Possible relationship between Seismic Electric Signals (SES) lead time and earthquake stress drop

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Abstract: Stress drop values for fourteen large earthquakes with $M_W \geq 5.4$ which occurred in Greece during the period 1983–2007 are available. All these earthquakes were preceded by Seismic Electric Signals (SES). An attempt has been made to investigate possible correlation between their stress drop values and the corresponding SES lead times. For the stress drop, we considered the Brune stress drop, $\Delta\sigma_B$, estimated from far field body wave displacement source spectra and $\Delta\sigma_{SB}$ derived from the strong motion acceleration response spectra. The results show a relation may exist between Brune stress drop, $\Delta\sigma_B$, and lead time which implies that earthquakes with higher stress drop values are preceded by SES with shorter lead time.

Keywords: Seismic Electric Signals (SES), lead time Δt, stress drop

Introduction

There has been an increased interest in the electromagnetic phenomena associated with earthquakes in a wide frequency range from DC to VHF (e.g., Hayakawa and Molchanov, 2002),[1] and Seismic Electric Signals (SES) is one of those seismo-electromagnetic phenomena in the DC range. In the early 1980s, the VAN group observed that variations in the electrotelluric field, so-called Seismic Electric Signals (SES), preceded the occurrence of large earthquakes in Greece. Since 1982, SES signals have continuously been monitored at various sites in continental Greece. It has been postulated that earthquakes, $M_W \geq 5$, can be predicted by analyzing the SES signals.[2]–[4] According to their duration, and mode of occurrence, the SES have been classified as single signal or as electrical activity which is sequence of electrical signals within a short time (e.g., some hours).[5]

One of the most important parameters of the SES is the lead time, Δt, which is the time difference between the SES detection and the earthquake occurrence. The start of the DC emission is easily recognized when the anomalous DC change exceeds significantly (of the order of a few mV/km) the background noise. A large number of SES and associated earthquakes showed that the lead time, Δt, can vary from a few hours to a few months.[2]–[5] Very short lead time (e.g., $\Delta t \sim 7$ h) seems to occur for aftershocks. Generally, SES electrical activities tend to have lead times covering a longer time span (e.g., weeks to a few months) than about two weeks of single SES. During the last decades, efforts have been undertaken to correlate different SES features with earthquake source parameters.[6] It has been reported[2,5] that the duration and the lead time, Δt, of a SES are not correlated to the magnitude of the corresponding earthquake while Δt might have a relation with the stress drop, $\Delta\sigma$, of the earthquake. Concerning the latter, preliminary results, that were based on only four earthquakes which occurred in western Greece, showed that Δt tends to be shorter for earthquakes with higher stress drop, $\Delta\sigma$, and vice versa.[7] The aim of the present paper is to examine the validity of the above findings by investigating an enriched data set from 1983 to 2007.

Stress drop

A fundamental scaling source parameter of an earthquake is the stress drop, $\Delta\sigma$. Over the last two decades, a number of stress parameters as Brune's stress drop, apparent stress drop, dynamic stress

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drop, etc. have been proposed yielding a variety of stress drop values.[8)–14)] In its original definition, stress drop is the difference between two states of stress at a point on a fault before and after rupture.[15)] Stress drop parameter can be obtained from teleseismic body waves[9),16),17)] or strong motion data.[18),19)] Among the seismic source models proposed for the estimation of stress drop, the most frequently used are the Brune's and Madariaga's models. The corner frequency as picked by Madariaga from his theoretical spectra is not consistent with the way in which corner frequencies were picked by Brune's thus leading to different $\Delta\sigma$ values.[8),20)–22)] Although values of stress drop obtained by authors using different source models are widely scattered, values derived from one model, preferably by same authors, may be useful in discussing the differences for different earthquakes. In the present work, we use the following Brune's stress drops.

In the Brune's model, the source displacement spectra of the far field body waves (teleseismic P and S waves) are used to obtain stress drop $\Delta\sigma_B$ using the equation:

$$\Delta\sigma_B = 0.44 M_o / r^3 \qquad [1]$$

The seismic moment M_o is derived from the formula:

$$M_0 = \frac{(4\pi\rho V^3 \Omega_0 R)}{(k R_{\theta\varphi})} \qquad [2]$$

where ρ is the density of the medium, R is the hypocentral distance between the source and the receiver, V is the P or S wave velocity near the source and Ω_o the low frequency spectral level, derived from P-waves and S-waves respectively. The factor k is the free surface operator and $R_{\theta\varphi}$ is the average radiation pattern coefficient. Finally, source radius, r, is computed using the spectral corner frequency f_o as

$$r = 0.37 V / f_o \qquad [3]$$

Strong motion data can also provide an estimation of stress drop based on response spectra according to the formula.

$$\Delta\sigma_{SB} = M_o f_o^3 \ (4.9 \times 10^6 \ \beta)^{-3} \qquad [4]$$

where β is the S wave velocity. The corner frequency f_o determines the acceleration amplitude and controls the frequency content of the earth-

quake generated at the source[23)] and, according to Andrews method,[24)] is given by the formula:

$$f_o = \frac{1}{2} \sqrt{S_{v2}/S_{d2}} \qquad [5]$$

where S_{v2} and S_{d2} are calculated by the following integrals

$$S_{v2} = \int_0^{+\infty} V^2(f) df \quad \text{and} \quad S_{d2} = \int_0^{+\infty} d^2(f) df \qquad [6]$$

where V(f) and d(f) are the velocity and displacement spectra respectively. Using the above computed corner frequency f_o, Margaris and Hatzidimitriou,[23)] calculated the classical Brune stress drop, noted here as $\Delta\sigma_{SB}$, from a set of strong motion accelerograms for some large earthquakes in Greece.

This stress drop value, $\Delta\sigma_{SB}$ derived from strong motion response spectra is different from the value $\Delta\sigma_B$, based on teleseismic body wave spectra by Eq. [1]. Stress drop derived from teleseismic (low frequency) body wave data is related to the large source dimensions. Stress drop values $\Delta\sigma_B$ and $\Delta\sigma_{SB}$ are different in analogy to the various magnitude values of a given EQ estimated from amplitudes at different frequencies.

Data and analysis

For the period 1983–2007, stress drop values of different definitions were available for 14 earthquakes with moment magnitude $M_W \geq 5.4$ in Greece. All these earthquakes were preceded by a SES signal with lead times, Δt, varying from some hours to a few months. We adopted, in the present paper, the above cited two categories of stress drop estimations: i) the Brune stress drop $\Delta\sigma_B$ and ii) the strong motion $\Delta\sigma_{SB}$, because both are based on the same Brune's source model and refer to the stress difference before and after EQ.

In the first category, the $\Delta\sigma_B$ values were estimated by different authors[25)] and the results indicate low stress drop for all studied events. In the second category, the obtained $\Delta\sigma_{SB}$ values were higher. The latter values were less scattered probably because they were calculated by the same authors.[23)] In this study, we will consider the average values of $\Delta\sigma_{SB}$ estimated at different Greek seismic stations (For most events one or two stations and for a very few cases 5–7 stations.) as reported by Margaris and Hatzidimitriou.[23)]

Table 1. All EQ with $M_W \geq 5.4$ during the period 1983–2007 in Greece with available stress drop values $\Delta\sigma_B$, $\Delta\sigma_{SB}$ along with SES, lead times Δt, and source mechanism type (strike-slip, normal or thrust). Bibliographical references for the stress drop values and the lead times are indicated by numbers in parenthesis

n	yy mm dd	H	MIN	S	LAT	LONG	Depth (km)	Mw	$\Delta\sigma_B$ bars	Ref	$\Delta\sigma_{SB}$ bars	Ref	SES station	SES Δt days	Source mechanism
1	83 01 17	12	41	29	38.09	20.19	10.1	6.9	14.0	38	45.1	23	PIR	0.5	strike slip+thrust
2	83 03 23	23	51	6	38.33	20.22	32.7	6.2			39.9	23	PIR	0.6	strike-slip
3	86 09 13	17	24	34	37.03	22.20	15.0	5.9	5.0	39	61.4	23	KER	5.0	normal
4	88 10 16	12	34	6	37.95	20.90	29.0	5.8			68.1	23	IOA	17.5	strike-slip
5	93 03 26	11	58	15	37.49	21.49	15.0	5.4			58.3	23	IOA	39.5	strike-slip
6	93 07 14	12	31	49	38.24	21.78	20.0	5.6			31.4	23	IOA	34.5	strike-slip
7	95 05 04	0	34	11	40.54	23.63	15.0	5.4	2.5	25	39.2	23	ASS	28.5	normal
8	95 05 13	8	47	15	40.16	21.67	15.0	6.5	6.3	25	78.9	23	IOA	25.5	normal
9	95 06 15	0	15	56	38.10	22.46	15.0	6.5	2.9	25			VOL	46.0	normal
10	97 10 13	13	39	46	36.1	22.04	44.2	6.4			291.4	23	IOA	10.0	thrust
11	97 11 18	14	7	53	37.33	20.84	22.9	6.6			222.4	23	IOA	45.0	stike-slip
12	99 09 07	11	56	56	37.97	23.6	15.0	6.0	3.0	40	37.1	23	LAM	6.0	normal
13	01 07 26	0	21	44	38.96	24.29	15.0	6.5	9.0	41			PIR	130.0	strike-slip
14	03 08 14	5	15	8	38.70	20.67	15.0	6.3	8.0	42			PIR	6.0	strike-slip

*for all Δt lead time values see Ref. 29.

Additional information concerning the source mechanism (strike-slip, normal or thrust type) is available also for all studied events by Harvard CMT solutions (e.g. Dziewonski *et al.*, 2007 and references therein `http://neic.usgs.gov/neis/sopar/`[26]).

All 14 earthquakes numbered in chronological order along with their dates, epicentres, depths, moment magnitudes M_w,[26] stress drop values ($\Delta\sigma_B$, and $\Delta\sigma_{SB}$), lead times Δt[29] and source mechanism type (strike-slip, normal or thrust) are listed in Table 1. Bibliographical references for the stress drop values are indicated by numbers in parenthesis. A map of Greece showing the epicenters of all earthquakes of Table 1 along with their focal mechanism and the position of the SES stations is given in Fig. 1. An inspection of Table 1 shows the following features:

First, as mentioned above, the values $\Delta\sigma_B$ (Brune stress drop based on far field displacement spectra) are systematically much lower than $\Delta\sigma_{SB}$ obtained from acceleration response spectra. Second, for the events number 10 and 11 we observe very high values for $\Delta\sigma_{SB}$ which are probably caused by significant errors in their estimation. Events 10 and 11 were the only ones that were recorded at distances $R > 100\,\text{km}$. It is expected that at long distances contamination of the high frequencies tend to make the estimate erroneous. For this reason, at the moment, these events will be excluded in our further analysis although further examination would be needed "on this point". Third, the source mechanism of the earthquake seems to be uncorrelated with the lead time. Strike–slip and normal type earthquakes have both short and long lead times.

In order to investigate to see if there is any relation between the lead time Δt and the stress drop values $\Delta\sigma_B$, and $\Delta\sigma_{SB}$, two diagrams have been plotted as shown in Figs. 2, and 3. A linear or power law fitting has been applied to the diagrams and the corresponding correlation coefficients R_L (linear) and/or R_P (power) are shown on the top of the diagrams.

Discussion

In the first diagram (Fig. 2), the Brune stress drop, $\Delta\sigma_B$, is plotted against the lead time Δt. An inspection of this diagram shows that there is not any evident linear correlation: a least square fitting to a straight line results in a correlation coefficient $R_L = 0.05$. A power law fitting (red line) shows a better correlation ($R_P = 0.44$) but still of not much significance. When, however, the earthquake number 13, which was the only one with considerably larger lead time ($\Delta t = 130$ days), is excluded from
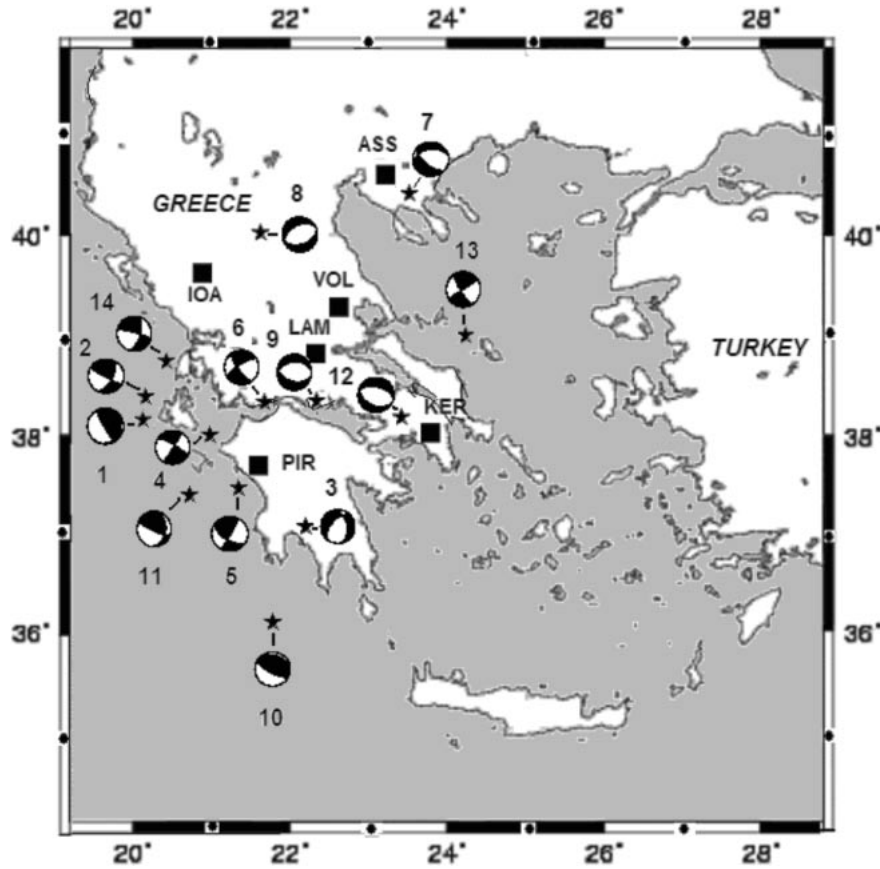
Fig. 1. All epicenters (denoted by stars) for the 14 earthquakes of $M_w \geq 5.4$ listed in Table 1, with available stress drop values, during the period 1983–2007 in Greece, along with their CMT fault plane solutions. A lower hemisphere projection is used with black and white quadrants (beach balls) for compression and dilatation respectively. Squares denote the position of SES stations. Numbers attached refer to the events in Table 1.

the data set, a better correlation is derived, as is shown in the inset of Fig. 2. More precisely, in this plot, both linear ($R_L = 0.57$) and power law ($R_P = 0.76$) correlation coefficient values were raised implying that the lead time Δt is shorter for larger stress drop $\Delta\sigma_B$. This result is in good agreement with the findings of a previous study.[7] The question remains, however, why the event (no. 13) deviates from the behavior of the others. This earthquake had a large magnitude $M_W = 6.5$ and its precursory SES signal, well distinguished from artificial noise,[27),28)] was documented by a prediction contained in a publication[29),30)] submitted on 25 March 2001, much prior to the earthquake occurrence (26 July 2001). As usual, this prediction based on SES was not explicit on the occurrence date except the date of SES, implying the earthquake was impending. The 26 July 2001 event (no. 13) was later

identified as the predicted one from the evolution of seismicity in the predicted area after the SES. We will have a closer look elsewhere on this extraordinarily long lead time of this particular earthquake.[31]

Stress drop values $\Delta\sigma_{SB}$, computed from strong motion data, do not show any significant correlation with lead time Δt as shown in Fig. 3. This could be attributed to two possibilities. One is that the stress drop derived from accelerograms is based only on the high frequency contents of the ground motion which may be more seriously contaminated by the local ray path and the site effects and the correlation might have been obliterated by contamination even if it existed. The other is that there is simply no correlation, while a correlation exists for $\Delta\sigma_B$.
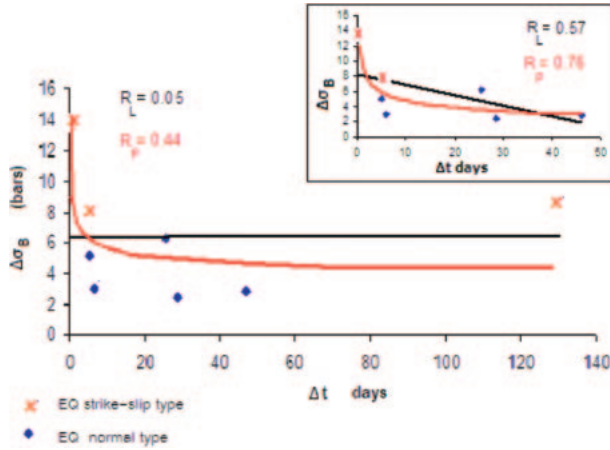
We will now discuss whether an interconnec-

Fig. 2. Plot of the Brune stress drop, based on far field body wave source spectra $\Delta\sigma_B$, against the lead time Δt. Crosses ✖ indicate earthquakes of strike–slip type and dots ◆ of normal type. A black line and red curve are used for the linear and power law fitting respectively and R_L and R_P are their correlation coefficients. The inset on right top refers to the same data but without event no. 13.

Fig. 3. Plot of the Brune stress drop, derived from strong motion data $\Delta\sigma_{SB}$, against the lead time Δt. A black line is used for the linear fitting and its correlation coefficient is depicted by R_L.

tion between Δt and stress drop can be physically understood. Let us first adopt the model originally suggested by Varotsos and Alexopoulos[32] for SES generation, i.e., SES are transient currents called the pressure stimulated polarization currents (PSPC) which are emitted from a solid containing electric dipoles upon a gradual increase of the pressure P (or stress σ). The argument goes as follows: Aliovalent impurities in a crystal form point defects for electrical neutrality. Due to the electrostatic attraction between the impurities and the defects, electric dipoles are formed. They change their orientation with relaxation time τ given by the relation

$$\tau = (\lambda\nu)^{-1}\exp(g/kT) \qquad [7]$$

where T denotes the temperature, λ the number of jump paths accessible to jumping species with an attempt frequency ν and g the Gibbs energy for the (re)orientation process. Pressure affects the value of g[33],[34] as expressed by,

$$v = (dg/dP)_T \qquad [8]$$

where v denotes the migration or the activation volume in general.[35],[36] Thus, if $v < 0$, an increase of pressure results in a decrease of the relaxation time τ. One can show that upon a gradual increase of pressure with a rate b ($= dP/dt$), the emission
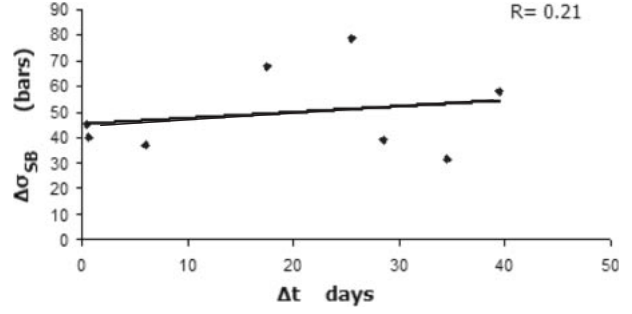
of a transient current, arising from a cooperative (re)orientation of dipoles, is sharply maximized when the pressure reaches a critical value $P = P_{cr}$ at which the following relation is obeyed:

$$\frac{bv}{kT} = -\frac{1}{\tau(P_{cr})} \qquad [9]$$

where τ (P_{cr}) is the relaxation time when $P = P_{cr}$. The lead time Δt between the emission of this current and the earthquake is given by

$$\Delta t = (P_{fr} - P_{cr})/b \qquad [10]$$

where P_{fr} is the critical stress for earthquake occurrence, namely fracture of the crust or seismic sliding of fault. Usually the value of Δt is positive in general, i.e., SES appears before earthquakes, suggesting $P_{fr} > P_{cr}$ and it becomes shorter for rapid stress increase (larger b). During the last preparatory stage of a given earthquake when in general non linear processes prevail, b value may change with time. Since it is conceivable that P_{cr} depends on b, Eq. [10] has to be improved as follows. From Eqs. [7] and [9], it can be shown[37] that

$$dP_{cr}/db(P_{cr}) = \tau(P_{cr}) \qquad [11]$$

which reflects that $dP_{cr}/db(P_{cr})$ is always positive. Hence, for larger values of b, the critical pressure P_{cr} becomes also larger. Then the numerator of the right hand side of Eq. [10] becomes smaller leading to the conclusion that an increase in the b value causes a two-fold decrease in the lead time and vice versa. For different earthquakes occurring in a broad area, if P_{fr} may approximately be assumed constant but the corresponding b values (and

therefore the P_{cr} values) may be larger or smaller, reflecting—from Eq. [10]—smaller or larger Δt values will result respectively. Question is if a similar situation can be expected for the relation between Δt and the stress drop,[25),38)–42)] because from physical point of view, stress drop is a quantity different from $(P_{fr} - P_{cr})$. On top of the above argument on the possible effect of b dependence of P_{cr}, that of P_{fr} may have to be considered, because in $\Delta t = (P_{fr}(b) - P_{cr}(b))/b = P_{fr}(b)/b - P_{cr}(b)/b$, the first term may be more explicitly related to stress drop. In simple physical sense, larger $P_{fr}(b)$ may cause larger stress drop, so that Δt may become larger for larger stress drop, which is contrary to our results. If, however, larger b value, namely higher rate of stress increase, results in lowering of $P_{fr}(b)$, it may help explaining our observation. Whether the fault strength depends on stress rate is the central question.

Acknowledgments

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