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Recent Seismic Electric Signals (SES) activities in Greece

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Abstract

Quite recently two intense Seismic Electric Signals activities were recorded at Pirgos station in western Greece. They have been followed by two strong earthquakes with magnitudes 6.1 and 6.9 that occurred in western Greece and southern Greece; the latter is the strongest earthquake that occurred in Greece during the last two decades. The compatibility of these results with some relationship between selectivity and earthquake focal mechanism suggested by Uyeda *et al*. (1999) is discussed.

Key words: Seismic Electric Signals, SES selectivity, natural time.

1. INTRODUCTION

Uyeda *et al*. (1999) investigated the selectivity characteristics of the SES (Seismic Electric Signals of the VAN method) along with the parameters of the earthquake that occurred in western Greece during the period 1983-1994. They found that:

(1) Pirgos station was sensitive only to strike slip earthquakes and

(2) the earthquake source mechanism changed from largely strike-slip type to thrust type at the end of 1987 in the zone west of Kefallinia to Peloponese, and this coincided with a shift of the site sensitive to the SES in this area from Pirgos (PIR) to Ioannina (IOA) VAN station.

Varotsos *et al*. (2006) subsequently studied the results for the period from 1 January 2002 to 25 July 2004, during which the SES sensitive site at PIR became active again. They found that two strike slip earthquakes (EQs) with magnitudes 6.4 and 6.5 that occurred on 14 August 2003 and 17 March 2004 have been preceded by SES activities recorded at PIR, thus providing additional evidence on the aforementioned result (1) reported by Uyeda *et al.* (1999). These EQs had epicenters at (38.7°N, 20.7°E) and (34.5°N, 23.3°E), i.e., in western Greece and close to the western part of Crete, respectively.

Quite recently, after the submission of the paper by Varotsos *et al.* (2006), two additional EQs occurred at 15:25 UT on 18 October 2005 and at 11:34 UT on 8 January 2006 with epicenters at (37.58°N, 20.86°E) and (36.21°N, 23.41°E), respectively. Their preliminary magnitudes, as announced by the Geodynamical Institute of the National Observatory of Athens (GI-NOA), were $M_s(\mathrm{ATH}) = 6.1$ and 6.9, respectively. (The symbol $M_s(\mathrm{ATH})$ stands for the magnitude defined by $M_s(\mathrm{ATH}) \equiv M_L + 0.5$, where M_L denotes the local magnitude reported by GI-NOA). It is the aim of the present paper to report what happened before these two EQs, which, for reasons of brevity, will be hereafter labeled EQ_1 and EQ_2, respectively. Note that EQ_2 is the strongest EQ that occurred in Greece during the last two decades.

2. THE SES ACTIVITIES RECORDED AT PIRGOS (PIR)

On 17 September 2005, two intense SES activities, with duration of several hours each, were recorded at PIR station. They are shown in Fig. 1. Among the 10 dipoles depicted, one (i.e., AL) was out of order, seven recorded the SES activities, while at the two upper ones (i.e., XYL and E_B) no clear disturbances can be visualized. (The configuration of the dipoles can be found in Fig. 2 of Varotsos *et al.* 2006.) Comparing these two SES activities to those preceding the 6.5 EQ that occurred close to western Crete on 17 March 2004 (depicted in Fig. 4 of Varotsos *et al.* 2006) we note the following: (i) the former have larger amplitude and (ii) the latter were recorded at all channels while the former – as mentioned – were not recorded at the upper two channels; this difference indicates that they are emitted from **different** focal areas. A third SES activity of appreciably smaller duration (~30 min) was recorded later, i.e., on 1 January 2006, but only at two long dipoles, i.e., those labeled "0202" and "ST". Here, we will focus on the first two SES activities.

Since the expected EQ magnitudes were estimated to be larger than (or equal to) 6.0-units, we followed a procedure similar to that explained in Varotsos *et al.* (2006) and in Varotsos (2005), i.e., all the relevant information on the SES recordings and their analysis were submitted on 22 October 2005 to international journals (i.e., Acta Geophysica Polonica in this case) in advance, i.e., **before** the EQ_2 occurrence.

3. THE EARTHQUAKES THAT OCCURRED AFTER THE SES ACTIVITIES

Almost one month after the SES recordings, the 6.1 EQ_1 occurred. The Centroid Moment Tensor solutions (CMT hereafter, e.g., see Scott and Kanamori 1985), as reported by USGS and Harvard (see the website http://earthquake.usgs.gov/recenteqsww/Quakes/ushrak.htm), show that EQ_1 is mainly of thrust type. If this EQ was correlated with one of the SES activities at PIR, this seems to deviate from the

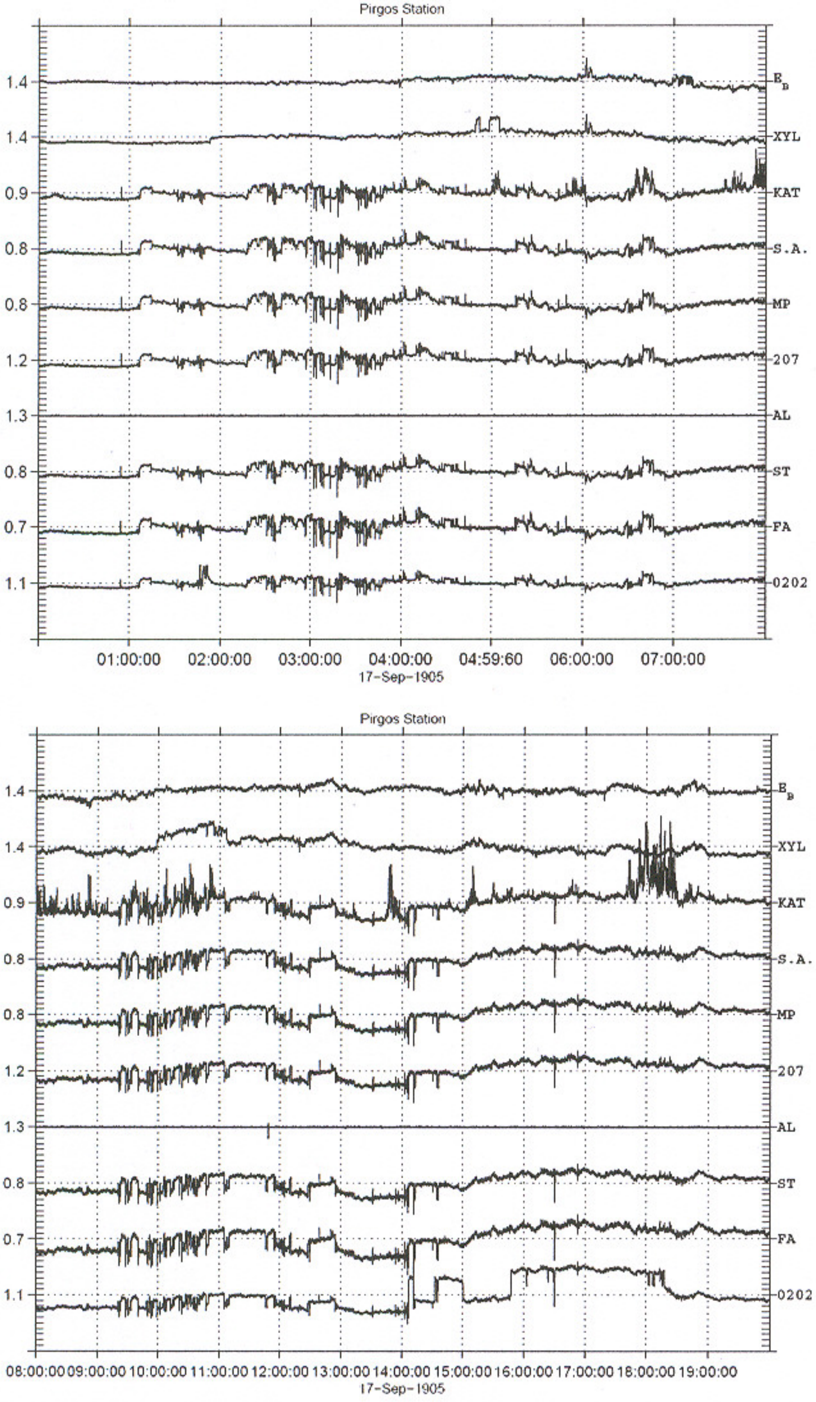

Fig. 1. The two SES activities recorded at PIR on 17 September 2005.

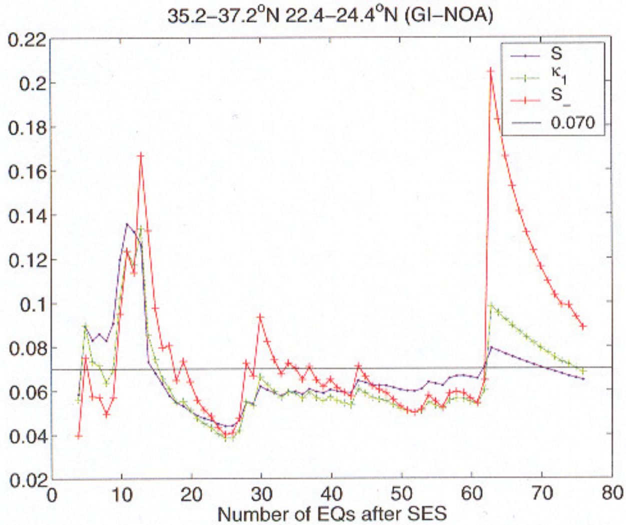

Fig. 2. The quantities κ_1, S and S_- , as they evolve by event, after the SES activities in a region 2 degrees × 2 degrees around the epicenter.

above mentioned conclusion (1) of Uyeda *et al.* (1999). Note that nowadays the exact position of PIR station is different from that at the time of Uyeda *et al.*, and this might be an important factor that could explain the aforementioned deviation.

We now turn to the 6.9 EQ_2 on 8 January 2006 for which USGS (as well as Harvard) reported preliminary CMT, which indicate that this EQ is also mainly of thrust type (with a relatively small strike slip component). Other institutes and/or organizations (see the website http://www.emsc-csem.org/cgi-bin/ALERT_datafile.sh?HB946 &MT) gave preliminary CMT that differ either slightly (e.g., ETHZ-Switzerland) or significantly (e.g., KAN-Turkey, INGV-Istituto Nazionale di Geofisica e Vulcanologia) from those reported by USGS. For example, the solutions of the latter organizations in general indicate that EQ_2 is mainly of thrust type, but with a strike slip component considerably different from that determined by Harvard. In spite of this difference, we can deduce the preliminary conclusion that the occurrence of EQ_2 does not seem to conform the interrelation that PIR is sensitive to strike-slip EQs suggested by Uyeda *et al.* (1999). However, this point merits further investigation (see also below).

We finally employ the analysis in natural time χ in order to investigate whether the time window of EQ_2 can be determined when following the procedure developed in Varotsos *et al.* (2001) (see also Varotsos 2005): If we set the natural time for seismicity zero at the initiation time of the concerned SES activities, we form time series of seismic events in natural time for various time windows as the number of consecutive (small) EQs increases. The investigation was made in a region almost (2 degrees × 2 degrees) surrounding the epicenter, i.e., we consider the (small) EQs within the region (35.2° to 37.2°)N, (22.4° to 24.4°)E, see Table 1. We then compute, for each of

Table 1

All earthquakes that occurred after the SES activities of 17 Sept. 2005, in the region 35.2-37.2°N, 22.4-24.4°E. The GI-NOA EQ catalogue (available on line on 10 Jan. 2006) is used

No.	Date	Time	Latitude	Longitude	Depth	M_L/MD
1	2005 Sep 18	$22^h46^m45^s$	37.11	23.58	10	3.4
2	2005 Sep 19	13 46 11.9	35.88	24.09	10	3.2
3	2005 Sep 22	19 45 12	35.35	23.38	10	3.2
4	2005 Sep 24	16 43 46.4	36.53	23.61	10	2.8
5	2005 Sep 25	18 50 12.7	35.41	23.36	10	3.2
6	2005 Sep 26	07 04 41.8	36.75	23.64	4	2.8
7	2005 Sep 29	17 38 56.5	35.86	23.20	13	2.9
8	2005 Sep 30	00 22 01.9	36.34	23.23	10	2.7
9	2005 Sep 30	14 30 42.1	36.70	23.73	32	2.9
10	2005 Oct 1	21 17 25.3	36.05	23.52	10	3.2
11	2005 Oct 4	00 23 12.2	35.60	23.20	16	3.3
12	2005 Oct 6	17 05 03.4	35.37	23.21	10	3.1
13	2005 Oct 8	12 20 25.3	36.43	23.07	22	3.7
14	2005 Oct 10	15 08 45.3	35.44	22.64	30	4.0
15	2005 Oct 13	08 35 17	35.91	23.39	10	2.6
16	2005 Oct 14	07 21 09.6	36.12	24.09	27	3.3
17	2005 Oct 14	10 15 17.1	35.76	23.91	13	3.7
18	2005 Oct 16	03 24 50.8	36.64	24.30	10	2.8
19	2005 Oct 17	04 19 32.3	35.54	22.50	5	3.7
20	2005 Oct 19	09 54 38.6	36.64	23.02	24	3.3
21	2005 Oct 21	05 04 17.1	36.57	23.08	21	3.1
22	2005 Oct 21	06 58 31.2	35.86	23.51	10	3.2
23	2005 Oct 22	15 40 31.6	35.99	22.45	31	3.2
24	2005 Oct 22	16 52 25.9	35.91	23.46	12	2.9
25	2005 Oct 31	06 46 58.5	35.36	23.31	10	3.0
26	2005 Nov 1	13 03 46.3	35.99	22.42	33	3.2
27	2005 Nov 1	17 20 40.2	35.64	22.69	32	3.4
28	2005 Nov 1	23 27 33	35.51	23.53	5	3.7
29	2005 Nov 1	23 34 37.8	35.57	23.49	18	3.2
30	2005 Nov 2	04 13 44.4	35.42	23.06	28	3.8
31	2005 Nov 3	07 59 19.7	36.31	24.20	10	3.0
32	2005 Nov 6	03 09 14.5	36.82	23.16	21	3.0
33	2005 Nov 6	15 18 59.3	36.34	22.52	5	3.0
34	2005 Nov 7	11 59 23.6	35.84	24.21	23	3.5
35	2005 Nov 9	07 10 21.3	35.97	22.42	19	3.3
36	2005 Nov 9	19 41 08.9	36.39	23.18	17	3.0
37	2005 Nov 12	04 31 44.4	36.04	23.94	18	3.5
38	2005 Nov 15	22 28 23.4	35.62	23.17	10	2.8
39	2005 Nov 17	16 13 11.6	35.72	22.75	14	3.1

40	2005 Nov 18	09 13 33.7	35.70	23.74	10	3.4
41	2005 Nov 18	12 40 01.5	35.67	23.41	4	3.0
42	2005 Nov 19	19 25 26.2	35.38	23.22	10	3.1
43	2005 Nov 21	22 20 15.8	35.66	23.13	39	3.1
44	2005 Nov 23	22 16 59.7	35.96	22.46	6	3.6
45	2005 Nov 29	00 14 43.2	36.31	23.32	10	2.9
46	2005 Nov 29	22 38 33.6	37.19	23.15	10	2.8
47	2005 Nov 29	23 54 47.7	36.54	23.23	2	3.1
48	2005 Nov 30	06 11 20.7	35.52	23.72	15	3.1
49	2005 Nov 30	06 25 33.5	35.58	23.78	17	2.8
50	2005 Nov 30	16 28 44.9	36.10	23.30	4	2.7
51	2005 Nov 30	20 04 27	35.75	24.20	19	2.9
52	2005 Dec 2	01 08 36.5	37.15	23.04	25	3.0
53	2005 Dec 5	01 36 39.3	36.03	23.66	10	3.2
54	2005 Dec 5	08 12 54.1	35.73	23.47	5	3.4
55	2005 Dec 5	16 25 34.1	35.59	23.77	4	2.8
56	2005 Dec 8	22 30 28.3	36.07	23.63	57	2.7
57	2005 Dec 11	06 01 33.8	36.62	22.67	81	3.4
58	2005 Dec 11	09 48 22.1	35.25	23.98	39	3.2
59	2005 Dec 11	10 03 47.8	35.51	23.68	10	3.1
60	2005 Dec 19	03 06 29.9	36.18	22.45	21	2.8
61	2005 Dec 19	03 11 53.9	36.08	22.42	4	2.8
62	2005 Dec 19	05 53 51.7	36.19	22.47	25	3.5
63	2005 Dec 23	07 09 56	35.33	23.32	95	4.6
64	2005 Dec 26	12 23 50.5	36.39	22.79	9	3.1
65	2005 Dec 26	19 09 48	36.30	22.71	12	3.2
66	2005 Dec 26	20 34 30.5	36.34	22.81	31	3.1
67	2005 Dec 26	22 31 10	36.32	22.75	21	3.0
68	2005 Dec 26	22 57 33.7	36.36	22.74	20	3.2
69	2005 Dec 27	03 04 12	36.28	22.73	12	3.4
70	2005 Dec 27	07 18 08.6	36.41	22.78	5	3.2
71	2005 Dec 28	07 16 16.3	36.40	22.74	3	3.1
72	2005 Dec 31	04 19 42.9	36.88	22.92	9	2.9
73	2005 Dec 31	07 59 22.9	35.35	23.6	5	3.4
74	2006 Jan 1	15 41 27.2	35.58	24.03	18	3.8
75	2006 Jan 6	12 46 42.4	36.93	22.95	17	2.9
76	2006 Jan 6	21 48 54.3	36.49	23.16	21	2.8
77	**2006 Jan 8**	**11 34 54**	**36.21**	**23.41**	**69**	**6.4**

the time windows, the following quantities: the variance $\kappa_1 \equiv <\chi^2> - <\chi>^2$, the entropy S in natural time as well as the entropy $S\_$ under (natural) time reversal. The results are plotted in Fig. 2 and show that κ_1 approaches the value 0.070 (which corresponds to a critical state) at the last but one small EQ. This occurred at 12:46 UT on 6 January 2005, i.e., almost two days before the occurrence of the mainshock. Further, both,

S and S_{-} values, are then smaller than the value $S_u = 0.096$ corresponding to the "uniform" (u) distribution, as they should (see Varotsos *et al.* 2005). In other words, the time window of EQ_2 is determined with an accuracy of 2 days. Note that the time window does not change significantly (i.e., it pertains up to one week before the main shock) if we employ a magnitude threshold of 2.9 or 3.0.

The above analysis in natural time shows that at least one of the two SES activities on 17 Sept. 2005 at PIR station was actually correlated with strike-slip EQ_2, but not also with strike-slip EQ_1. Whether these correlations contradict with Uyeda *et al.* (1999) is uncertain in view of the fact that the exclusive sensitivity of PIR station was well established by Uyeda *et al*. for the region around EQ_1 with enough data available, but not for the region around EQ_2 due to the lack of data. The present results leave the possible correlation of one out of the two SES activities recorded at PIR on 17 Sept. 2005 still open. It may be also possible that the two SES activities on one day were in fact one SES activity. These points will be clarified of course if a new strong EQ will again occur in the region under discussion.

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