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SEISMIC ELECTRIC SIGNALS AND SEISMICITY: ON A TENTATIVE INTERRELATION BETWEEN THEIR SPECTRAL CONTENT

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Abstract

We show that the spectral content of the seismic activity, in the area candidate to suffer an earthquake and which evolves consecutively in time with every new event, falls on the spectral content of the Seismic Electric Signals (SES) activity, just before the occurrence of the main shock. The key point is that both spectra have to be defined and calculated in a new time domain, termed as "natural" time. Thus, since the spectrum of the SES is known well in advance, the continuous inspection of the spectrum of the evolving seismic activity may lead to an estimation of the time window of the impending main shock with an accuracy of around a few days. Both spectra exhibit a feature compatible with that obtained from the theory of dynamic phase transitions (critical phenomena).

Key words: seismic electric signals activity, natural time.

1. INTRODUCTION

Seismic Electric Signals (SES) are low frequency (≤ 1 Hz) changes of the electric field (E) of the earth that have been found in Greece (e.g., Varotsos *et al.*, 1996; Kanamori, 1996; Uyeda, 1996) and Japan (Uyeda *et al.*, 2000) to precede earthquakes (EQs) with lead times ranging from several hours to a few months. Their analysis may lead to an estimation of the epicentral area (e.g., Varotsos *et al.*, 1996). It has been recently found that such an estimation can be significantly improved if the time-difference between the SES electrical variations and the associated magnetic field variations have been measured (e.g., this time-difference was of the order of 1 s for the SES activities that preceded the 6.6 EQ at Grevena-Kozani on May 13, 1995; see Varotsos *et al.*, 2001a, b). Thus, it is of interest to investigate if an improvement of the estimation of the time window for the occurrence of the impending EQ can be also achieved. The present paper examines this possibility by studying the spatio-temporal complexity relating electromagnetic phenomena and subsequent seismicity, that have been developed recently in Greece (Varotsos, 2001; 2002; Varotsos *et al.*, 2001c; 2002).

It has been recently found that the SES activities collected before major EQs in Greece, exhibit spectra that are consistent with those theoretically expected for the critical phenomena (Varotsos *et al.*, 2001c; 2002). Here we show that an interrelation exists between the time evolution of the seismic activity (measured from the start of the SES recording and thus evolving in time with every new event) and the spectrum characteristics of the SES. This, however, can be *only* achieved if we depart from the conventional time t by introducing instead the "natural" time χ (see below) suggested recently (Varotsos *et al.*, 2001c).

The present paper is organized as follows: In Section 2, we recapitulate the basic concepts of the "natural" time. Following these concepts, we analyse in Section 3 the data related to the four strongest mainshocks in Greece since 1988 (i.e., the SES activities as well as the subsequent evolving seismic activities as observed until the corresponding mainshocks).

This analysis reveals that the two resulting "natural" power spectra (i.e., the one of the SES activity and that of the evolving seismicity) fall onto the same (normalised) curve just before the occurrence of the mainshock. Section 4, explains that this curve is just the one emerged from the theoretical analysis of critical phenomena (dynamic phase transitions) applied to the SES generation. An Appendix is reserved to draw attention to the fact that, interestingly, this curve is closely related to that resulting from a long period study of the evolution of seismicity, but when it is carried out in the "natural" time domain. Finally, Section 4 presents the main conclusions.

The following point should be clarified: In this paper, we use the values of the local magnitude *ML* of the earthquakes (EQs) taken from the catalogue of National Observatory of Athens (NOA), that is currently available from www.gein.noa.gr. In a separate study, Varotsos *et al.* (2001c) obtained conclusions similar to those reported here although they used the preliminary NOA catalogue (available from the same source, but before November 2001).

2. THE "NATURAL" TIME-DOMAIN

We follow Varotsos *et al.* (2001c): The "natural" time χ serves as the subsequent index of an event (reduced by the total number of events). Let us, therefore, denote by

Q_k the duration of the k-th transient pulse (single SES) of an SES activity comprised of N pulses (Fig. 1a). The "natural" time χ is introduced by ascribing to this pulse the value $\chi_k = k/N$. If we now consider the evolution (χ_k, Q_k), we can define the continuous function $F(\omega)$ (this should not be confused with the discrete Fourier transform):

$$F(\omega) = \sum_{k=1}^{N} Q_k \exp\left(i\omega \frac{k}{N}\right),$$

where $\omega = 2\pi\phi$, and ϕ stands for the **"natural" frequency**. We normalize $F(\omega)$ by dividing it by $F(0)$

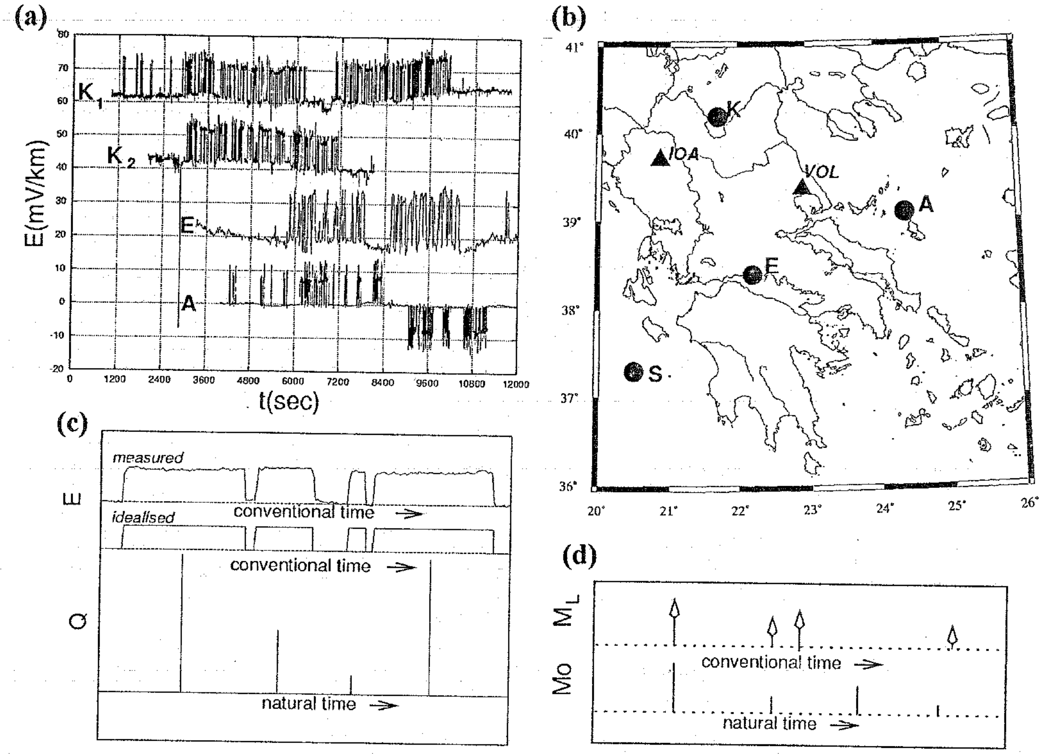

Fig. 1: (**a**) SES activities recorded before the main shocks K, E, S and A given in Table 1; K_1 and K_2 refer to the two SES activities (recorded on April 18 and 19, 1995, respectively) before the EQ labeled K. The upper two SES activities were recorded at IOA, while the lower two at VOL. (**b**) Map showing the EQ epicenters (circles) and the sites (triangles) of the SES measuring stations. Explanation how a series of electric pulses (**c**) or a series of seismic events (**d**) can be read in "natural" time. In both cases the time serves as an index of the occurrence of each event (reduced by the total number of events), while the amplitude is proportional to (c) the duration of each electric pulse and (d) to the seismic moment M_0.

$$\Phi(\omega) = \frac{\sum_{k=1}^{N} Q_k \exp\left(\mathrm{i}\omega \frac{k}{N}\right)}{\sum_{k=1}^{N} Q_k} = \sum_{k=1}^{N} p_k \exp\left(\mathrm{i}\omega \frac{k}{N}\right), \tag{1}$$

where $p_k = Q_k / \sum_{n=1}^{N} Q_n$. Thus, the quantities p_k describe a "probability" to observe the transient at natural time χ_k. From eq. (1), we can obtain the normalized power spectrum

$$\Pi(\omega) = \left|\Phi(\omega)\right|^2 . \tag{2}$$

For natural frequencies ϕ less than 0.5, $\Pi(\omega)$ or $\Pi(\phi)$ reduce to a characteristic function for the probability distribution p_k in the context of probability theory. The procedure of reading a series of electric pulses in the natural time domain is depicted in Fig. 1c.

Table 1

All EQs with *Ms* (USGS) ≥ 6.0 since 1988 within $N_{36.5}^{41.5}$ $E_{19.0}^{26.0}$
and the relevant SES activities

EQ label	K	E	S	A
Main earthquakes				
Date	13 May 1995	15 June 1995	18 Nov. 1997	26 July 2001
Time	08:47	00:15	13:07	00:21
Epicenter	40.2N–21.7E	38.4N–22.2E	37.3N–20.5E	39.1N–24.4E
Ms (USGS)	6.6	6.5	6.4	6.6
SES activities				
Date	18 and 19 Apr. 1995	30 Apr. 1995	03 Oct. 1997	17 Mar. 2001
Time	10:04	05:41	18:24	15:34
Station	IOA	VOL	IOA	VOL
Reference	Varotsos *et al.* (1996)	Varotsos *et al.* (1996)	Varotsos *et al.* (2001d)	Varotsos *et al.* (1998)
Region considered *⁾				
Coordinates	$N_{39.2}^{40.5}$ $E_{20.3}^{22.0}$	$N_{37.5}^{39.7}$ $E_{21.5}^{25.0}$	$N_{37.0}^{38.5}$ $E_{20.3}^{21.7}$	$N_{38.7}^{39.5}$ $E_{22.0}^{25.0}$

*⁾ Excluding those mentioned in each of the Tables 2–5 separately

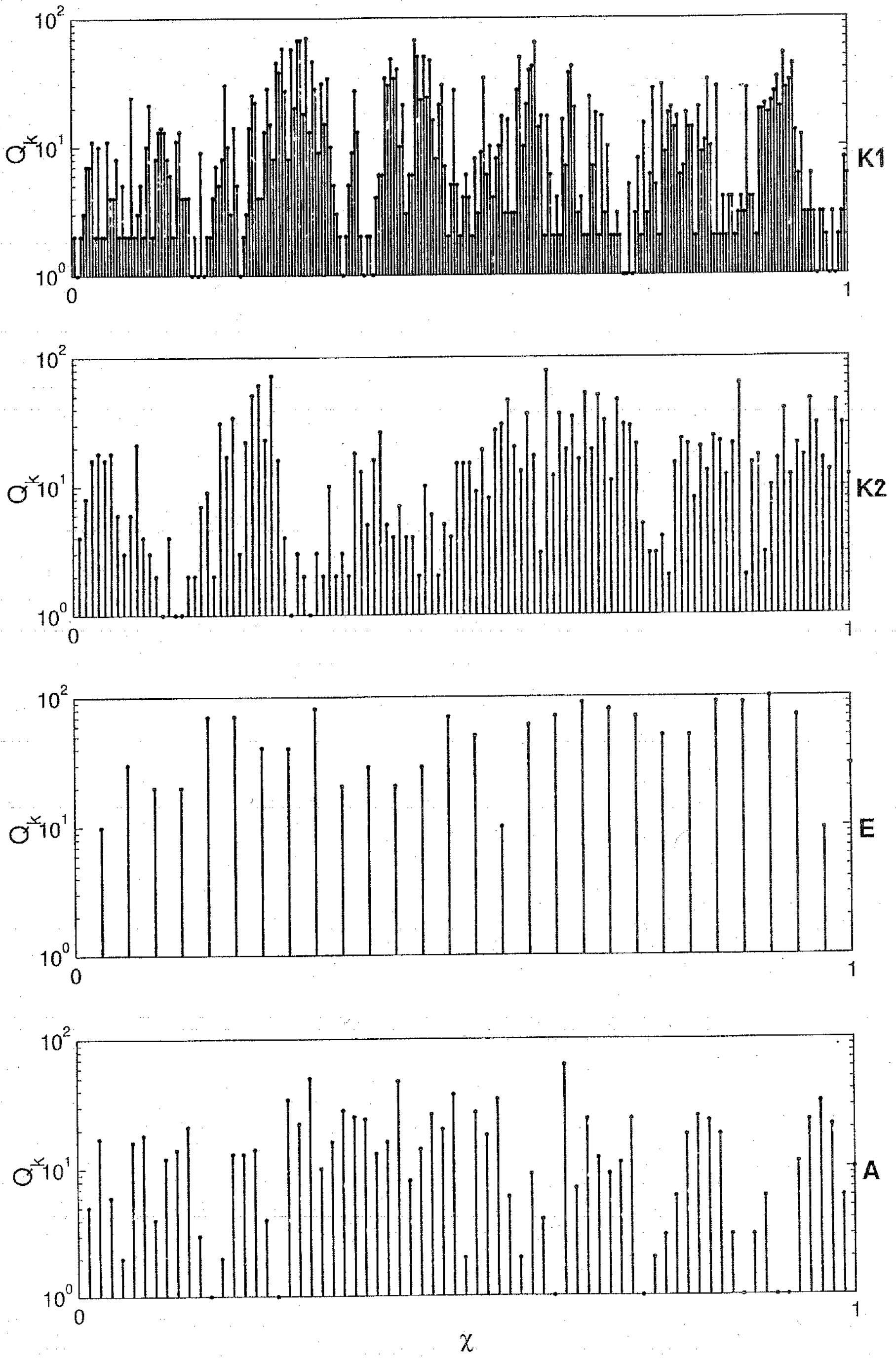

Fig. 2. Illustration how the SES activities, depicted in Fig. 1a, are read in the "natural" time.

We now consider the evolution of the seismic activity in the same framework by ascribing to the k-th event (**after** the recording of the SES activity), instead of Q_k, the corresponding seismic moment M_{0k}; the corresponding continuous function is defined $F'(\omega)$ in an analogous manner

$$F'(t,\omega) = \sum_{k=1}^{N'(t)} M_{0k} \exp\left(i\omega \frac{k}{N'(t)} \right)$$

and after normalization

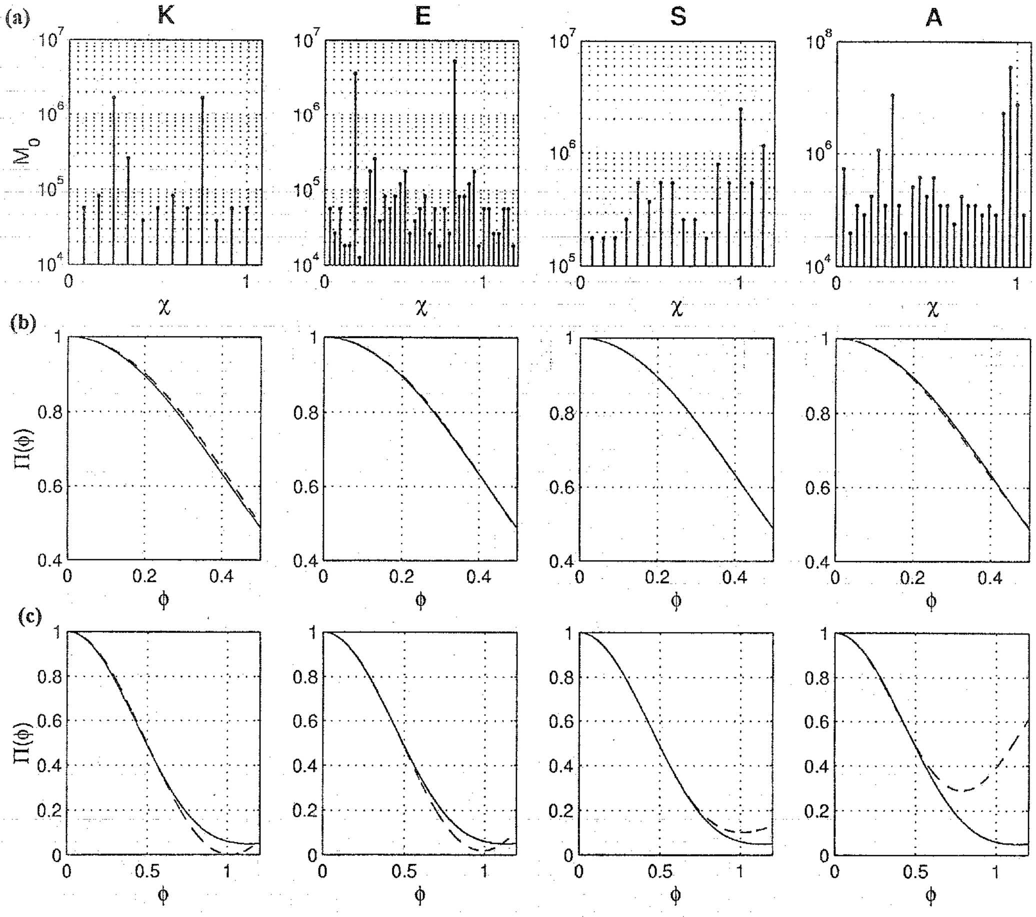

Fig. 3: (**a**) Illustration how the EQs that preceded the main shocks K, E, S and A (see Tables 2–5) are read in "natural" time. (**b**) and (**c**) Comparison of the normalised power spectra $\Pi(\phi)$ for EQs shown in (a) (broken lines) with those predicted from eq. (3) (solid lines). Note that (b) refers to the range $0 < \phi \leq 0.5$, while (c) to $0 < \phi \leq 1.2$.

$$\Phi'(t,\omega) = \frac{\sum_{k=1}^{N'(t)} M_{0k} \exp\left(i\omega \frac{k}{N'(t)} \right)}{\sum_{k=1}^{N'(t)} M_{0k}} = \sum_{k=1}^{N'(t)} p'_k \exp\left(i\omega \frac{k}{N'(t)} \right). \qquad (1')$$

A schematic example of the seismic activity transform to the "natural" time domain is shown in Fig. 1d.

In what follows, we apply this procedure to the data related to the four strongest EQs (labelled K, E, S and A, see Table 1 and Fig. 1b) that occurred in Greece since 1988. The seismic moment M_0 (Kanamori and Anderson, 1975) was estimated using the relation $\log(M_0) = 1.64\ M_L + \text{const}$ (Roumelioti, 1999). The data for the EQs that preceded the main shocks K, E, S and A are given in Tables 2–5 (cf., the corresponding data, but from the preliminary NOA catalogue, can be found in Varotsos *et al.*, 2001c; Tables A2 to A5).

Figure 2 shows how the SES activities, depicted in Fig. 1a, are read in "natural" time, while Fig. 3a shows the corresponding readings for the EQs that preceded the mainshocks K, E, S and A.

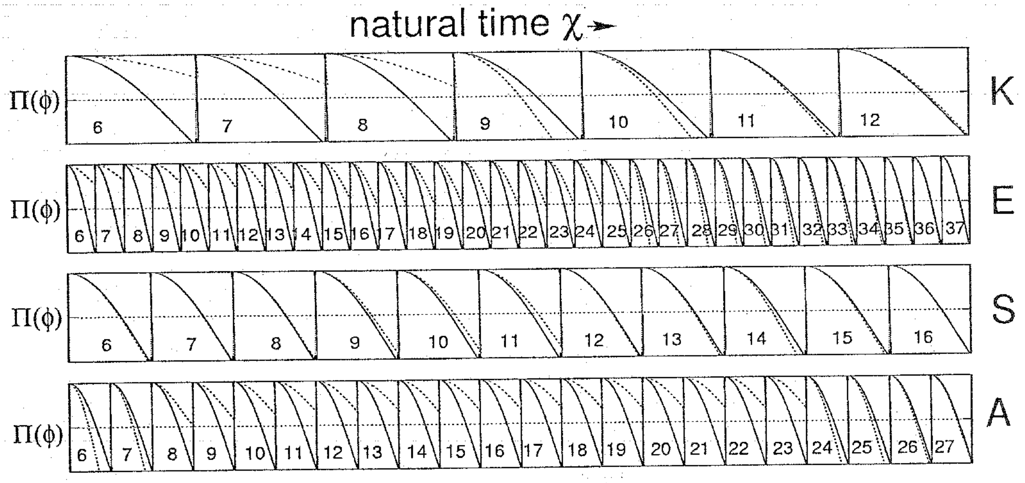

Fig. 4. Time evolution of the normalized power spectra $\Pi(\phi)$, in the window $0 < \phi \le 0.5$, of the seismic activities (broken lines) along with those obtained for the SES activities (solid lines) for the cases of the strong EQs labeled K, E, S and A. The numbers refer to the last event considered in order to calculate the seismicity spectrum (and correspond to the events reported in the Tables 2–5). For the SES activities K_1, K_2, their average is used, while for S the theoretical estimation (eq. 3) is plotted (because the relevant recording of the SES activity depicted in Varotsos *et al.* (1998) did not contain sufficient number of pulses). The final "collapse" of the two spectra, i.e., the SES activity and the subsequent seismicity in each case, can be also seen in Fig. 6.

3. INTERRELATION OF THE "NATURAL" SPECTRA OF SES ACTIVITIES AND THE EVOLUTION OF SUBSEQUENT SEISMIC ACTIVITIES

The continuous lines in Fig. 4 depict the normalized power spectra, $\Pi(\phi)$, deduced from the analysis of the SES activities. In the same figure, we plot (broken lines) the corresponding quantity $\Pi'(\phi)$ obtained from the seismic activity for each case (related to the four main shocks K, E, S, A mentioned above), as it evolves **after** the SES detection, with each new event after the previous events. A careful inspection of this figure shows that the broken lines fall on the continuous line **a few days** before the main shock, **at the most** (see also Fig. 5). We emphasize that this occurs only if we consider the totality of the SES activity, and we do not, e.g., omit a significant portion of its initiation; and this is true in spite of the fact that, in the aforementioned four strong EQs, the corresponding lead times have a large diversity (lying between 3 weeks and 4.5 months; compare the first case with the last one in Table 1).

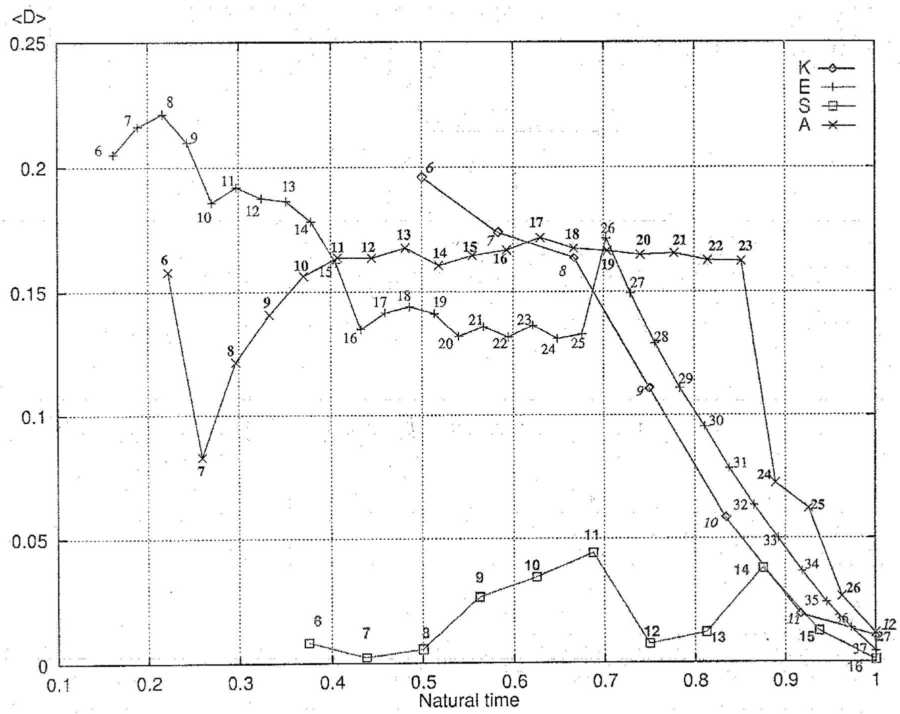

Fig. 5. The average distance D between the $\Pi(\phi)$ curves of the SES activities and the seismic activities *versus* the "natural" time. Main shocks K, E, S, and A correspond to those listed Table 1. The distance drastically decreases only a few days before the main shock. The numbers correspond to the events listed in Tables 2–5.

Table 2

All EQs within $N_{39.2}^{40.5}$ $E_{20.3}^{22.0}$ that occurred after the SES at IOA on April 18 and 19, 1995 until the 6.6 (*Ms* from USGS) main shock at Kozani-Grevena (K) on May 13,1995

No.	Year	Mon.	Day	Hour	Min.	Second	Lat.	Long.	Depth	*ML*
1	1995	Apr.	27	15	16	55.3	39.5	21.13	10	2.9
**)	1995	Apr.	28	20	3	16.7	39.19	20.35	17	3.5
2	1995	Apr.	30	6	58	24.8	39.79	20.72	29	3
3	1995	Apr.	30	7	50	32.14	40.44	21.85	3	3.8*)
4	1995	Apr.	30	21	12	42.6	40	20.66	5	3.3
5	1995	Apr.	30	23	24	54.7	39.81	20.5	10	2.8
6	1995	Apr.	30	23	46	42.5	39.58	20.58	5	2.9
7	1995	May	1	1	49	55.5	39.89	20.74	5	3
8	1995	May	1	22	47	21.1	39.9	21.01	5	2.9
9	1995	May	2	15	52	18.6	39.55	20.58	5	3.8
10	1995	May	5	2	58	5.8	39.38	20.35	10	2.8
11	1995	May	7	5	19	50.3	40.12	20.52	5	2.9
12	1995	May	10	0	1	4.2	40.34	21.79	10	2.9
13	1995	May	10	15	23	2.4	39.28	21.69	10	2.9
14	1995	May	10	18	24	56.3	39.91	20.72	5	2.9
15	1995	May	11	9	14	24.1	39.94	21.28	10	3.1
16	1995	May	13	8	42	12.3	40.07	21.75	5	3.7
17	1995	May	13	8	43	18.7	40.02	21.77	5	4
EQ	1995	May	13	8	47	17	40.18	21.71	39	6.1

*) This event is not reported by NOA but comes from USGS with *ML* (THE).

**) This is just in the boundary of the region selected. Note that if the calculation includes this event but disregards the aforementioned (*) one, i.e., *ML* (THE) = 3.8, a collapse of the spectra is again observed on May 10, 1995.

4. COMPARISON OF THE EXPERIMENTAL NORMALISED "NATURAL" POWER SPECTRUM $\Pi(\Phi)$ WITH SOME ASPECTS OF THE THEORY OF CRITICAL PHENOMENA

According to the model of piezo-stimulated currents, a (re)orientation of the electric dipoles occurs (Varotsos and Alexopoulos, 1986), when approaching a **critical** pressure. Furthermore, it was argued (Varotsos and Alexopoulos, 1986; see p. 404) that the (re)orientation process of each electric dipole has a migration volume orders of magnitude larger than the mean atomic volume, thus involving a large number of atoms (cooperativity). Actually, recent laboratory measurements strengthen the suggestion that the emission of the SES activities could be discussed in the frame of the theory of **dynamic phase transitions** (Varotsos, 2001). In such a frame, Varotsos *et al.* (2001c), by considering also the very stochastic nature of the relaxation process

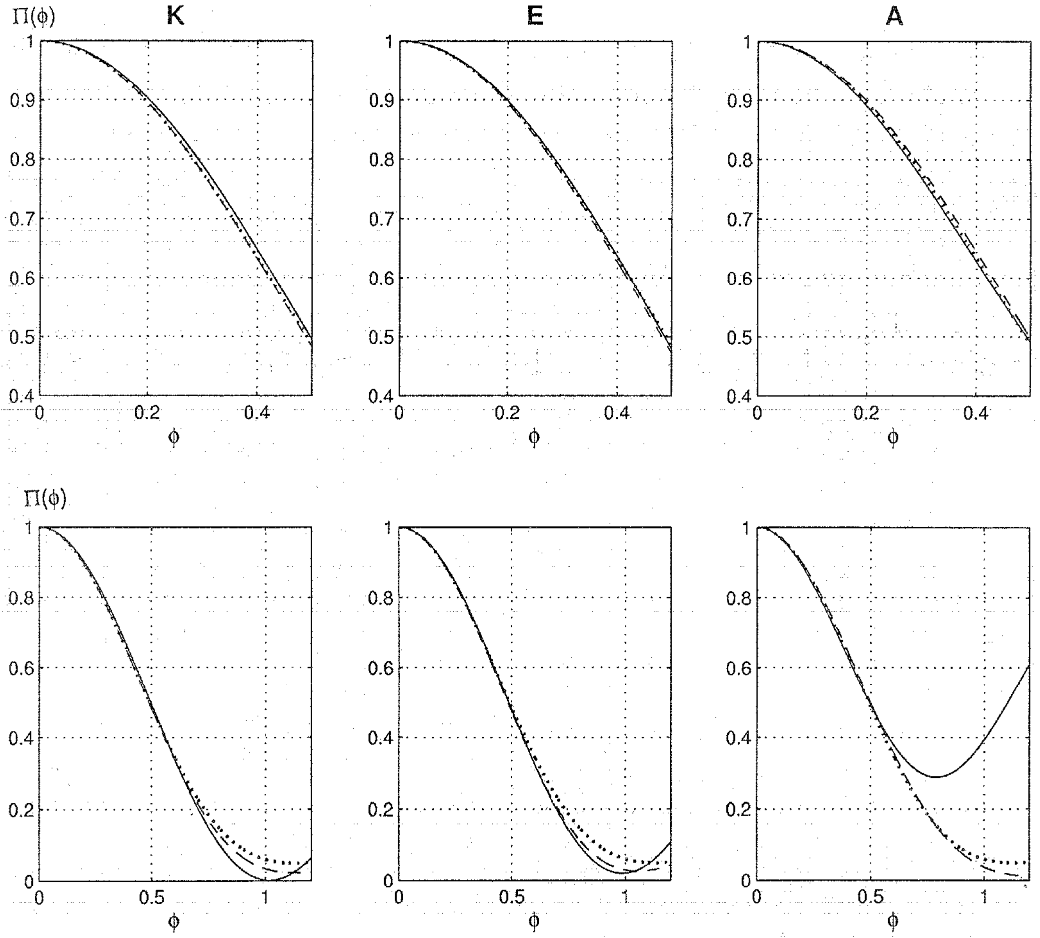

Fig. 6. Comparison of the normalised power spectra $\Pi(\phi)$ of the EQs labeled K, E and A (solid lines) with those corresponding to the relevant SES activities (broken lines) as well as with those estimated from the theoretical considerations (dotted lines; see eq. 3). Upper pannels: $0 < \phi \leq 0.5$; lower pannels: $0 < \phi \leq 1.2$

(Jonscher, 1996 – see p. 354, and references therein), finally obtained that the normalized power spectrum is given by

$$\Pi(\omega) = \frac{18}{5\omega^2} - \frac{6\cos\omega}{5\omega^2} - \frac{12\sin\omega}{5\omega^3}. \tag{3}$$

Expanding eq. (3) around $\omega = 0$, we get $\Pi(\omega) = 1 - 0.07\omega^2 + \ldots$. This implies that the variance of χ is $\kappa_1 = \langle\chi^2\rangle - \langle\chi\rangle^2 = 0.07$ (Varotsos *et al.*, 2001c), which coincides with that obtained for the SES activities when they are analyzed in the "natural" time do-

Table 3

All *) EQs within $N_{37.5}^{39.7}$ $E_{21.5}^{25.0}$ that occurred after the SES at VOL on April 30, 1995 until the 6.5 (*Ms* from USGS) main shock at Eratini-Egio (E) on June 15,1995

No.	Year	Mon.	Day	Hour	Min.	Second	Lat.	Long.	Depth	*ML*
1	1995	Apr.	30	19	4	41.7	38.82	21.45	9	2.9
2	1995	May	2	8	26	56.1	38.2	21.76	32	2.7
3	1995	May	4	16	11	49	38.33	22.05	5	2.9
*	1995	May	6	1	44	12.6	37.7	21.46	10	2.5
4	1995	May	6	17	44	59.5	38.51	21.5	24	2.6
5	1995	May	6	23	10	21.4	38.44	21.8	5	2.6
6	1995	May	8	5	11	9.1	38.32	22.14	21	4
7	1995	May	9	12	48	34.8	38.32	22.09	10	2.5
8	1995	May	10	15	23	2.4	39.28	21.69	10	2.9
*	1995	May	12	7	25	13	39.12	24.48	31	3.6
9	1995	May	13	11	53	1.1	39.56	22.53	10	3.2
10	1995	May	13	13	31	55.2	38.52	22.04	5	3.3
11	1995	May	15	20	15	13.4	38.13	21.66	9	2.8
*	1995	May	16	5	15	44.5	38.97	23.18	33	3.6
12	1995	May	16	10	1	30.6	38.93	21.77	5	3
13	1995	May	17	23	5	25.5	39.73	21.89	5	2.9
14	1995	May	17	23	10	52.7	39.7	21.91	5	3
15	1995	May	17	23	20	30.9	39.74	21.97	5	3.1
16	1995	May	18	4	48	27.8	38.3	22.18	22	3.2
17	1995	May	19	23	19	49.2	38.24	21.87	11	2.7
18	1995	May	19	23	59	26.6	38.12	22.65	34	2.8
19	1995	May	20	20	32	33.3	38.41	21.79	9	2.9
20	1995	May	22	17	35	27.2	39.54	22.43	5	3
21	1995	May	23	2	56	49.2	39.51	22.25	10	2.7
22	1995	May	25	16	41	31.4	39.08	23.5	10	2.9
*	1995	May	25	20	32	11.6	39.74	21.57	35	3
23	1995	May	26	1	28	47.3	38.36	22.63	10	2.6
24	1995	May	26	7	9	25.1	38.36	22	5	2.9
25	1995	May	26	21	30	35.5	38.43	21.81	6	2.7
*	1995	May	28	16	14	44	38.9	25.04	49	3.2
26	1995	May	28	19	56	41	38.38	21.96	5	4.1
27	1995	May	28	20	9	14.7	38.4	21.9	5	3
28	1995	May	28	21	51	1.6	38.28	22.67	10	3
*	1995	May	29	13	3	3.7	37.61	22.78	5	2.8
29	1995	May	30	9	6	31.6	38.5	21.74	5	3.1
*	1995	May	31	12	25	42.5	39.21	22.88	10	3
*	1995	May	31	21	43	30.7	39.39	22.63	29	3
30	1995	June	1	14	4	53.5	38.13	21.74	5	3.2
*	1995	June	2	14	47	46.8	39.2	23.14	32	3.1
31	1995	June	4	18	47	35.5	38.5	22.25	5	2.6

Table 3 (cont.)

No.	Year	Mon.	Day	Hour	Min.	Second	Lat.	Long.	Depth	*ML*
32	1995	June	5	15	4	40.6	38.88	21.51	5	2.9
33	1995	June	5	16	50	24.9	38.86	21.47	5	2.9
34	1995	June	5	18	34	46	38.98	21.47	12	2.7
35	1995	June	5	18	35	31	38.97	21.47	7	2.7
36	1995	June	6	20	12	14.5	38.8	21.58	5	2.9
37	1995	June	12	20	27	7.2	38.21	22.22	39	2.9
38	1995	June	13	2	48	39.8	38.29	22.47	10	2.6
39	1995	June	14	11	8	41.6	38.04	21.54	28	2.5
EQ	1995	June	15	0	15	51	38.37	22.15	26	5.6

*) Excluding those close to (VOL) and inside the Peloponese, as stated in the prediction text (Varotsos *et al.*, 1996).

main. Furthermore, for the region of natural frequencies $0 < \phi \leq 0.5$, where $\Pi(\phi)$ should be considered as a characteristic function for p_k, the experimental results (for both, the EQs and SES activities) scatter around the theoretical estimation of eq. (3), as seen in Fig. 6.

We must clarify, however, that the aforementioned theoretical lines of Varotsos *et al.* (2001c) were developed for the SES activities only. The fact that the seismicity "natural" spectrum falls (in the region $0 < \phi \leq 0.5$) a few days before the main shock on that of the preceding SES activity (Fig. 4; this cannot be attributed to chance, see Table 6) indicates that eq. (3) is a good approximation (Fig. 3b) for the seismic events as well. We stress, however, that the latter agreement occurs **only if** the seismicity is sampled from the region that has been estimated to suffer the major EQ (on the basis of the available SES analysis). The importance of eq. (3) is further strengthened from the finding that the study of the seismicity, for long time periods, results in a "natural" spectrum that has a certain connection to eq. (3) (see the Appendix). This point, however, merits further investigation.

5. CONCLUSIONS

The main conclusion of this paper is that the use of the concept of "natural" time may open up the possibility of estimating the time of the occurrence of an impending mainshock with accuracy better than hitherto available. Specifically, once an SES activity has been recorded, we can proceed to its analysis and find its normalized "natural" power spectrum $\Pi(\phi)$. Then, the continuous inspection of the corresponding spectrum of the evolving seismicity (after the SES recording) in the candidate area, reveals when it falls (in the region $0 < \phi \leq 0.5$) on that of the preceding SES activity. The data

Table 4

All *) EQs between $N_{37.0}^{38.5}$ $E_{20.3}^{21.7}$ that occurred after the SES at IOA on Oct. 3 and 5, 1997 until the 6.4 (*Ms* from USGS) main shock at Strofades (S) on Nov. 18, 1997

No.	Year	Mon.	Day	Hour	Min.	Second	Lat.	Long.	Depth	*ML*
*	1997	Oct.	3	2	51	25.6	37.52	21.26	5	3
1	1997	Oct.	3	23	3	50	37.69	21.38	5	3.2
2	1997	Oct.	4	17	57	57.7	37.74	20.38	5	3.2
*	1997	Oct.	8	0	0	41.6	37.89	21.25	8	2.7
3	1997	Oct.	9	2	34	45.9	37.3	20.65	5	3.2
*	1997	Oct.	9	9	27	25.6	37.33	20.63	5	2.9
*	1997	Oct.	10	3	31	13.1	38.11	20.56	5	3
4	1997	Oct.	11	23	1	41.5	37.8	21.28	5	3.3
5	1997	Oct.	13	23	12	19.2	37.44	20.73	5	3.5
6	1997	Oct.	15	22	39	20.3	38.3	21.72	5	3.4
*	1997	Oct.	17	19	47	36.9	37.1	21.49	5	2.9
*	1997	Oct.	18	2	56	25.4	37.41	20.78	10	2.8
*	1997	Oct.	18	5	49	34.4	37.37	21.62	10	2.8
*	1997	Oct.	18	5	52	57	37.81	21.1	10	2.9
*	1997	Oct.	19	0	13	33.2	38.34	21.66	5	2.9
*	1997	Oct.	19	12	29	9.7	37.56	20.79	23	2.9
*	1997	Oct.	20	0	29	54.9	38.53	21.62	36	2.8
*	1997	Oct.	20	17	29	31.5	37.67	21.18	5	2.8
*	1997	Oct.	20	20	26	23.9	37.58	21.26	5	2.8
*	1997	Oct.	21	0	30	42	37.78	21.14	7	2.8
*	1997	Oct.	21	3	12	27.2	37.69	21.47	5	2.9
*	1997	Oct.	22	11	3	49.4	37.46	21.09	28	2.8
*	1997	Oct.	24	2	18	52.2	37.57	21.3	5	2.9
*	1997	Oct.	24	10	24	57.7	37.69	21.47	5	2.8
*	1997	Oct.	25	23	2	4.8	38.31	21.67	5	2.8
*	1997	Oct.	26	4	47	2.4	37.79	21.64	36	2.7
*	1997	Oct.	26	23	43	19.6	37.3	20.47	5	3.1
7	1997	Oct.	27	1	29	33.4	37.44	20.7	5	3.5
*	1997	Oct.	27	8	25	5.1	38.32	21.72	5	2.9
*	1997	Oct.	28	14	0	26.3	37.5	21.09	10	2.9
*	1997	Oct.	31	11	46	10.3	38.34	20.46	25	3.1
8	1997	Nov.	1	6	8	15.5	37.68	21.4	5	3.5
9	1997	Nov.	1	8	33	28.6	37.65	21.36	5	3.3
*	1997	Nov.	1	20	27	37.5	37.62	21.28	10	2.7
*	1997	Nov.	1	20	31	42.5	37.62	21.48	10	2.8
*	1997	Nov.	3	0	42	16.9	37.6	21.33	5	2.9
*	1997	Nov.	3	8	29	33	37.47	21.45	31	3
*	1997	Nov.	3	17	56	43.9	37.5	21.25	27	2.8
*	1997	Nov.	4	17	10	13.5	37.58	21.32	10	2.9
*	1997	Nov.	4	19	56	59.7	37.62	21.55	10	2.6

Table 4 (cont.)

No.	Year	Mon.	Day	Hour	Min.	Second	Lat.	Long.	Depth	*ML*
10	1997	Nov.	4	21	24	44.2	37.54	21.26	5	3.3
*	1997	Nov.	6	19	38	7.8	37.66	21.36	5	3
*	1997	Nov.	6	20	29	19.9	37.19	20.63	5	2.9
11	1997	Nov.	8	4	31	30.4	37.68	21.51	5	3.2
12	1997	Nov.	10	0	55	8.7	37.91	20.69	5	3.6
*	1997	Nov.	11	4	6	48.3	37.05	20.81	5	2.9
*	1997	Nov.	12	4	37	12.4	37.78	21.12	10	3
13	1997	Nov.	12	11	19	23.6	37.93	20.89	5	3.5
*	1997	Nov.	13	1	35	55.8	37.68	21.35	5	2.8
14	1997	Nov.	13	10	30	17.2	36.99	21.5	5	3.9
15	1997	Nov.	16	18	38	51.6	37.2	20.33	10	3.5
16	1997	Nov.	17	6	58	9.8	37.61	21.42	22	3.7
*	1997	Nov.	17	22	51	26.8	37.61	21.34	5	3
EQ	1997	Nov.	18	13	7	36.9	37.26	20.49	5	6.1

*) Only EQs with $ML \geq 3.2$ were included in the calculations.

Table 5

All *) EQs within $N^{39.5}_{38.7}$ $E^{25.0}_{22.0}$ that occurred after the SES at VOL on Mar. 17, 2001 until the 6.6 (*Ms* from USGS) main shock in Aegean sea (A) on July 26, 2001

No.	Year	Mon.	Day	Hour	Min.	Second	Lat.	Long.	Depth	*ML*
1	2001	Mar.	23	23	13	43.3	38.74	23.6	5	3.5
2	2001	Mar.	25	11	29	24.9	38.85	23.43	10	2.8
3	2001	Apr.	13	21	24	2.5	39.09	23.45	5	3.1
4	2001	Apr.	16	3	27	41	39.11	22.46	5	3
*	2001	Apr.	16	6	39	38.4	38.68	22.41	29	3.1
5	2001	Apr.	24	11	39	9.7	39.19	22.71	10	3.2
6	2001	May	14	8	33	6.1	38.79	23.68	4	3.7
7	2001	May	14	17	26	3.9	38.98	23.19	6	3.1
8	2001	May	19	3	11	16.1	39.16	22.57	5	4.3
9	2001	May	20	1	36	21.4	39.49	22.55	37	3.1
*	2001	May	20	3	37	46	38.85	22.01	5	3.5
10	2001	May	23	1	24	10.7	38.74	23.84	10	2.8
11	2001	May	25	22	23	21	38.83	24.85	10	3.3
12	2001	May	27	0	46	38.2	38.83	24.71	27	3.4
13	2001	May	30	7	37	58.9	38.88	23.68	5	3.2
*	2001	June	4	18	3	51.2	38.97	21.99	2	3.3
14	2001	June	8	23	40	37.3	39.08	23.17	5	3.4
15	2001	June	9	2	1	17.3	39.33	23.07	2	3.1

Table 5 (cont.)

No.	Year	Mon.	Day	Hour	Min.	Second	Lat.	Long.	Depth	M_L
*	2001	June	11	5	28	45	39.16	25.02	10	3.7
*	2001	June	12	3	4	22.2	38.69	24.96	30	3.7
16	2001	June	20	6	34	5.5	38.86	23.3	21	3.1
17	2001	July	4	19	57	43.9	39.48	22.23	5	2.9
*	2001	July	5	2	49	16.6	39.08	22	5	2.9
18	2001	July	7	11	39	24.5	39.51	23.07	18	3.2
19	2001	July	10	22	26	49.5	39.36	23.02	10	3.1
20	2001	July	12	1	49	9	39.32	22.96	5	3.1
21	2001	July	12	3	2	40.7	39.34	23.57	13	3
22	2001	July	13	1	52	55.8	39.31	23.07	5	3.1
23	2001	July	19	20	11	19	39.31	23.42	37	3
24	2001	July	21	12	45	59.8	39.1	24.35	21	4.1
25	2001	July	21	12	47	38.7	39.06	24.35	18	4.6
26	2001	July	25	15	43	13.4	39.06	24.32	19	4.2
27	2001	July	25	16	35	40.6	39.04	24.19	5	3
EQ	2001	July	26	0	21	39.3	39.05	24.35	19	5.3

*) Excluding those outside the predicted area (see Varotsos *et al.*, 2001d).

Table 6

The estimated probability P to achieve the behaviour depicted in Fig. 4 by chance

General conditions	Case	Minimum of D between the:	P*) (in %)
a) The distance $D \leq 0.012$ (see Fig. 5). b) Continuous decrease of D in the last three events. c) The seismic spectrum approaches the theoretical curve from below (eq. 3). d) D becomes minimum a few days only before the main shock (see the 3rd column).	K	12th and 15th event	< 5.9 ± 1.1
	E	37th and 39th event	< 1.4 ± 0.2
	S	15th and 16th event	< 1.9 ± 0.2**)
	A	26th and 27th event	< 1.6 ± 0.3

*) Value resulting from continuous scanning of the EQ catalogue, since 1966 until the main event in each case. The calculation was made in each of the four regions mentioned in Tables 2–5.

**) The distance $D \leq 0.0033$ was used in this case.

analysis shows that this "collapse" seems to occur only a few days before the occurrence of the main shock.

The form of the normalized "natural" power spectrum $\Pi(\phi)$, obtained from the analysis of the SES activities related to the four strongest main shocks in Greece since 1988 (as well as that of the evolving seismicity, after the SES recording until each main shock), agrees with that emerged from the theory of dynamic phase transitions (critical phenomena).

APPENDIX

THE FEATURE EMERGED FROM A LONG PERIOD STUDY OF THE SEISMICITY IN THE "NATURAL" TIME DOMAIN

In order to further investigate the point concerning the appropriateness of eq. (3) to describe the evolution of seismicity, but under certain conditions (with respect to the geographical region and the time period elapsed since the SES recording until the main shock), we proceeded to the following analysis: the seismic data, available from NOA, were analyzed in the natural time domain for the whole Greek region, during the period 1966–2001 (Fig. A1a). The calculation was made in each case by considering a number of subsequent events, from 6 to 40 (i.e., around the limits in the number of the EQs used in the curves depicted in Figs. 3b, c and 4), and scanning the whole catalogue. An inspection of Fig. A1a reveals that the local maxima of the curves, each one of which was drawn for a certain φ-value, correspond to $\Pi(\varphi)$ values that lie very close to those predicted from eq. (3). This figure indicates that, when considering the totality of the events with a low magnitude threshold, e.g., $M_L \geq 2.5$ (solid lines), such an agreement is not so evident; on the other hand, when selecting a considerable threshold, e.g., $M_L \geq 4.3$ (dotted lines), an agreement between the $\Pi(\varphi)$ values, corresponding to the maxima of the curves, and those predicted form eq. (3) becomes apparent (thus, probably indicating that the catalogue for a larger magnitude threshold is more complete). Note that Varotsos *et al.* (2001c) found this agreement when analyzed, in the natural time domain, the totality of the seismic data since 1966 until the main shock under discussion, for each of the regions mentioned in Tables 2–5 (Fig. A1a). This agreement also holds for other seismic areas, e.g., if we consider the seismic data for the San Andreas fault system (Fig. A1b); the same curves are practically obtained if the number of subsequent events is changed, e.g., within the limits 6–100. The slight differences between Fig. A1a and Fig. A1b might be associated with the different b-values in the usual Gutenberg-Righter relation, $\log N = a - b\,M$, in the two areas studied.

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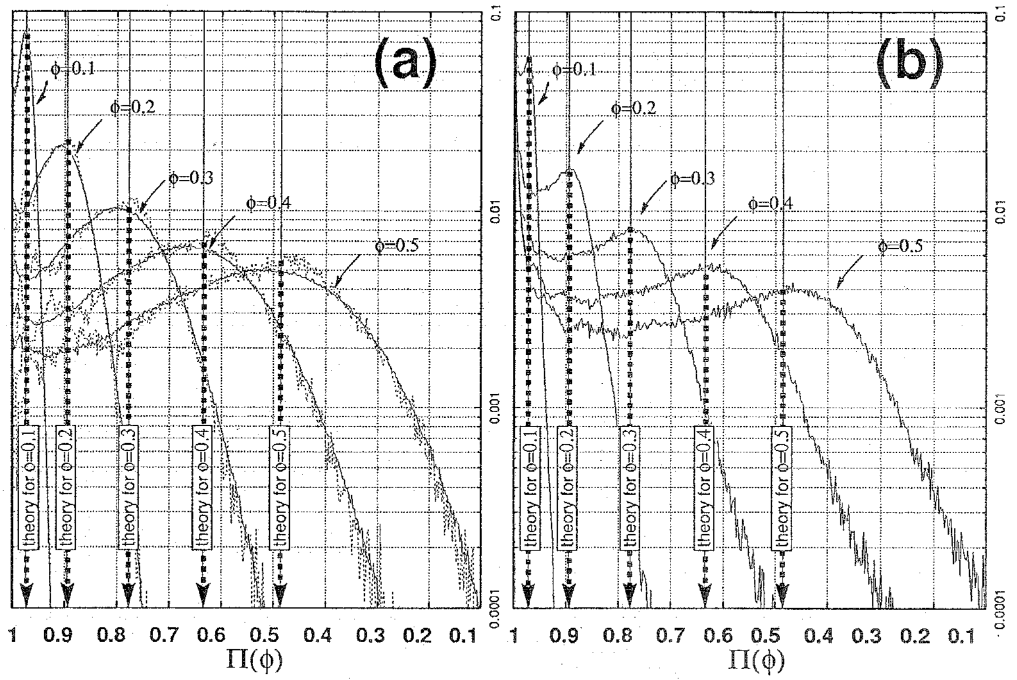

Fig. A1. The observed probability $P[\Pi(\varphi)]$ to obtain a given value of $\Pi(\varphi)$ *versus* the normalized "natural" power spectra $\Pi(\varphi)$ for the seismicity: (a) For the whole Greek area during the period 1966–2001 (the solid lines are calculated with a magnitude threshold $M_L \geq 2.5$, while the dotted ones correspond to the EQs with $M_L \geq 4.3$). (b) For the case of the San Andreas fault system using the USGS catalogue, available from: http://neic.usgs.gov/neis/epic/epic.html, for the period 1973–2001, within the area $N_{31}^{42}\ W_{125}^{114}$. (The moment magnitude relations available from Global Seismological Services at the site, http://www.seismo.com/msop/nmsop/03%20source/source6/source6.html, were considered for the different magnitude scales reported in this catalogue).

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