901-1985 (Papazachos, 1990). The exclusion of fore- and aftershocks was made by manual compilation of the above catalogue. This is a reliable procedure for deleting fore- and aftershocks as Gardner and Knopoff (1974) state.

METHODOLOGY

In order to test the statistical significance of any unimodal or bimodal trend in the occurrence of earthquakes, that is a trend in occurrence at one or two opposite seasons, we applied the Rayleigh test (Lord Rayleigh, 1880), known also as the Schuster test (Schuster, 1897). Unlike other methods, this test was found to meet the need for avoiding any a priori grouping of data (see also Shlien, 1972; McClellan, 1984;

Stothers, 1990).

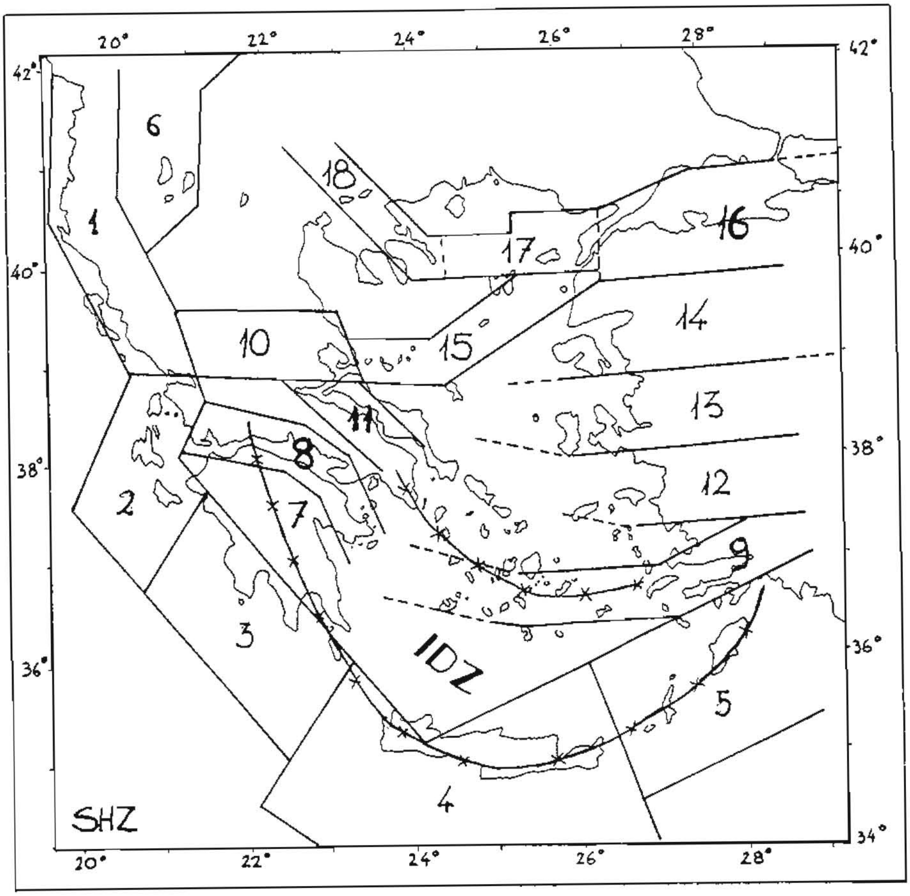

Fig.1. Location of the seismic zones (Modified after Papazachos 1980, 1990).

As used here, the test measures the tendency of a set of events to occur near the same time ('phase') of the year. Each earthquake datum is converted to a phase angle β (β=earthquake datum x $(2\pi/365)$) and the N phases are vectorially added, N being the length of the dataset. If $A=\sum\cos\beta$ and $B=\sum\sin\beta$ then the resultant vector is at phase $\varphi=\arctan(B/A)$ and has a length $r=\sqrt{A^2+B^2}$. The vectorial sum of the earthquake set will point towards the season of the year that earthquakes tend to occur, and its magnitude, r, is indicative of the strength of this tendency.

In order to investigate any bimodal trend in the occurrence of earthquakes, a modification of the Rayleigh test was used (see also Shlien, 1972). This was decided since the test, as it is originally devised, would not detect an existent bimodal trend. In this modified form the phase angle β is β=eq.datum x $(2\pi/183)$.

The probability that the resultant is larger than r, or that earthquake dates come from a random distribution, is $P=\exp(-r^2/N)$, where $N\geq10$, assuming that earthquakes occur independently of the seasons. In the present work, any value of P lower than 0.05 will be considered as significant (corresponding to the 95% level of significance).

The Rayleigh test was also applied to investigate whether seasonality is a function of the Sun's position. To do this the Sun's longitude was computed for each earthquake datum. The Sun's longitude is the angle along the ecliptic measured from the first point of Aries in the direction of motion of the Sun. In the present work, the mean solar longitude (MSL) is used, corrected for precession. It represents the longitude of a fictitious Sun moving along the ecliptic at a uniform rate, as would be the case if the Earth's orbit was a circle. The MSL can be used as a measure of the phase of a periodicity, the period being in our case the interval between two successive passages through the vernal equinox (unimodal trend) and a passage through the vernal and autumnal equinox (bimodal trend).

RESULTS

The probabilities P resulting from the application of the Rayleigh test for an unimodal and bimodal trend are listed in Table 1.

UNIMODAL TREND

Probability that the observed dates are randomly distributed is low for events with $M\geq5.2$ in three out of the eighteen shallow zones, namely SHZ 10 (P1=0.01, φ=108.4°), 13 (P1=0.01, φ=102.4°) and 15 (P1=0.001, φ=57.2°), implying a strong spring trend (at the 97% level of significance) in the occurrence of earthquakes. A strong trend is also found when considering SHZ 6-18 (i.e. the 'internal zones') (P1=0.05, φ=77.6°), while $M\geq6.0$ events in SHZ 10, 13 and 15 were too few to be properly treated with the Rayleigh test. Values of P1 vary from 0.11 to 0.95 for the rest of the shallow zones. Intermediate depth events with $M\geq6.0$ were also found to show a strong seasonal trend in their occurrence (P1=0.03), however shifted towards late spring -early summer (φ=217.6°) (see also Polimenakos, 1992). Evidence for a spring trend is also strongly supported after considering the Rayleigh test results for the Sun's longitude. For the seismicity zones for which a strong seasonal trend is observed, the Sun's longitude (at the 97% significance level) is between 330° and 30°, located around the vernal equinox.

Table 1. Results of the Rayleigh test. Shallow zones (SHZ 1-18): M≥5.2, M≥6.0 (1911-1985); indermediate depth zone (IDZ): M≥6.0 (1900-1985).

		Unimodal trend			Bimodal trend		
Zone	N	φ°date	φ°Sun	P1	φ°date	φ°Sun	P2
Ms≥5.2							
SHZ 1	52	292.4	211.8	.39	208.9	48.1	.49
2	54	109.1	29.7	.61	231.7	72.5	.83
3	29	253.7	173.0	.31	72.7	269.6	.80
4	77	137.5	57.3	.95	137.6	340.1	.53
5	40	200.0	119.6	.86	244.7	86.2	.44
6	20	45.1	324.3	.25	78.3	277.8	.47
7	15	187.9	107.2	.59	351.7	187.9	.76
8	35	44.9	323.9	.24	32.0	229.7	.45
9	22	16.8	296.4	.64	223.6	63.4	.72
10	12	108.4	29.0	.01	213.6	54.1	.14
11	9	318.6	237.6	.62	235.4	84.6	.92
12	14	178.7	98.1	.29	119.0	316.3	.82
13	24	102.4	22.2	.01	15.1	215.6	.10
14	23	335.9	255.3	.31	266.1	107.4	.51
15	14	57.2	336.7	.001	141.9	343.2	.10
16	15	231.8	150.9	.37	127.0	327.0	.03
17	11	194.7	115.1	.76	60.8	261.3	.10
18	12	180.3	100.4	.58	340.1	181.4	.87
1-5	252	236.8	155.7	.78	194.0	35.3	.43
6-18	226	77.6	357.3	.05	83.3	280.6	.42
1-18	478	86.5	6.7	.49	140.5	341.1	.58
Ms≥6.0							
SHZ 1	8	322.8	241.5	.92	243.5	82.6	.71
2	16	266.5	185.4	.49	130.4	329.5	.70
4	14	188.5	108.2	.64	89.6	288.6	.98
8	6	92.5	12.5	.13	209.7	53.6	.82
9	8	81.3	0.8	.73	270.9	110.4	.25
10	8	102.3	21.8	.08	194.9	35.0	.14
14	9	330.6	249.0	.85	230.5	71.3	.21
1-5	46	257.6	176.2	.78	193.3	338.3	.40
6-18	62	97.8	17.7	.11	186.3	27.5	.43
1-18	108	101.5	26.1	.51	164.2	4.6	.24
IDZ	29	217.6	137.1	.03	92.9	291.5	.72

BIMODAL TREND

From Table 1 is evident that only shallow zone 16 exhibits a strong bimodal trend at the 95% level (P2=0.03) with corresponding phase angle 127.0°. This implies a significant spring-autumn trend in the above zone. The Sun's longitude for zone 16 is 327.0° and is located near the vernal equinox.

DISCUSSION

The above results provide evidence for a highly significant seasonal trend, confined to limited portions of the whole area of Greece.

Hence, the following points can be made:

a. The reality of the seasonal trend. A plot of the P value versus the frequency of events occurred in the interval day 50 -day 200 (hereby defined as the 'spring frequency') for each zone (Fig.2) reveals that the 'spring percentage' is generally high (30-60%) in all cases while it reduces with increasing P1 value. Hence, there is a seasonal 'background' in the seismicity in the area of Greece.

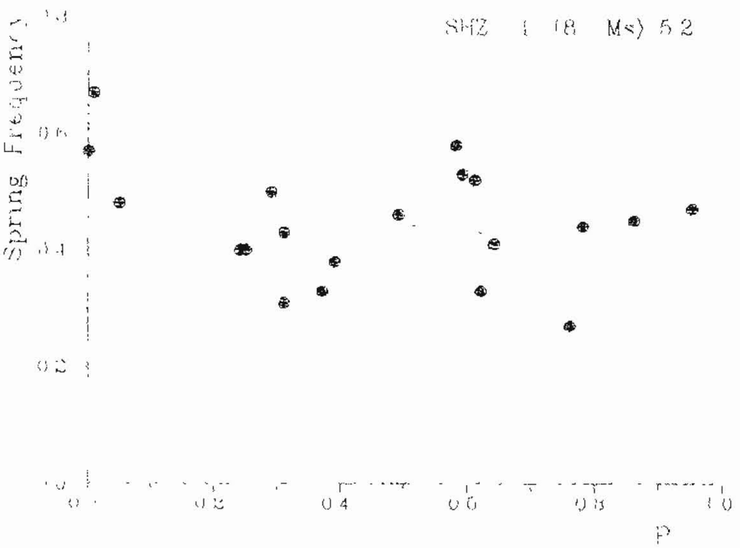

Fig.2. Spring Frequency (SF) versus P1 for the shallow zones. Dashed line calculated by least squares: SF = 0.49 - 0.10 P1 (SHZ 13 is excluded from calculations)

b. The appearance of the seasonal trend with respect to the seismicity zones. It appears that seasonality is observed in those zones which have a simple seismogenic layout: for example SHZ's 10 and 15 in contrast to SHZ's 2 and 5 (for information on the seismotectonics of the zones see Papazachos, 1990). This might not necessarily mean a single, dominant fault but, more likely, a seismotectonic framework which functions in a uniform way within the given distribution of stresses throughout the area of Greece (see also Polimenakos,1992).

Another interesting observation from Table 1 is that the seasonal trend, as expressed by the P1 value, reduces when going from the external zones to the internal ones, that is to the north and east. Evidence for the above comes from the considerable decrease in the P1 value for both M≥5.2 and M≥6.0 events when comparing the results of SHZ 1-5 with SHZ 6-18. This suggests a passage from a complex seismotectonic environment to a reasonably simpler one and is in general agreement with the distribution of the b-value in the area of Greece (c.f. Papazachos, 1980; Hatzidimitriou et al., 1985; Papadopoulos and Kijko, 1991). The distribution of P1 with respect to the b-value is presented in Figure 3.

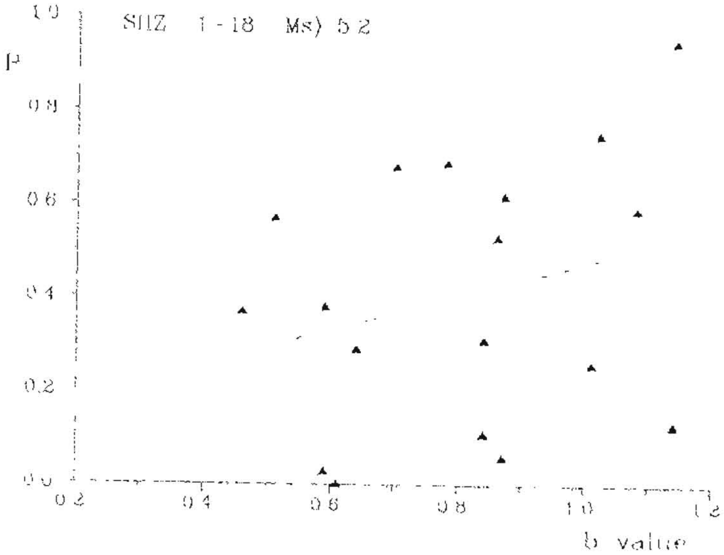

Fig.3. P1 versus the b-value. Dashed line calculated by least squares: P1 = 0.11 + 0.36 b. b-value data from Papadopoulos and Kijko (1991)

On the other hand, it is to be pointed out that the observed trend of earthquakes to occur in spring (in zones 10,13 and 15) is not observed on an annual basis. To illustrate the point we plotted the cumulative number of all earthquakes and that of earthquakes which occur in spring ('spring'= 22 Feb-21 Jul) versus time (Fig.4). The deviation of the spring events' curve demonstrates the non-annual periodicity of springtime occurence. It, thus, appears that annual processes may be of minor importance with regard to seasonality.

An important issue related with the observed non-annual periodicity of the seasonal trend is whether this trend is influenced by dominant stress relaxation patterns characterizing a seismogenic area which are of recurrent nature , otherwise called 'seismic cycles'. McClellan (1984) has pointed out that the seasonal trend observed with Californian earthquakes is strongly connected with the 'seismic cycle' which appears to govern the stress discharge at the San Andreas fault. The cumulative number of all M≥6.0 events which is plotted with respect to time in Figure 4 was used in order to see if there

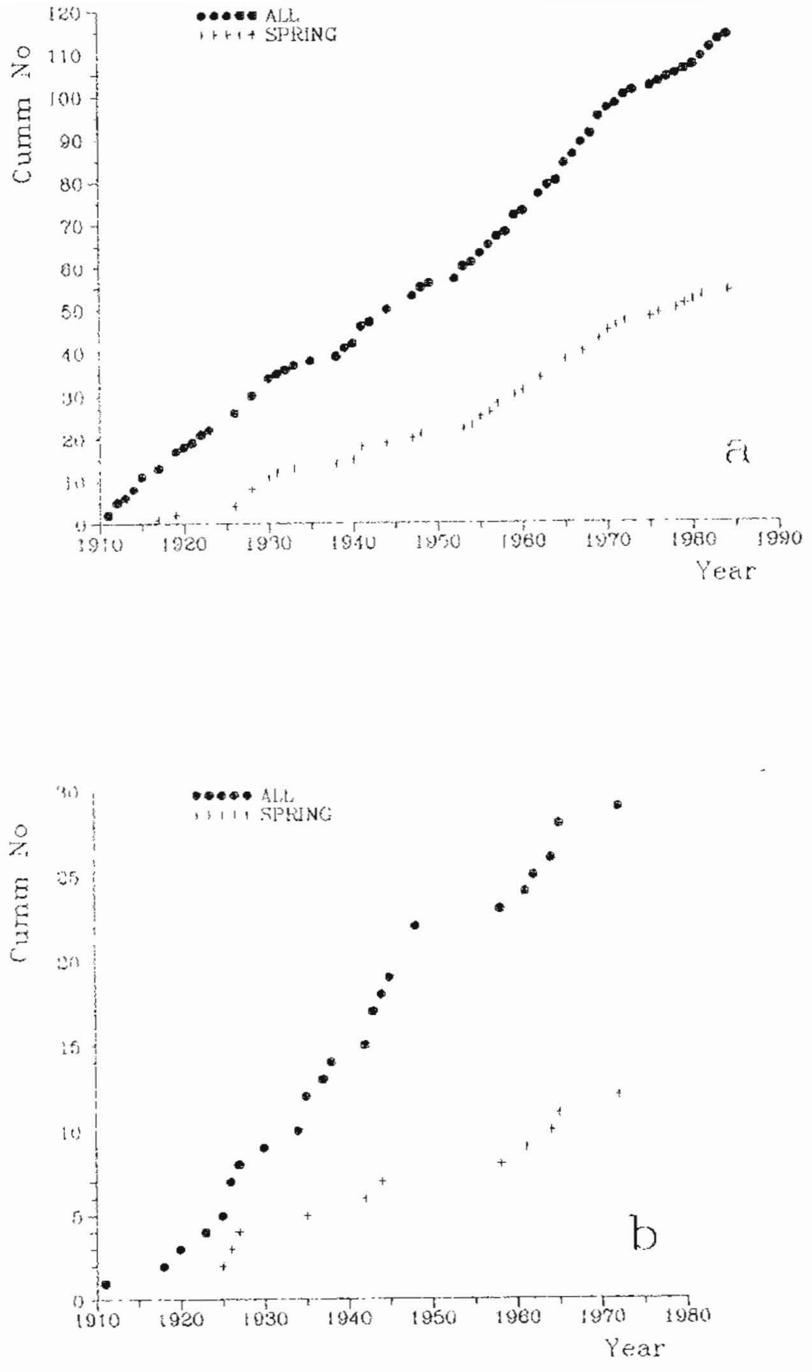

Fig.4. Cumulative number of earthquakes versus time. (a) shallow events (SHZ 1-18); (b) intermediate depth events (IDZ).

exist periods of intense activity interchanging with periods of non-intense activity. As illustrated, there appear successive low and high activity intervals of about 9 years length. It is of interest to observe that intervals of intense activity coincide with intervals of high 'spring' activity. Hence, it is evident that, as in the case of Californian events, the significant seasonal trend appears in the latter (and most intense) part of a 'seismic cycle'.

As a plausible physical explanation of the observed seasonality, various factors may be considered. Two major mechanisms, that is (a) pore-fluid pressure increase due to water influx and tidal factors and (b) increase in shear stress due to fluctuations in plate motion have been proposed by McClellan (1984). Ostrovsky (1989), in commenting McClellan's results, suggested that seasonal fluctuations of the wind speed might be associated with increase in seismic activity.

The reasoning for seasonal pore fluid pressure increase as a potential earthquake triggering factor seems to fit the depth ranges associated with shallow events. But it certainly does not with depths associated with the intermediate depth events (h:70-160 km). Moreover, one has to note that only three out of the eighteen shallow zones do actually show a seasonal trend. Similarly, atmospheric and/or sea level fluctuations seem not to be related, particularly in the Aegean, to earthquakes at shallow or intermediate depths, as stated in the work of Shlien (1972) and of Churchin and Pennington (1987). However, there has been no attempt to correlate rainfall or pressure fluctuations with seismic activity in the area of Greece. It appears that stresses in the Earth's crust rised due to the tidal effects caused by the Sun and Moon are small compared to the existing stresses along faults.

The distribution of stresses within the lithosphere, associated with the relative motion of the colliding plates across the Hellenic Arc might be responsible for the observed seasonality (see also Discussion in Polimenakos, 1992). This is strongly supported by the seasonal trend observed with the intermediate depth events. Evidence for the existence of a seasonal effect on the plate motion comes from observations such as those on fluctuations of the rotation rate of the Earth (Lambeck and Hopgood, 1982). Fluctuations of the rotation rate are generally thought to be an important factor for both short and long term changes in global geodynamics, affecting earthquake occurrence, volcanism etc. (Wezel, 1988; Morner, 1988). Such fluctuations are expressed through the variation of the length of day (LOD). Lambeck and Hopgood (1982) acknowledge two kinds of fluctuations associated with the LOD. A 'high frequency' component accounts for annual fluctuations of meteorological origin, which arrive at their maximum during late spring and summer. As a result an interaction at plate boundaries of torques at the core-mantle boundary results from the spring time deceleration of the Earth's rotational spin. A 'low frequency' component consists of 3-5 yr and 20-30 yr period fluctuations originating in geophysical processes.

Should seasonality be associated with the seasonal variation of the earth's rotation rate, peaks in seasonality at other solar longitudes should emerge. To test this we fitted the earthquake frequency for every 20 degrees of solar longitude to a truncated Fourier series, using moving averages. Four such series were generated for respective sets of zones and different magnitude thresholds. Figure 5 illustrates a very interesting difference in the trend which is followed by every set. Especially noticeable is the difference between sets 1-5 and 6-18 ($M \geq 5.2$) as well as between sets 1-18 for $M \geq 5.2$ and $M \geq 6.0$, respectively. A Fourier series representation of the observed seasonality of the earth's rotation rate is also presented for comparison. A correspondence between the rotation rate series and that of sets 1-18 ($M \geq 5.2$) and 6-18 ($M \geq 5.2$) is present. However, this does not necessarily imply a connection between the variations in the earth's rotation rate and triggering of earthquakes.

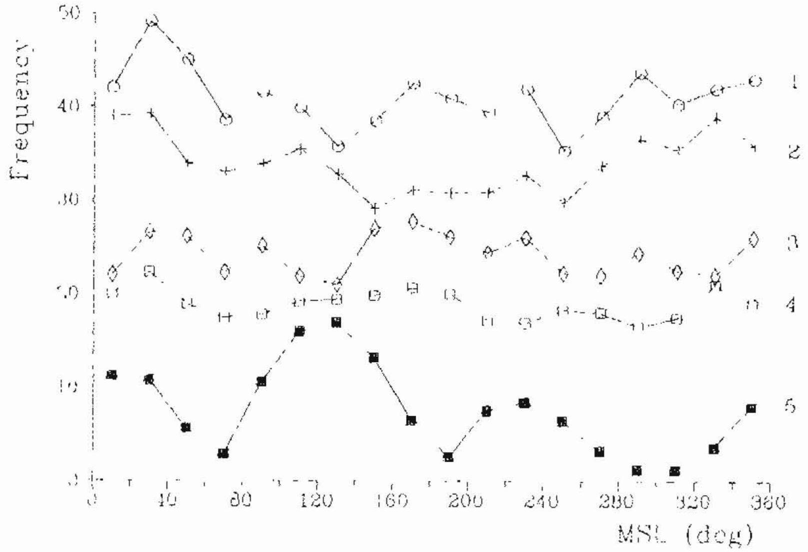

Fig.5. Fourier series representation of the earthquake occurrence frequency with respect to the Mean Solar Longitude. Frequency scale is arbitrary.
1- SHZ 1-18 $M \geq 5.2$; 2- SHZ 1-18 $M \geq 6.0$;
3- SHZ 1-5 $M \geq 5.2$; 4- SHZ 1-18 $M \geq 5.2$; 5- Rotation rate.
Rotation rate data from Lambeck and Hopgood (1981).

In conclusion, the investigation of seasonality reveals a complex interaction of various potential factors. Seasonality shall be regarded as a part of a system rather than an independent phenomenon.

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