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Additional evidence on some relationship between Seismic Electric Signals (SES) and earthquake focal mechanism

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Abstract

Investigating the period 1983–1994 for western Greece, a possible correlation between the selectivity characteristics of the SES (seismic electric signals of the VAN method) and earthquake parameters has been reported by Uyeda et al. [Uyeda, S., Al-Damegh, K.S., Dologlou, E., Nagao, T., 1999. Some relationship between VAN seismic electric signals (SES) and earthquake parameters, Tectonophysics, 304, 41–55.]. They found that the earthquake source mechanism changed from largely strike-slip type to thrust type at the end of 1987, and this coincided with a shift in the SES sensitive site from Pirgos (PIR) to Ioannina (IOA) VAN station. Here, we report the results for the period January 1, 2002–July 25, 2004, during which the SES sensitive site of PIR became again active, after a 10-year period of "quiescence". This activation was followed by strike slip earthquakes (on August 14, 2003 and March 17, 2004 with magnitude 6.4 and 6.5, respectively) in the Hellenic arc, which provides additional evidence on the correlation reported by Uyeda et al. The SES activities recorded at PIR have been discriminated from "artificial" noise by employing the natural time-domain analysis introduced recently.

Keywords: VAN method; Earthquake prediction; SES (Seismic Electric Signals); CMT solutions; Greece; Selectivity

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1. Introduction

Seismic Electric Signals (SES) are low frequency ($\leq$1 Hz) electric signals that have been recorded in Greece (e.g., Varotsos and Alexopoulos, 1984a,b, 1986, Varotsos et al., 1993, 1996) and Japan (Uyeda et al., 2000, 2002) to precede earthquakes (EQs) (see also Kanamori, 1996; Uyeda, 1996). *Selectivity* is one of the most important SES physical properties (e.g., Varotsos and Lazaridou, 1991), which refers to the experimental fact that a (sensitive) monitoring station is capable to detect SES only from a restricted number of seismic areas. A map showing the seismic areas that emit SES detectable (for EQs above a magnitude threshold) at a given station is called "*selectivity map of this station*" (e.g., Varotsos et al., 1993; Uyeda, 1996; Kondo et al., 2002). Here we focus on the selectivity maps of the following two stations: First, the Ioannina station (IOA), which is located near the village of Perama (suburb of Ioannina City) at about 400 km northwest of Athens. Second, the Pirgos station (PIR), which is located about 200 km west of Athens.

The selectivity effect is a complex phenomenon that may be attributed to a superposition of the fol-

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lowing three factors: "*source characteristics*", "*travel path*" and "*inhomogeneities close to the station*" (Varotsos and Lazaridou, 1991; Varotsos, 2005). Analytical solutions of Maxwell equations (Varotsos et al., 2000), as well as numerical ones (Sarlis et al., 1999), convince that *selectivity* results from the fact that EQs occur by slip on faults, which are appreciably more conductive than the surrounding medium. This is the main point of the explanation of the selectivity effect that was suggested by Varotsos and Alexopoulos (1986) (see also Varotsos et al., 1993). A possible correlation between SES characteristics and earthquake parameters was investigated by Uyeda et al. (1999) in western Greece for the period January 1, 1983–December 31, 1994. They studied the SES records of the two stations IOA and PIR. A simultaneous change in EQ source mechanism and selectivity has been noticed, as it will be further explained later.

It has recently been shown (Varotsos et al., 2001, 2002a, 2003a,b,c, 2005a) that the analysis of SES activities in a newly defined time-domain (Varotsos et al., 2001), termed natural time χ, allows their distinction from "artificial" noises. In these studies, all the available SES activities of large amplitude were successfully distinguished from a variety of artificial noises. In particular, all the signals that have been classified as SES by means of the previously used criteria (the four criteria listed in the Appendix of Varotsos and Lazaridou, 1991, see also below) have been also confirmed as such by means of natural time. In a time series comprised of N events, the *natural time* $\chi_k=k/N$ serves as an index (Varotsos et al., 2001, 2002a) for the occurrence of the kth event. It is, therefore, smaller than, or equal to, unity. For the analysis of SES activity, the time evolution of the pair of two quantities, i. e., (χ_k, Q_k) is considered, where Q_k denotes the duration of the kth pulse (event). For this purpose, the following continuous function $F(\omega)$ was introduced (Varotsos et al., 2001, 2002a).

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

where $\omega=2\pi\phi$, and ϕ stands for the *natural frequency*. $F(\omega)$ should not be confused with the ordinary discrete Fourier transform, and it can be normalised by dividing by $F(0)$:

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

where

$$p_k=Q_k\Big/\sum_{n=1}^{N} Q_n$$

A kind of normalised power spectrum $\Pi(\omega)$ can now be defined:

$$\Pi(\omega)=|\Phi(\omega)|^2$$

The properties of $\Pi(\omega)$ or $\Pi(\phi)$ are studied for natural frequencies ϕ less than 0.5, since in this range of ϕ, $\Pi(\omega)$ or $\Pi(\phi)$ reduces (Varotsos et al., 2001, 2002a) to a characteristic function for the probability distribution p_k in the context of probability theory. When the system enters into the *critical* stage (infinitely long ranged correlations in time, scale invariance), the following relation can be proven (Varotsos et al., 2001, 2002a):

$$\Pi(\omega)=\frac{18}{5\omega^2}-\frac{6\cos\omega}{5\omega^2}-\frac{12\sin\omega}{5\omega^3} \tag{1}$$

which for small values of ω ($\omega\rightarrow 0$) gives:

$$\Pi(\omega)\approx 1-0.07\omega^2 \tag{2}$$

This reflects (Varotsos et al., 2001, 2002a, 2003a,b) that the variance of χ is given by:

$$\kappa_1=\langle\chi^2\rangle-\langle\chi\rangle^2=0.07 \tag{3}$$

It has been shown (Varotsos et al., 2001, 2002a) that, in the range $0\leq\phi\leq 0.5$, all SES activities fall on a *universal* curve, which coincides with the thick (upper) solid curve of Fig. 5. On the other hand, the "artificial" noises are characterized by κ_1-values which obey the inequality:

$$\kappa_1\geq 0.083 \tag{4}$$

where the value of 0.083 corresponds to the variance of χ in a "uniform" distribution (Varotsos et al., 2001, 2003a,b).

After an almost 10 year "quiescence" of the SES sensitive station of PIR, i.e., no intense SES was identified in the PIR records and thus no relevant prediction was issued, this station became again active by recording intense SES electrical activities during the last 2 years, i.e., 2003–2004. It is the main scope of this paper to investigate whether this fact is consistent with the aforementioned correlation between the SES selectivity properties and the EQ source mechanism noticed by Uyeda et al. (1999). This paper is organized as follows: In Section 2, we report the (seismic, as well as the electrical) data analyzed. In Section 3 we explain the procedure followed for the analysis in the natural time-domain (Varotsos et al., 2001, 2002a, 2003a,b,c, 2004) of the SES activities' data treated in this paper. This procedure was found necessary to be followed in the present case, since the conventional criteria to distinguish true SES from noise (i.e., mainly the $\Delta V/L$ criterion, see Varotsos and Alexopoulos, 1984a,b; Varotsos and Lazaridou, 1991), which can be used when a combination of short electric dipoles (i.e., with length $L \approx$ a few term to 200 m) and long ones (i.e., $L \sim$a few km to around 10 km) is available, could not be applied here, in view of the absence of short electric dipoles in PIR (see below). In Section 4, we discuss the results, while in Section 5 we summarize our conclusions.

2. The data analyzed and the results obtained

The real time data collection allows the recognition of the electrical precursor(s) and their analysis well before the EQ occurrence. The sites of the VAN stations that are currently telemetrically connected to a suburb of Athens (Glyfada) are depicted in Fig. 1. In all these stations (except of PIR) short electric dipoles, as well as long ones have been installed. Furthermore, in four stations, i.e., IOA, LOU, ASS and VOL, the variations of the magnetic field (B) are continuously monitored by using coil magnetometers (i.e., DANSK magnetometers, for details in this instrumentation see Varotsos et al., 2003d; Varotsos, 2005). The configuration of the long electric dipoles operating in PIR can be seen in Fig. 2. Each of these dipoles measures (with sampling rate 1 Hz) the potential difference ΔV between each of the sites depicted in Fig. 2 and the site located at the center of Pirgos city (labelled with a square in Fig. 2).

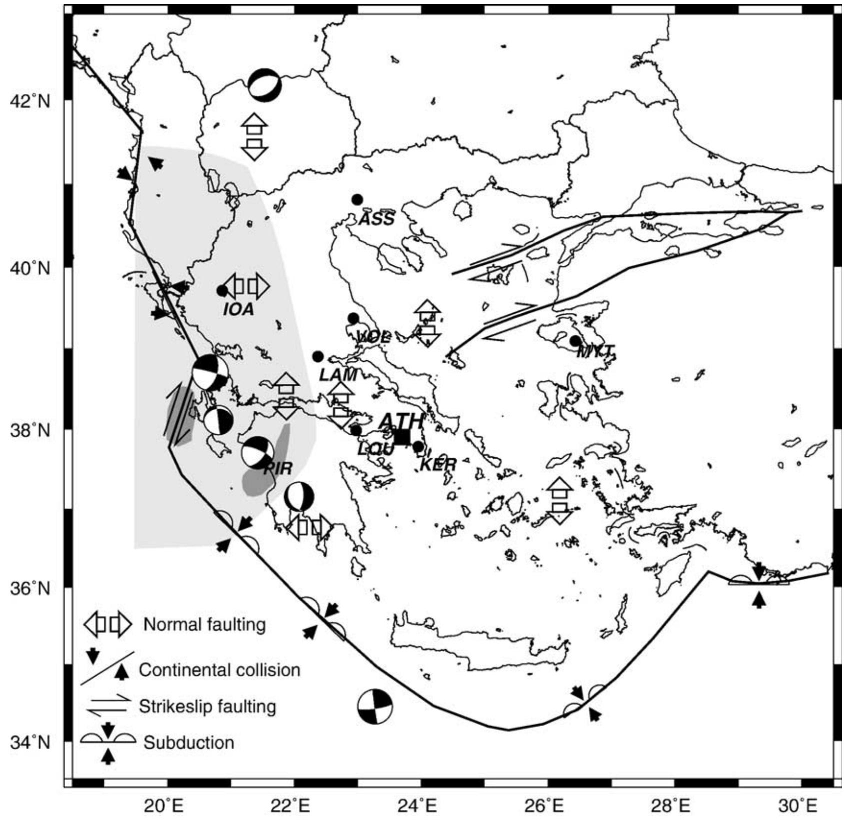

Fig. 1. A map of the sites of the VAN stations that are currently telemetrically connected to Athens (for the detailed instrumentation and the configuration of dipoles at each station, see Varotsos, 2005) along with the main tectonic features of the region. The CMT solutions (available from http://www.seismology.harvard.edu/CMTsearch.html) for the six earthquakes of Table 1 as well as the selectivity maps of PIR and IOA are also depicted. The seismotectonic main features of this map as well as the selectivity maps are reproduced from Uyeda et al. (1999).

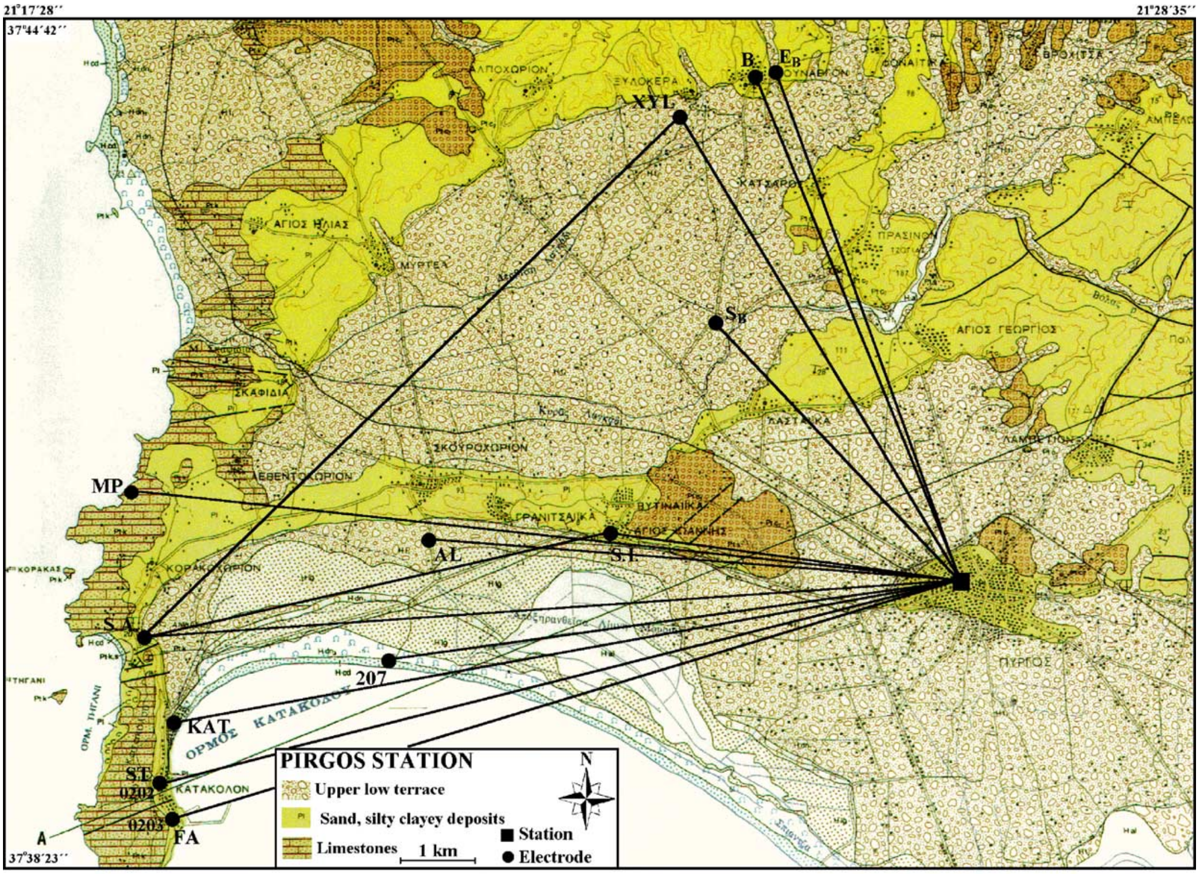

Fig. 2. Configuration of the long measuring dipoles in Pirgos (PIR) area.

According to Varotsos and Alexopoulos (1984a,b) and Varotsos and Lazaridou (1991), the VAN stations have been calibrated, with respect to the magnitude announced by the Seismological Institute of the National Observatory of Athens (SI-NOA). This magnitude, labelled Ms in the Preliminary Seismological Bulletin (PSB) of SI-NOA, is derived from the approximate formula $M_S = M_L + 0.5$, where M_L is the local magnitude measured by SI-NOA. This M_S is *not* the surface wave magnitude M_S reported by USGS and hence, to avoid confusion, it is labelled M_S(ATH) hereafter. In accord with a recommendation of the Special Scientific Committee for Earthquake Prediction of the European Council in the end of 1995, predictions were issued *only* when the expected magnitude M_S(ATH) is larger than (or equal to) 6.0-units or $m_b(\text{USGS}) \geq 5.5$. (This threshold, during 1985–1995, was lower, i.e., $M_S(\text{ATH}) \geq 5.0$). All these predictions, which include all the relevant information on the SES recordings and their analysis, were submitted for publication in international journals well in advance, i.e., before the EQ occurrence.

Table 1 summarizes (for details see Varotsos et al., 2002b, 2003e, 2005b) all the intense (i.e., large amplitude) SES activities recorded during the period January 1, 2002–July 25, 2004. (Earlier SES activities associated with earthquakes that occurred during 1983–2001 are compiled by Varotsos, 2005). In the same table we also include the EQs with $M_S(\text{ATH}) \geq 6.0$ within the area $N_{34.5}^{42.5}E_{19}^{25}$. In Fig. 3 we give the time-chart of the totality of these EQs during the period 2002–2004 along with the totality of the aforementioned SES activities. The intent of such time-charts is to show the following: in the initial period of this research (1983–1995) we considered a low magnitude threshold for the EQs, and hence there were many events, which arouse arguments concerning "chancy correlations" between SES activities and EQs. On the other hand, when increasing the magnitude threshold of the EQs (as in the present investigation), the number of the EQs drastically decreases, and hence the reader can better visualize their correlation with the SES activities. In the time-chart of Fig. 3, we note that there are long periods of time during which no intense SES activities was

Table 1
All EQs within $N_{34.5}^{42.5}E_{19}^{25}$ with M_L(ATH) ≥ 5.5 or m_b(USGS) ≥ 5.5 along with the relevant SES activities

Date (Y-M-D)	Epicenter (°N–°E)	Magnitude			Related SES activities	
		m_b(USGS)	M_L(ATH)	M_s(ATH)	Station	Y-M-D
2002-04-24	42.2–21.5	5.6	–	–	IOA	2002-02-05[a]
2002-12-02	37.7–21.4	5.2	5.3	5.8	IOA	2002-09-19[b]
2003-08-14	38.7–20.7	5.6	5.9	6.4	PIR	2003-08-08[c]
					IOA	2003-08-04[c]
2003-11-16	38.1–20.8	4.8	4.8	5.3*	PIR	2003-09-30[d]
2004-03-01	37.2–22.1	5.5	5.0	5.5*	IOA	2004-01-10[c,d]
2004-03-17	34.5–23.3	5.8	6.0	6.5	PIR	2004-03-14[e]

Period January 1, 2002–July 25, 2004. Epicenters according to the CMT solutions available from http://www.seismology.harvard.edu/CMTsearch.html.

*These EQs, although smaller than the magnitude threshold, are tabulated, because they are related with the preceding SES activities.

[a] Varotsos et al. (2002a).

[b] Varotsos et al. (2003e).

[c] These SES activities bring a question mark in Fig. 3, because the data did not allow the application of *all* known criteria for their distinction from artificial noises.

[d] Varotsos et al. (2005b).

[e] These are the two SES activities Pir_1 and Pir_2 discussed in the text.

recorded and no strong EQ occurred. This provides convincing evidence of causality between SES and EQs.

Table 1 shows that, during the period under discussion, two EQs of large magnitude occurred on August 14, 2003 and March 17, 2004. Both these EQs were preceded by intense SES activities recorded at PIR on August 8, 2003 and March 14, 2004. For example, we give in Fig. 4a and b the two SES activities that have been recorded on March 14, 2004 (which, for the sake of brevity, will be called hereafter Pir_1 and Pir_2, respectively). Note that Fig. 4a or b depicts the $\Delta V/L$-values resulted from measuring the potential difference between each point depicted in the map of Fig. 2 and the site (labelled with square in Fig. 2) at which the

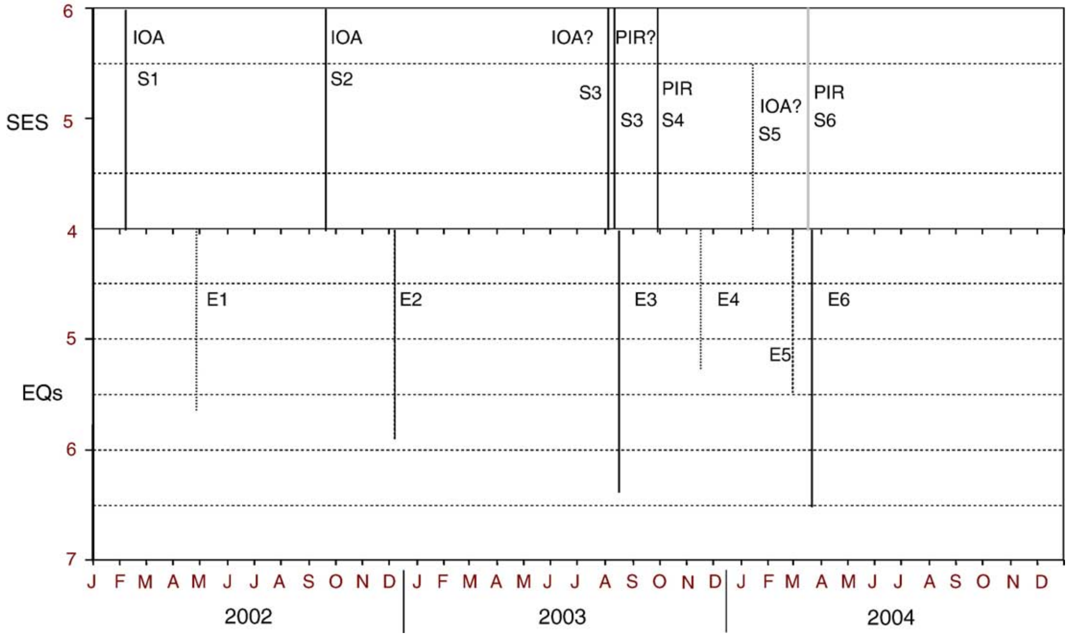

Fig. 3. Time chart of all SESs on the basis of which predictions were issued (upper panel) during the period January 1, 2002–July 20, 2004 and all EQs with M_L(ATH) ≥ 5.5 (full bars in the lower panel) within $N_{34.5}^{42.5}E_{19}^{25}$. The dotted bars correspond to smaller EQs related with the predictions. All the relevant data, including those indicated with question mark, are compiled in Table 1. The symbols E1–E6 (S1–S6) correspond to the earthquakes (SES activities) as they are reported in the six rows of Table 1.

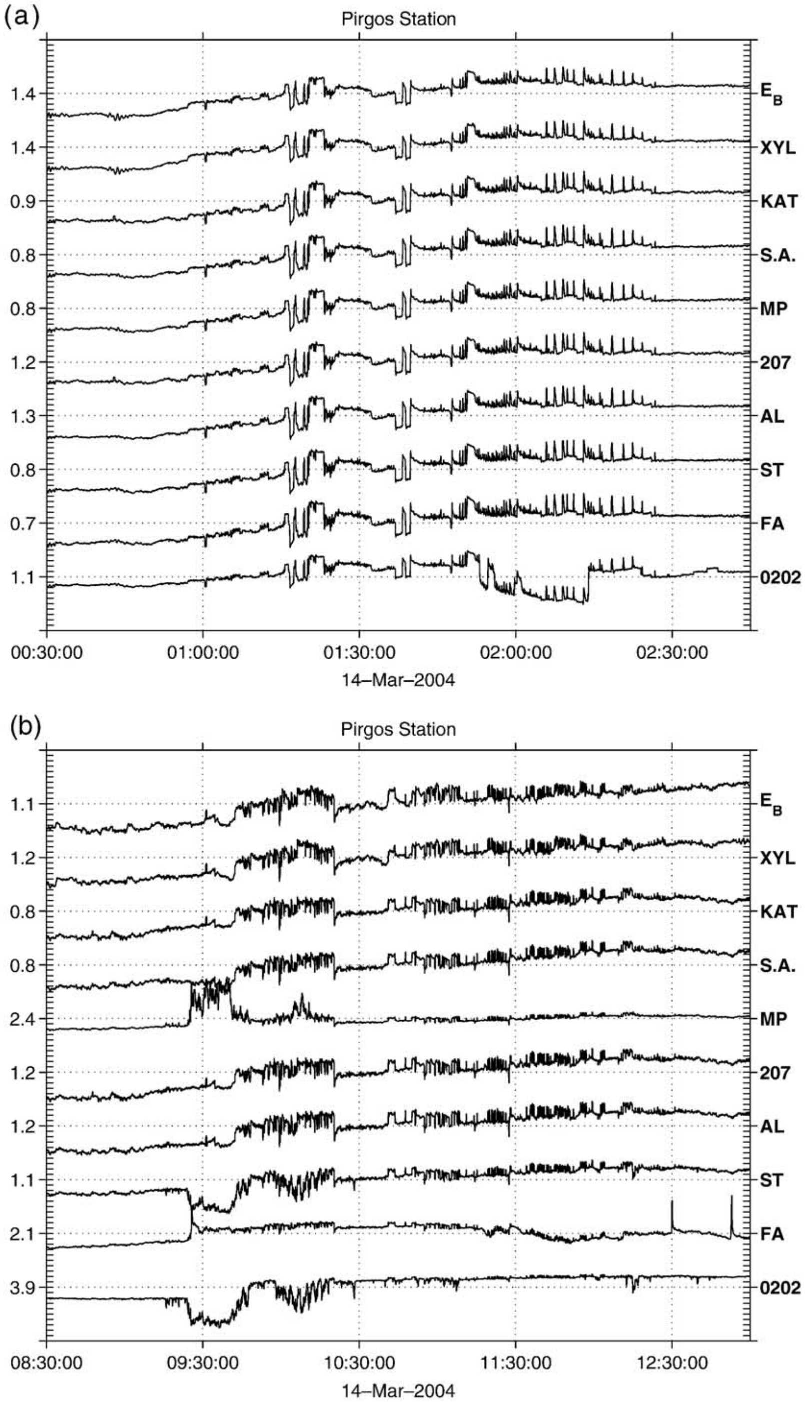

Fig. 4. Recordings on March 14, 2004, at ten dipoles (out of 16) operating at PIR station that recorded the SES activities Pir_1 (a) and Pir_2 (b), respectively. The label in each channel stands for the dipole that connects this electrode with the central station (square) depicted in Fig. 2.

recording system is located. In other words, all these measuring dipoles have the latter site as a common point (electrode). We emphasize, however, that it has been excluded that the signals come from disturbances produced in the immediate vicinity of this point (because we confirmed that when subtracting the ΔV-values of two dipoles the signals do not disappear). We now explain, in the next section, the procedure through which it was verified that the latter signals cannot be attributed to “artificial” noises.

3. The analysis of the SES activities in the natural time-domain

This is the analysis that was employed here in order to verify that the electric signals recorded at PIR (reported in Table 1) were true SES activities. Other techniques to distinguish them from "artificial" noise could not be applied, because, as mentioned, neither short dipoles (to testify the $\Delta V/L$-criterion, see Section 1), nor coil magnetometers (to measure the time-difference between the electric field and the time-derivative of the magnetic field, as explained in Varotsos et al., 2003d) were operating at PIR.

The behaviour of Eqs. (1)–(3) can be visualised in Fig. 5, where the thick (upper) solid curve has been plotted on the basis of Eq. (1) (and hence this curve corresponds to $\kappa_1 = 0.070$). Actually, when analysing the SES activities Pir$_1$ and Pir$_2$ (which, in the *conventional* time, are depicted in Fig. 4a,b, as mentioned) in the natural time-domain, we find (see Fig. 5) that, in the range $0 \leq \phi \leq 0.5$, almost coincide with the thick (upper) solid curve.

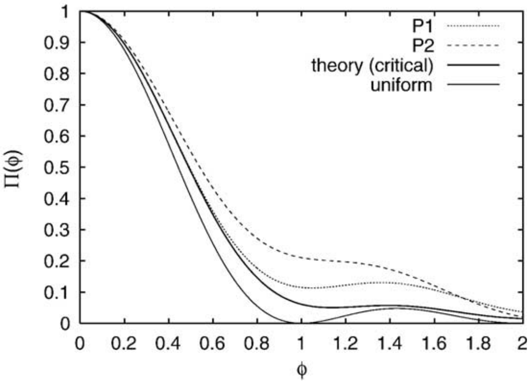

Fig. 5. The normalized power spectra $\Pi(\phi)$ in natural time-domain for the SES activities Pir$_1$ (dotted) and Pir$_2$ (broken) recorded at PIR on March 14, 2004. The thick (upper) solid curve corresponds to a theoretical estimation emerged from the theory of critical phenomena (see the text), while the thinner (lower) one corresponds to the "uniform" distribution (Varotsos et al., 2001, 2002a).

Table 2
The parameters resulted from the analysis in the natural time-domain of the SES activities recorded at PIR on March 14, 2004 (depicted in Fig. 4a,b)

SES activity	κ_1	S	λ_s
Pir$_1$	0.074 ± 0.009	0.100 ± 0.06	1.36 ± 0.12
Pir$_2$	0.062 ± 0.005	0.097 ± 0.012	1.16 ± 0.08

For the distinction of SES from artificial noise see also Varotsos (2005).

We now proceed to the investigation of the entropy S in the natural time-domain (which is *dynamic* Varotsos et al. (2004, 2005a) and *not* simply statistical entropy). This is defined as:

$$S = \langle \chi \ln \chi \rangle - \langle \chi \rangle \ln \langle \chi \rangle \qquad (5)$$

and is a causal operator that can capture the true time arrow (Varotsos et al., 2005a). When the system enters into the *critical* stage, the S-value is smaller (Varotsos et al., 2003b,c) than the value $S_u = 0.0966$ of a "uniform" distribution, i.e.,

$$S < S_u \qquad (6)$$

On the other hand, the "artificial" noises obey the inequality (Varotsos et al., 2003b,c):

$$S \geq S_u \qquad (7)$$

The confidence intervals of the S-statistics have been discussed in Ref. [28] of Varotsos et al. (2003a), as well as in Varotsos et al. (2004). In Table 2 one can verify that the entropies of both P_1 and P_2 could be considered as obeying the inequality (6), but *only* if the experimental errors are taken into account (see below).

Finally, we study the fluctuations δS of the entropy S in the natural time-domain that were recently employed to distinguish similar looking electric signals emitted from systems of different dynamics (Varotsos et al., 2003c, 2004, 2005a). Along these lines, the complexity measure λ for the δS variability has been introduced, which is defined as follows: When the time-window length changes from a short value, e.g., 5 pulses, to a shorter one, e.g., 3 pulses, the corresponding δS-value also changes. This variation, in the short(s) range (i.e., in reality scale *increase*), is quantified by the measure $\lambda_s = \delta S_5 / \delta S_3$, where the subscript in δS denotes the time-window length chosen. We emphasize that the study of this measure is found to be necessary in cases in which the S-value happens to lie very close to S_u. (which is the case of Pir$_1$ and Pir$_2$ studied here, as can be seen in Table 2), and the following conclusion has been drawn (Varotsos et al., 2003c): Systems that are characterized by *critical* dynamics (e.g., the SES activities, but *not* the "artificial" noises) exhibit λ_s-values that approach that of the Markovian (dichotomous) case. The value of the latter has been calculated equal to $\lambda_s(M) = 1.20 \pm 0.04$. Comparing the λ_s-values of Pir$_1$ and Pir$_2$ (see Table 2) to that of $\lambda_s(M)$, we conclude that these signals can be considered that exhibit *critical* behavior.

In summary, the study of the power spectrum in the natural time-domain, as well as the study of the parameters κ_1, S and λ_s point to the conclusion that Pir_1 and Pir_2 are true SES activities.

4. Discussion

Concerning the seismotectonics of the area, Uyeda et al. (1999) summarized it as follows: The area of their concern forms a part of the collision zone between the Eurasian and the African plates (see Fig. 2 of Uyeda et al. (1999), see also Fig. 1). Thrust faulting is observed along the convex side of the Hellenic Arc. In the northwest, however, there is no evidence for subduction (no Wadati-Benioff zone, etc.) and the collision between the two continental lithospheric blocks (Eurasian-Apulian) is occurring, resulting in thrust faults with the P-axis nearly perpendicular to the coastline of Albania–western Greece. Along the island of Kefallinia, strike-slip faulting connects this zone of compression with the zone of thrusting along the outer Hellenic Arc. The mainland of Greece and the central Aegean Sea areas are characterized by shallow normal faulting EQs in E–W-striking planes. The direction of the T-axis is almost N–S. The northern Aegean area is dominated by strike-slip events. This is attributed to the extension of the North Anatolian fault into the Aegean.

Concerning the data used by Uyeda et al. (1999): They used the USGS PDE m_b scale, and also listed the Harvard moment magnitude M_w when available. 75 EQs with $m_b \geq 5.0$ occurred during the period January 1, 1983 to December 31, 1994,in the area 19–25°E, 36–42°N. Among them, 55 had an epicenter inside the selectivity maps of the IOA and PIR stations. The study was focused only on 29 EQs for which Centroid Moment Tensor solutions (CMT hereafter, see Scott and Kanamori, 1985) were available. They listed the fault plane solutions and principal axes parameters of these earthquakes as given by the CMT solutions of the Dziewonski's school. The characteristics of the corresponding SES, recorded at either the IOA or PIR station, were also given for each case. The related SES data were taken from the publications of Varotsos et al. : 18 of the 29 EQs were preceded by SES at the IOA station, whereas the other 11 were preceded by SES at the PIR station. *No EQs were preceded by simultaneous SES at both stations*.

Uyeda et al. (1999)revealed the following two main points: First, all the nine EQs of Fig. 4 of Uyeda et al. (1999) with thrust mechanisms were predicted by SES at the IOA station. Earthquakes predicted by SES at the PIR station were (mostly) strike-slip-type with varying degree of normal component. However, the IOA station detected the SES not only from thrust type earthquakes, but also from strike-slip-normal type earthquakes. Second, the PIR station was one of the most effective VAN stations between 1983 and the late 1987. After the end of 1987, however, although the Kefallinia region still had earthquakes with considerable magnitudes, PIR seems to have ceased to be sensitive. Instead, the EQs in the same area began to produce SES to the IOA station. Namely, the sensitivity of PIR and IOA to the EQs of the Kefallinia area was found to be mutually exclusive in time. More interestingly, it can be noted that all the EQs in the area changed their source mechanism from strike-slip type to thrust type at the same time. Thus, the change in the source mechanism of the area from strike-slip to thrust type in late 1987 resulted in a simultaneous shift of sensitive station from PIR to IOA. It was therefore concluded that there is "*a close correlation between the selectivity properties of VAN stations and the EQ mechanism*". Here, we found that after an almost 10-year period (1993–2003) during which the PIR sensitive station seems to have ceased, it became again active twice, i.e., on August 8, 2003 and on March 14, 2004. In both cases these SES activities were followed by strong EQs, i.e., (i) M_s(ATH)=6.4 on August 14, 2003 with an epicenter in Western Greece and (ii) M_s(ATH)=6.5 on March 17, 2004 in Southern Greece. In both EQs, the CMT solutions of the Dziewonski's school reveal strike-slip events (see the http site http://www.seismology.harvard.edu/CMTsearch.html, see also Fig. 1). In other words, the present results are in fundamental agreement with the conclusion of Uyeda et al. (1999) that PIR becomes active for strike-slip events along the Hellenic arc.

The interrelation between selectivity and EQ focal mechanism seems to be, in principle, compatible with the solutions of Maxwell equations (Varotsos et al., 2000, Sarlis and Varotsos, 2001, 2002) in the following context: These solutions show that the electric current (produced in the focal area by an electric current dipole source) actually follows the neighboring conductive path, which in most cases, coincides with a pre-existing fault, and becomes measurable only at specific regions of the Earth's surface (sensitive sites). At such sensitive sites, the VAN stations are located. In other words, an SES sensitive site is located close to the outcrop of a conductive channel which passes from the vicinity of an emitting dipole source. The angle between the emitting dipole and the conductive path plays an important role because the solutions of Maxwell equations reveal the following (Varotsos et al., 2000; Sarlis and Varotsos, 2001, 2002): when the emitting dipole is oriented almost perpendicular to the path "*overamplification*" occurs, which means that the amplification of the electric field, with respect to its value in the absence of the conductive structure, close to the outcrop is larger than the resistivity contrast, i.e., the ratio of the conductivity of the path compared to the conductivity of the surrounding medium, see also Varotsos (2005). Since the change of the focal mechanism reflects a change of the orientation of the emitting dipole source (see Chapters 6 and 12 of Varotsos (2005)), the following situation may happen: upon changing the orientation of the dipole it may become perpendicular to a different neighbouring conductive path, which may have a different outcrop thus resulting to a different SES sensitive station. Such a simplified scheme seems to explain the interrelation between the EQ focal mechanism and selectivity but the real situation may be more complex and hence other source parameters may play an important role.

We now further comment on the aforementioned fact that the earthquake source mechanism changed from largely strike-slip type to thrust at the end of 1987 (and this coincided with the shift in the SES sensitive site from PIR to IOA). Focusing on Kefallinia area and following Uyeda et al. (1999), we note that this area is considered to be a transform fault connecting one thrust zone with one collision zone (see Fig. 1), where small change in the relative plate motion may cause a shift of source mechanism. The change with time in the source mechanism is strikingly reminiscent of the following change reported by Press and Allen (1995) from their study of earthquakes in southern California. These earthquakes occur on the San Andreas fault system of vertical right-lateral predominantly strike slip faults and a second system of faults that includes thrust, oblique slip, left-lateral and other faults. Analyzing all earthquakes with $M \geq 5.5$ from 1915 to 1994, Press and Allen (1995) found that epochs of seismic release occur in which one or the other system is the predominant form of earthquake activity. In particular, for the last two decades they reported that the second system has been the active one. They also suggested that small changes in the direction of the plate movements account for this phenomenon.

Concerning the experimental results presented in this paper, the following point, which is related to the latter case, still remains unclear: Two SES activities, Pir_1 and Pir_2, were recorded on March 14, 2004 (see Fig. 4), as already mentioned, while only one major EQ occurred on March 17, 2004. If we accept that Pir_1 (which has larger amplitude than Pir_2), is actually associated with this EQ, the other SES activity Pir_2 might be connected to the seismic activity that occurred in the sea area of PIR during the period May 21–May 31, 2004 (EQs marked with “b” in Table 3). However, the strongest EQ of the latter activity, i.e., $M_s(\text{ATH}) = 5.1$ on May 30, seems to be weaker than the one expected (~6.0 magnitude units). If we consider that the expected magnitude, estimated on the basis of the SES amplitude, may differ up to ±0.7 magnitude units from the actual one, e.g., see Varotsos et al. (1996). The difference between the actual magnitude and the predicted one may not be that significant if we consider that even the magnitudes reported from various institutes differ by ~0.5 units (for the EQ under discussion, e.g., Patras University (Prof. Akis Tselentis, private communication), reported a magnitude larger by ~0.5 magnitude unit compared to that reported by PSB of SI-NOA).

Table 3
All EQs within $N_{34.5}^{42.5}E_{19}^{25}$ for the time period March 14 to July 25, 2004 with $M_L(\text{ATH}) \geq 4.0$, epicenters and M_L from PSB of SI-NOA

Year	Mon	Day	Hours	Min	Sec	Lat	Lon	Depth	M_S(ATH)
2004	3	17	5	20	58.2	34.5	23.3	24	6.5
2004	3	21	3	18	53.4	41.6	19.7	33	5.2
2004	3	28	14	54	36.8	35.5	22.9	83	4.9
2004	3	30	8	7	34.4	39.3	24.1	38	4.7
2004	4	7	1	32	28.3	40.7	20.4	90	5.2
2004	4	12	22	29	0.4	36.1	23.5	20	4.5
2004	4	15	13	54	23.8	34.7	24.8	82	4.8
2004	4	28	7	26	58.4	38.3	21.8	15	4.6[a]
2004	5	21	2	26	38.5	37.9	20.7	7	4.6[b]
2004	5	30	6	59	8	37.1	21.5	17	5.1[b]
2004	5	30	21	23	30.2	37.9	20.7	18	4.5[b]
2004	5	31	6	30	39.8	37.1	21.5	16	5.0[b]
2004	6	7	14	54	49.2	34.8	24.9	4	4.5
2004	6	17	11	58	24.5	34.6	24.5	37	4.6
2004	6	19	21	44	48.6	41.5	20.0	14	4.7
2004	6	24	19	25	57.5	36.0	21.3	5	4.5
2004	7	15	21	33	32.1	34.7	24.3	8	4.6
2004	7	24	19	0	56.1	35.4	23.6	11	4.8

[a] EQ in the sea area of Patras (PAT). The seismological institute of Patras reported a 5.0 magnitude.

[b] EQs in the sea area of PIR.

5. Main conclusions

Additional experimentation at the SES sensitive station PIR shows that the station became active during the last 2 years, after a 10-year period of “quiescence”, i.e. after a period for which no SES at PIR was identified in the records and thus no relevant prediction was issued. The analysis in the natural time-domain of the SES activities recorded at PIR, led to values of the variance κ_1, the entropy S and the complexity measure λ_s which are compatible with those reported from a similar analysis of earlier SES activities in Greece. This activation was followed by two major strike slip EQs (on August 14, 2003 and March 17, 2004 with magnitudes 6.4 and 6.5, respectively) in the Hellenic arc, which is consistent with the conclusions of Uyeda et al. (1999) obtained from the investigation of the period 1983–1994 in Western Greece.

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