Nat. Hazards Earth Syst. Sci., 9, 17–23, 2009
www.nat-hazards-earth-syst-sci.net/9/17/2009/

Natural Hazards and Earth System Sciences

Power law relationship between parameters of earthquakes and precursory electrical phenomena revisited

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Received: 7 October 2008 – Revised: 1 December 2008 – Accepted: 1 December 2008 – Published: 7 January 2009

Abstract. The power law relation between the stress drop of "non thrust" earthquakes and the lead time of precursory Seismic Electric Signals (SES), obtained by Dologlou (2008a), has been tested by using additional data from the most recent earthquake that occurred on 8 June 2008, in Andravida, NW. Peloponnesus, Greece and from two other destructive earthquakes that occurred in the past in Ionian sea. A critical exponent α=0.33 is derived which is close to the one (e.g. 0.29) reported by Dologlou (2008a). The above preliminary result strengthens the hypothesis that probably signatures of criticality are present in the earthquake preparation and precursory SES processes and that both phenomena are governed by same physics.

1 Introduction

Low frequency (<1 Hz) transient changes of the electrotelluric field, the so called Seismic Electric Signals (SES), have been monitored at different sites in Greece since 1981 and were found to precede large earthquakes (Varotsos and Alexopoulos, 1984a, b; Varotsos et al., 1986). The SES signals are characterized by some features as: the selectivity, which states that a SES station can be sensitive to specific seismic areas at long distances and inactive to some others at shorter distances; the lead time, Δt, which is the time difference between the SES detection and the earthquake occurrence with a lead time span of few months (Varotsos and Alexopoulos, 1984a, b, 1987; Varotsos et al., 1993). To distinguish the SES signal from artificial noise the criterion $\Delta V/L$=constant is applied, where ΔV is the potential difference between two points on the ground at a distance L measured by a pair of buried electrodes (Varotsos and Alexopoulos, 1984a; Sarlis et al., 1999; Varotsos et al., 1998, 2003). (This distinction is alternatively achieved by using the criteria based on a new time domain, termed the "natural time", see Varotsos et al. (2004) and references therein). The quantity $\Delta V/L$ is the SES amplitude E which is connected to the magnitude M of the impending earthquake by the experimental formula:

$$\log E = \alpha M + b \tag{1}$$

where a≈0.3−0.4 and b is a site constant. This in fact is a power law relation that is reminiscent of the theory of critical phenomena (Varotsos and Alexopoulos, 1984a, b; Varotsos, 2005).

Before an earthquake, the pressure increases in the future focal area and produces changes in various physical properties like porosity, conductivity (Varotsos, 1981), dielectric constant (Varotsos, 1978, 1980), etc. In addition, it affects the relaxation time of electric dipoles which are formed in an ionic solid between introduced aliovalent impurities (Varotsos and Miliotis, 1974) and vacancies created for charge compensation (Varotsos and Mourikis, 1974; Kostopoulos et al., 1975). This relaxation time, τ, is given by the equation

$$\tau = (\lambda\nu)^{-1}\exp(g/kT) \tag{2}$$

where ν is the attempt frequency for a jump to a number of λ accessible paths (Varotsos and Alexopoulos, 1980a, 1981) in the vacancy vicinity, T is the temperature and g the Gibbs energy for the orientation process.

As the pressure increases the relaxation time becomes significantly smaller, provided that the migration volume v=$(dg/dP)_T$ (Varotsos et al., 1982, 1999) or the activation (Varotsos and Alexopoulos, 1980b) is negative, and when the pressure reaches a *critical* value, P_{cr}, a transient current is emitted due to the cooperative re-orientation of dipoles (Varotsos and Alexopoulos, 1986).

Beyond the above model the electrokinetic effect (Ishido and Mizutani, 1981; Mizutani et al., 1976) has been suggested for the SES generation, in terms of criticality, which

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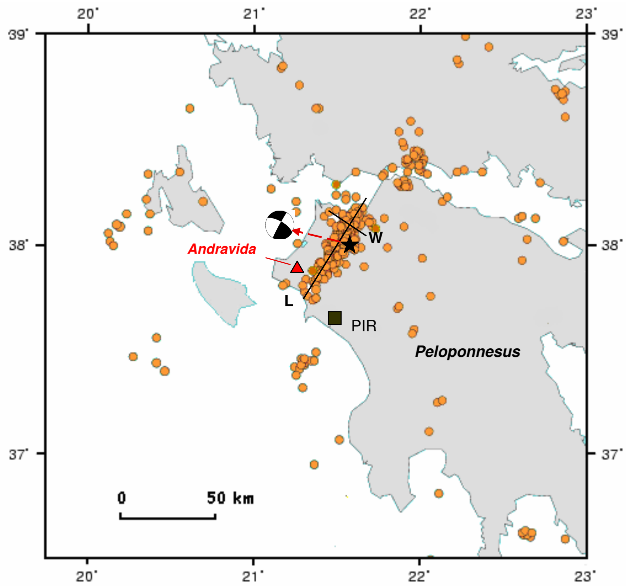

Fig. 1a. Map of Western Greece, with the distribution (forming a cluster) of all reported by USGS aftershocks with $M_w \geq 3$ **(a)** for Andravida earthquake (8 June 2008) for the period 8 June 2008 to 20 September 2008 **(b)** for Strofades earthquake (18 November 1997) for the period 18 November 1997 to 31 May 1998 and **(c)** for Killini earthquake (16 October 1988) for the period 16 October 1988 to 1 March 1989. The epicentres of the corresponding main shocks are presented by stars and their focal mechanisms by a lower hemisphere projection with black and white quadrants for compression and dilatation, respectively (beach ball). Representative aftershock areas of length L and width W for all cases are marked. Black squares denote the position of the SES station of PIR and IOA and red triangles the cities of Andravida and Killini.

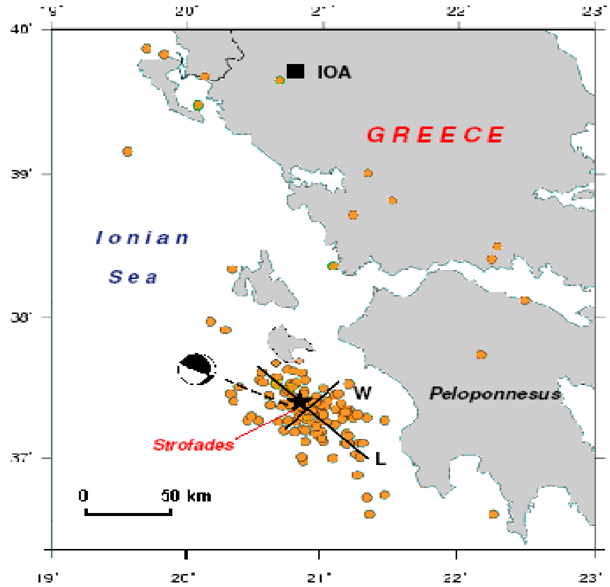

Fig. 1b. Continued.

leads to an exponent of 0.3–0.4 for critical phenomena (Surkov et al., 2002). Alternatively, Sornette et al. (1989) support the hypothesis that fracture processes exhibit critical behavior expressed by a power law relation with critical exponent values of 0.33 and 0.47 for 2 and 3 dimensions, respectively.

In previous papers by Dologlou (2008a, b) a power law relation with fractal critical exponent has been obtained between the earthquake stress drop and the SES lead time. Stress drop is an earthquake parameter which basically reflects the difference between two states of stress at a point on a fault before and after rupture (Kanamori and Anderson, 1975).

It is of great interest and the purpose of the present work to check the validity of this relation by using additional data from three destructive earthquakes which occurred in Greece, the first in Andravida on 8 June 2008, the second in Strofades on 18 November 1997 and the third in Killini on 16 October 1988.

2 Data and analysis

In previous papers (Dologlou, 2008a, b) we referred to earthquakes for which Brune's stress drop values have been reported in literature. In this work, in order to extend our data set, we tried to overcome the lack of published stress drop values for some events by using an indirect method based on the aftershock area (Kiratzi et al., 1991). This technique can be only applied to strong and shallow earthquakes (i.e. $M>5.8$ depth<40 km) since a rich aftershock sequence is required to well define the aftershock area. Thus, earthquakes of considerable depth such as the two large events which occurred in Greece on 8 January 2006 with M_w=6.7 and depth h=66 km in Kithira and on 6 January 2008 with M_w=6.2 and h=75 km in Leonidio, can not be treated with this method.

On 8 June 2008 at 12:25 UTC an earthquake of magnitude M_w=6.3 occurred in Andravida (37.9 N 21.5 E) NW of Peloponnesus, Greece (Fig. 1a) and caused severe damage and human losses. It was preceded by a SES activity recorded at PIR station (Fig. 1a) on 29 February 2008 which was published on 29 May 2008 (Sarlis et al., 2008). The lead time of this event was Δt=98 days. Additionally on 18 November, 1997 at 14:07 UTC a strong earthquake of M_w=6.6 occurred near Strofades island (37.33 N 20.84 E) in Ionian sea and it was preceded by a SES activity at IOA station on 4 October 1997 with Δt=45 days. Furthermore, on 16 October 1988 at 12:34 UTC a damaging earthquake of M_w=5.9 occurred near Killini (37.95 N 20.90 E) in Ionian sea with precursory SES activity recorded at IOA station with Δt=17.5 days.

Table 1. The updated version of the table reported by Dologlou (2008a) including Andravida, Strofades and Killini cases (events no. 16, 9 and 5). All 16 earthquakes are presented with available stress drop values and precursory SES signals in Greece from 1981 to 2008, along with their dates, epicentres, depths, moment magnitudes M_w, stress drop values ($\Delta\sigma_B$), SES station, SES lead times Δt and mechanism type (strike-slip, normal or thrust). Events are numbered in chronological order and references for the stress drop values are given in the last column.

n	yy mm dd	H	min	S	Lat	Long	Depth (km)	M_w	$\Delta\sigma_B$ bars	SES Δt (days)	Source mechanism	References
1	81 12 19	14	10	50.7	39.24	25.23	12	6.8	9.01	0.3	strike-slip	Dologlou (2008a)
2	82 01 18	19	27	24.5	40	24.32	6	6.6	10.5	0.3	strike-slip	Dologlou (2008a)
3	83 01 17	12	41	29	38.09	20.19	10	6.9	14.0	1.8	strike+thrust	Stavrakakis and Blionas (1990)
4	86 09 13	17	24	34	37.03	22.2	15	5.9	5.0	5	normal	Papazachos et al. (1988)
5	88 10 16	12	34	06	37.95	20.90	29	5.9	2.53	17.5	strike-slip	see text
6	95 05 04	0	34	11	40.54	23.63	15	5.4	2.5	28.5	normal	Chouliaras-Stavrakakis (1997)
7	95 05 13	8	47	15	40.16	21.67	15	6.5	6.3	25.5	normal	Chouliaras-Stavrakakis (1997)
8	95 06 15	0	15	56	38.1	22.46	15	6.5	2.9	46	normal	Chouliaras-Stavrakakis (1997)
9	97 11 18	14	7	53	37.33	20.84	22.9	6.6	1.42	45	strike slip	see text
10	99 09 07	11	56	56	37.97	23.6	15	6	3.0	6	normal	Stavrakakis-Chouliaras (2002)
11	01 07 26	0	21	44	38.96	24.29	15	6.5	9.0	130	strike-slip	Benetatos et al. (2002)
12	03 08 14	5	15	8	38.7	20.67	15	6.3	8.0	6	strike-slip	Papadimitriou (2007)
13	08 01 06	5	14	20	37.22	22.69	75	6.2	9.0	60	thrust+strike	Papadimitriou (2008)
14	08 02 04	20	25	9.5	38.08	21.94	20	5	1.6	25	strike-slip	Papadimitriou (2008)
15	08 02 14	10	9	22.7	36.5	21.67	29	6.9	9.0	30	thrust	Papadimitriou (2008)
16	08 06 08	12	25	29.7	37.96	21.52	16	6.3	1.83	98	strike-slip	see text

Since stress drop values for these events were not available in literature, the Brune's stress drop (Brune, 1970, 1971) has been calculated using the formula by Hanks and Wyss (1972):

$$\Delta\sigma_B = 0.44 M_o / r^3 \quad (3)$$

where M_o is the seismic moment and r the radius for a circular fault derived from P and S teleseismic waves displacement spectra. In our case, the radius r is estimated from the dimensions of the aftershock area according to Kiratzi et al. (1991) for the three events as follows:

All aftershocks of Andravida, Strofades and Killini earthquakes with $M_w \geq 3$ reported by USGS for the periods, 8 June 2008 (12:30) to 20 September 2008, 18 November 1997 (14:07) to 31 May 1998 and 16 October 1988 (12:34) to 1 March 1989, respectively are shown on three separate maps in Figs. 1a,b, and c, along with their main shock epicentres, denoted by a star and their focal mechanisms presented by a beach ball. From the distribution of the aftershock epicentres, which forms a well defined cluster, an area $S = L \times W$ with length L and width W is estimated in all cases (Fig. 1a, b, c). For Andravida event the range of values for L and W, due to estimation error, is considered as (60–70) km and (18–22) km, for Strofades earthquake (80–90) km and (30–38) km and for Killini (35–40) and (8–12), respectively . The radius r is obtained from the relation $S = \pi r^2$. Two slightly different seismic moment values $M_{01} = 3.9 \times 10^{25}$ dyn. cm $M_{02} = 3.1 \times 10^{25}$ dyn. cm are

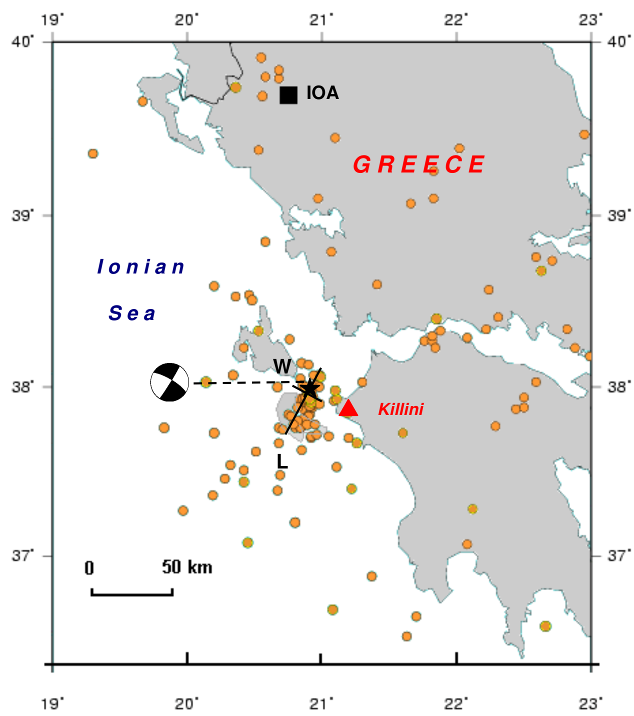

Fig. 1c. Continued.

Table 2. The date, the magnitude M_w and the seismic moment of Andravida earthquake along with the range of values in the dimensions of the aftershock area L and W, and the corresponding calculated values for $\Delta\sigma_B$. Mean values are given in the last row.

Date	M_w	Mo (10^{25} dyn. cm)	L (km)	W (km)	$\Delta\sigma_B$ (bars)
yy mm dd					
08 06 08	6.3	3.9	60–70	18–22	2.6–1.58
		3.1	60–70	18–22	2.14–1.26
Mean value		3.5	65	20	1.83

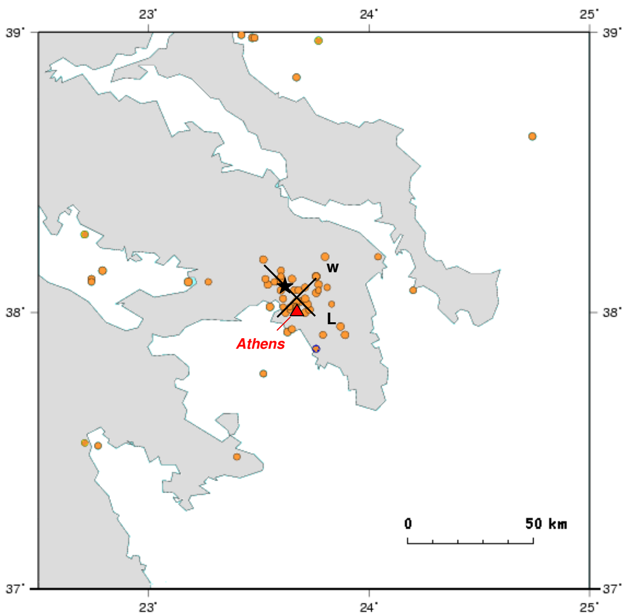

Fig. 2a. Map of central Greece with the distribution (forming a cluster) of the all reported by USGS aftershocks with $M_w \geq 3$ **(a)** for Athens earthquake (7 September 1999) for the period 7 September 1999 to 7 September 2000 and **(b)** for Egion earthquake (15 June 1995) for the period 15 June 1995 to 15 June 1996. The epicentres of the corresponding main shocks are presented by stars. Representative aftershock areas of length L and width W for both cases are marked. Red triangles denote the position of the cities of Athens and Egion, respectively.

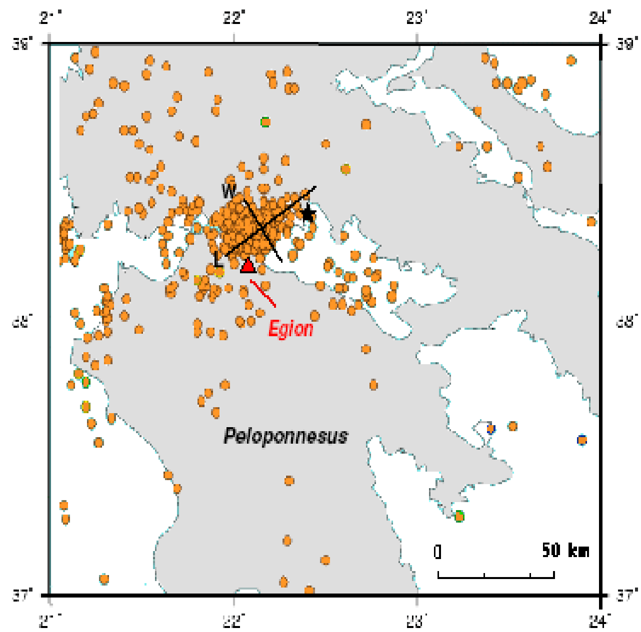

Fig. 2b. Continued.

reported for Andravida by USGS while for Strophades and Killini events the seismic moment is 9×10^{25} dyn. cm and 7.5×10^{24} dyn. cm, respectively. The stress drop $\Delta\sigma_B$ is calculated through Eq. (3) in all cases (Tables 2, 3 and 4). The critical exponent α in the power law relation between the stress drop and the lead time is derived from the list (Table 1) of $\Delta\sigma_B$ and Δt values of all "non thrust" earthquakes, included the Andravida, Strofades and Killini events. It is difficult to give an explanation why earthquakes of thrust type mechanism do not obey the power law relationship. A very tentative suggestion could be the fact that geodynamics of thrust mechanism are quite different from those of other mechanisms (i.e., normal, strike-slip). Earthquakes of thrust type usually occur in collision or subduction zones which are characterized by high accumulation of strain.

Table 1 is the updated version of the table reported by Dologlou (2008a) by adding Andravida, Strofades and Killini earthquakes (events no. 16, no. 9 and no. 5), and includes all sixteen earthquakes numbered in chronological order along with their seismic parameters (dates, epicentres, depths, moment magnitudes M_w), source mechanism (strike-slip, normal or thrust type), stress drop $\Delta\sigma_B$ and SES lead times. Bibliographical references for the stress drop values are given in the last column of this Table and the lead times, Δt, for events no. 1, 2 are reported by Varotsos and Alexopoulos (1984a) – see their Figs. 2 and 3, respectively – while for events no. 3–12 by Varotsos (2005). The three recent events (no. 13–15) are given by Varotsos et al. (2007), for the event no. 13 and Varotsos et al. (2008) for no. 14, 15.

Table 3. The date, the magnitude M_w and the seismic moment of Strofades earthquake along with the range of values in the dimensions of the aftershock area L and W, and the corresponding calculated values for $\Delta\sigma_B$. Mean values are given in the last row.

Date	M_w	Mo (10^{25} dyn. cm)	L (km)	W (km)	$\Delta\sigma_B$ (bars)
yy mm dd 97 11 18	6.6	9	80–90	30–38	1.88–1.10
		Mean value	85	34	1.42

Table 4. The date, the magnitude M_w and the seismic moment of Killini earthquake along with the range of values in the dimensions of the aftershock area L and W, the corresponding calculated values for $\Delta\sigma_B$, the critical exponent α and associated correlation coefficient R. Mean values are given in the last row.

Date	M_w	Mo (10^{25} dyn. cm)	L (km)	W (km)	$\Delta\sigma_B$ (bars)	α	R
yy mm dd 88 10 16	5.9	0.75	35–40	8–12	3.9–1.77	0.32–0.34	0.80–0.79
		Mean value	37.5	10	2.53	0.33±0.1	0.80

Table 5. Date, epicenters, magnitude M_w, seismic moment Mo, range of values in the dimensions of the aftershock area L and W, corresponding calculated values for $\Delta\sigma_B$, mean value $\Delta\sigma_{B\text{mean}}$ and reported $\Delta\sigma_B$ for Egion and Athens earthquakes.

EQ	Date yy mm dd	Lon (N)	Lat (E)	M_w	Mo (10^{25} dyn. cm)	L (km)	W (km)	$\Delta\sigma_B$ (calclulated) (bars)	$\Delta\sigma_{B\text{mean}}$ (bars)	$\Delta\sigma_B$ (reported) (bars)
Egion	95 06 15	38.4	22.3	6.5	6	45–50	25–30	3.9–2.5	3.2	2.9
Athens	99 09 07	38.1	23.6	6	1.1	20–35	20–25	3.4–1.05	2.2	3.0

The value range for the estimated dimensions L and W and the corresponding calculated stress drop $\Delta\sigma_B$ for Andravida, Strofades and Killini events, are given in Tables 2, 3 and 4, respectively. The derived critical exponent α with the associated correlation coefficient are shown in Table 4. A mean value of α with its error is also inserted.

Event no. 11 is excluded from the present paper for the same reasons referred by Dologlou (2008a) and thoroughly discussed by Dologlou et al. (2008). Briefly, this earthquake, with an unusual long lead time, occurred in an area which is characterized by specific structural features such as small thickness of the crust (Le Pichon et al., 1984) and high heat flow rate (Jongsma, 1974).

3 Discussion

In order to check the compatibility between the reported Brune's stress drop values and those derived by using the dimensions of the aftershock area we tested two well known for the severe casualties and victims cases, the Athens earthquake on 7 September 1999 and the Egion earthquake on 15 June 1995.

The USGS seismic moment value for the fist event was $Mo_1=1.1\times10^{25}$ dyn. cm and for the second $Mo_2=6\times10^{25}$ dyn. cm. The space distribution of all reported by USGS aftershocks with $M_w\geq3$ for the period 7 September 1997 to 7 September 2000, for Athens earthquake and from 15 June 1995 to 15 June 1996, for Egion (Fig. 2a, b), define the corresponding areas with dimensions L and W. In a similar way to Andravida Strofades and Killini cases, we calculated the stress drop for the upper and the lower limit of the value range of L and W, for both events, as well as their mean value $\Delta\sigma_{B\text{mean}}$ and the results along with the reported Brune's stress drop values are given in Table 5. A comparison between the reported and calculated $\Delta\sigma_B$ for Athens and Egion earthquakes does not show remarkable difference, thus implying that the calculated stress drop for Andravida, Strofades and Killini is quite reliable. The

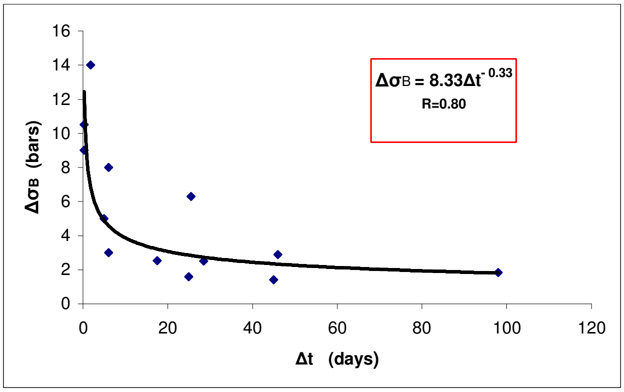

Fig. 3. The plot of the relation between the stress drop and the lead time of all "non thrust" earthquakes, including the Andravida, Strofades and Killini data, which are listed in Table 1. Event no. 11 is excluded. The derived power law equation along with the corresponding correlation coefficient R are displayed on the top of the diagram.

derived power law relation between the stress drop and the lead time values of all "non thrust" earthquakes, (except event no. 11), listed in Table 1, is given by the formula:

$$\Delta\sigma_B = 8.33\Delta t^{-0.33} \quad (4)$$

which is close to the one obtained by Dologlou (2008a). Additionally, is notable from Table 4 that even when the value range of L and W is considered, the critical exponent α is not considerably affected and varies within the limits 0.32–0.34 with a correlation coefficient $R>0.79$ in all cases.

The following comment might be worthwhile to be added. After the SES recording, upon studying the order parameter of seismicity defined in the natural time domain (Varotsos et al., 2005), the time-window of an impending main shock can be shortened to a few days. Since this parameter is just the power spectrum in natural time (for frequencies close to zero) of the seismicity evolving in the area suspected for the occurrence of the main shock, on the basis of SES properties, it might reveal a deep interconnection between the lead time and seismological parameters confirming the above mentioned power law relation of Eq. (3) between $\Delta\sigma_B$ and Δt.

4 Conclusions

New data from the destructive Andravida, Strofades and Killini earthquakes were used to test the credibility of the obtained by Dologlou (2008a) critical exponent α=0.29 in the power law relation between the stress drop and the precursory SES lead time for "non thrust" earthquakes. The new derived critical exponent value α=0.33, after including the Andravida, Strofades and Killini events, with correlation coefficient R=0.80, is close to the previous one reported by Dologlou (2008a). This experimental result strengthens the hypothesis that signatures of criticality might be present in the SES generation and the earthquake preparation indicating that probably both processes are governed by the same physics. The accumulation of additional data in the future will check the degree of the validity of these preliminary findings.

Edited by: M. Contadakis
Reviewed by: S. Uyeda and another anonymous referee

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