What happened before the last five strong earthquakes in Greece: Facts and open questions

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Abstract: During the period October 2005 - January 2006, five strong earthquakes occurred in Greece as follows: three magnitude 6.0 consecutive earthquakes with almost the same epicenter in the Aegean Sea close to the western coast of Turkey, one magnitude 6.1 in western Greece and one magnitude 6.9 in southern Greece. In March 2005 and September 2005, intense anomalous geoelectric changes were observed at two different stations respectively: one in the Aegean Sea and the other in western Greece. These changes were immediately reported to international journals well in advance of earthquake occurrences. Natural time analysis of seismicity subsequent to the September changes around the epicenter of the last 6.9 earthquake is made. The results indicate that the occurrence time of the 6.9 earthquake can be specified with a narrow range around two days.

Key words: Natural time; seismicity; Seismic Electric Signals.

Introduction. Five earthquakes (EQs), with magnitude M_s(ATH) equal to 6.0 or larger, occurred in Greece (see Fig. 1) during the last three months (the symbol M_s(ATH) stands for the magnitude defined by $M_s(ATH) \equiv M_L + 0.5$ and M_L denotes the local magnitude reported by the Geodynamical Institute of National Observatory of Athens, GI-NOA). Three of them, with $M_s(ATH) \approx 6.0$, occurred within 4 days (i.e., two on October 17, and one on October 20, 2005) at approximately the same epicenter, i.e., at 38.15˚N, 26.68˚E, in the eastern Aegean Sea close to the western coast of Turkey. Occurrence in such a short time of three equally strong earthquakes in the same focal area is rare. A fourth EQ with $M_s(ATH) = 6.1$ occurred on October 18, 2005 in western Greece at 37.58˚N, 20.86˚E. Finally, on January 8, 2006, a fifth EQ with $M_s(ATH) = 6.9$ occurred in southern Greece at 36.21˚N, 23.41˚E. It is the aim of the present paper to report what was observed before these five EQs, focusing particularly on the last 6.9 EQ, which is the strongest EQ that occurred in Greece during the last twenty years. As will be explained below, before all these five EQs, we observed clear geoelectric changes that might have been the relevant SES (Seismic Electric Signals of the VAN method) activities. Further, since the magnitudes of the expected EQs estimated from the SES activities were larger than (or equal to) 6.0, quick reports on the relevant information, summarized in the next section, was submitted to international journals[1)-3)] well in advance of the EQ occurrence. This convention has been followed during the last decade in accordance with the recommendation of European Advisory Committee for earthquake prediction of the Council of Europe (see p.101 of Ref. 4).

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The three earthquakes close to the western coast of Turkey. A sequence of four strong electrical disturbances was recorded on March 21 and 23, 2005 at MYT station, which is installed on the island Lesvos lying in the northeastern Aegean Sea close to the western coast of Turkey. They had "amplitudes appreciably larger than those hitherto recorded"[1),2)] and were identified as SES activities by applying the well established criteria of discriminating SES from artificial noise.[5)-9)] Namely, the variance $\kappa_1 \equiv \langle\chi^2\rangle - \langle\chi\rangle^2$ (χ stands for natural time) and the entropy S in both forward (S) and reverse (S_-) natural times, defined as:

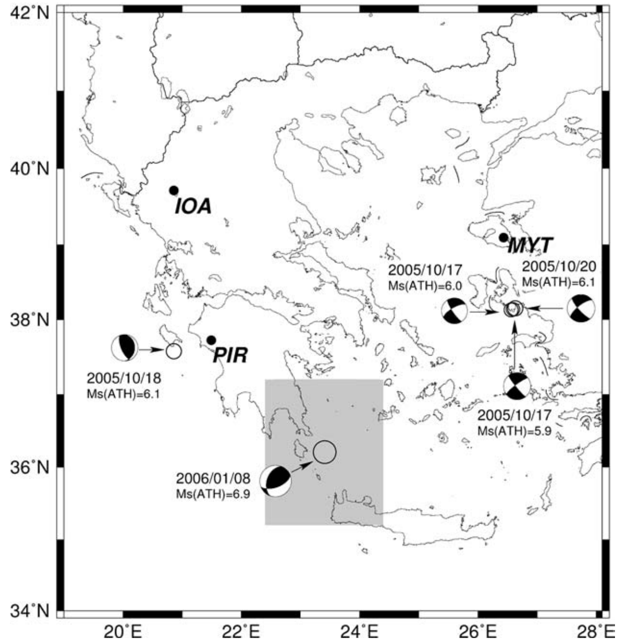

Fig. 1. Map of Greece showing the sites of the three stations MYT, PIR and IOA (solid circles). The epicentral locations (open circles) of the EQs discussed in the text along with their centroid moment tensor fault plane solutions (http://www.seismology.harvard.edu/CMTsearch.html) are also depicted. The seismicity, that occurred after the SES activity at PIR on Sept. 17, 2005, has been analyzed in natural time in the shaded region surrounding the 6.9 EQ epicenter.

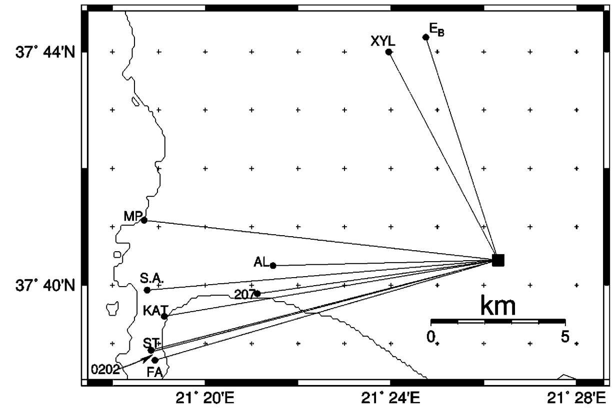

Fig. 2. Configuration of the measuring electric dipoles (solid lines) operating at PIR. The square shows the site of the data collection, where a common electrode of all dipoles is located. The other electrode of each dipole is shown with a solid dot.

$$S = \langle \chi \ln \chi \rangle - \langle \chi \rangle \ln \langle \chi \rangle$$

of these signals have all shown that $\kappa_1 \approx 0.070$, $S < S_u$, $S_- < S_u$, where the value $S_u (= \frac{1}{2}\ln 2 - \frac{1}{4} \approx 0.0966)$ is the entropy of a "uniform" distribution (as defined in Refs. 5, 8). These results revealed that the observed disturbances could not be attributed to artificial source, but were SES activities.

The three consecutive earthquakes with magnitude around 6.0 occurred in the eastern Aegean Sea in October 2005 as mentioned in Ref. 1. (Ref. 1 originally submitted before the earthquakes (Ref. 2, arXiv: physics/0510215 v1)) has undergone revisions to mention about the earthquakes that occurred during the review process (Ref. 2 (arXiv: physics/0601178 v1)). In an attempt to determine the time-window of this group of earthquakes, we considered the regions A: $N_{37.0}^{39.5}\ E_{25.5}^{28.0}$ and B: $N_{37.5}^{39.5}\ E_{26.5}^{28.0}$ and studied in natural time, the evolution of seismicity that occurred after the initiation of the SES activities. This study showed that the critical point was approached during the period from October 13 to early in the morning of October 17, 2005. (Details can be found in Ref. 2 (arXiv: physics/0601178 v1)). Actually, at 05:45 UT on October 17, 2005, the first magnitude 6.0 earthquake occurred at 38.15 °N, 26.68 °E at a distance of around 100 km from MYT. Two more magnitude 6.0 EQs subsequently occurred at almost the same epicenter within four days, as mentioned in the introduction. The probability that these events, i.e., SES activities and EQs, occurred by chance has been estimated to be much less than 5%.[1)] Hence, although the lead time between SES activities and EQs was unusually long in this case, a chancy correlation between the SES activities at MYT and the subsequent EQs can be precluded. The following question, however, remains: Four SES activities have been recorded but only three EQs of magnitude 6.0 occurred. It was noted[1)] that the fourth SES activity had a polarity opposite to the previous three ones, possibly indicating[2)] that it corresponded to a future EQ in the Aegean Sea, either at the same region but with different source mechanism, or in a different region. We shall come back to this question in the discussion section.

The two earthquakes in western Greece and southern Greece. Two intense electric disturbances, with duration of several hours each, were recorded[3)] at PIR station on September 17, 2005. Further, a third electrical disturbance of appreciably smaller duration (~30 min) was recorded later on January 1, 2006, but only at two long dipoles, i.e., those labeled "0202" and "ST" in Fig. 2. Since it was recorded only at two dipoles, the cri-

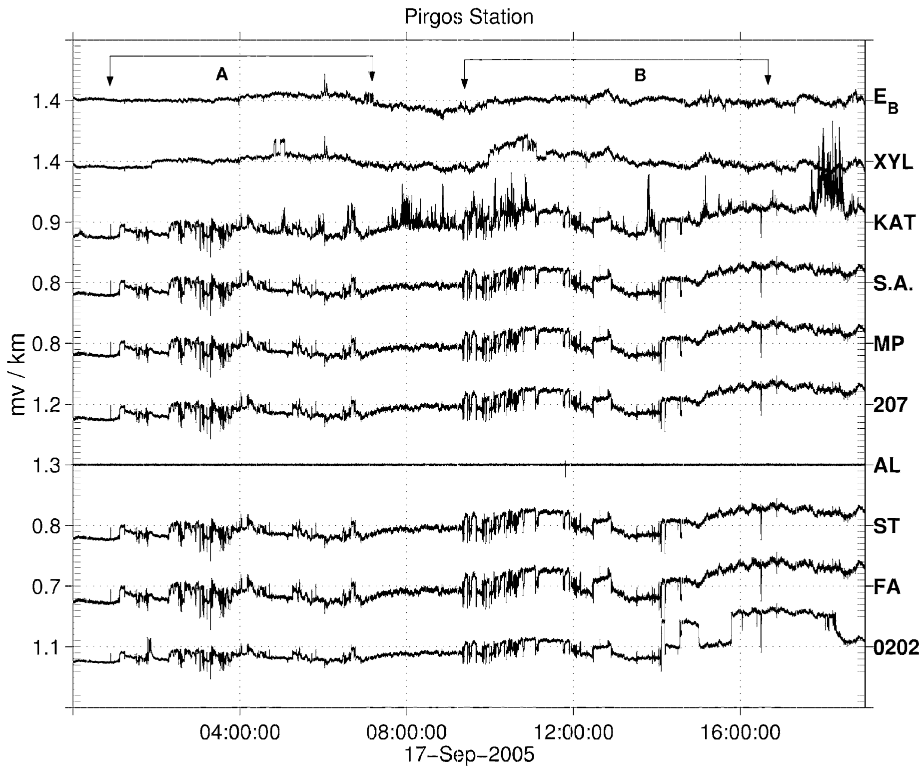

Fig. 3. The two geoelectric disturbances recorded at PIR on September 17, 2005.

teria to distinguish SES from noise could not be appropriately applied to this disturbance. Hence, we will focus on the first two disturbances, which are depicted in Fig. 3. Seven out of the 10 dipoles recorded them, while the two (XYL and E_B) did not. (One dipole, AL, was out of operation). Since dipoles XYL and E_B were nearly in the N-S direction, it could be interpreted that the electric change was oriented approximately in the E-W direction.

The two disturbances of Fig. 3 were compared to the SES, also recorded at PIR,[10] that preceded the 6.5 EQ occurred close to western Crete on March 17, 2004. The comparison revealed the following: First, the disturbances of Fig. 3 have larger amplitudes, and second, they are not recorded at the two dipoles in contrast to those recorded[10] in 2004. This difference may indicate that they are emitted from different focal areas.

Almost one month after the disturbances of Fig. 3, the 6.1 EQ occurred in western Greece on October 18, 2005. USGS and Harvard reported that this EQ was mainly of thrust type. Uyeda *et al.*[11] found that, for the EQs in the transform fault zone west of Kefallinia, PIR was mainly sensitive to strike slip type while IOA mainly sensitive to thrust type. Hence, if the disturbances recorded at PIR on September 17, 2005 were real SES activities and were actually correlated with this EQ, it may be seen as a case improving the PIR selectivity map.

Later, on January 8, 2006, the 6.9 EQ occurred in southern Greece. For this EQ, USGS and Harvard reported preliminary source characteristics indicating that it is mainly of thrust type with a relatively small strike slip component. Other Institutes and/or Organizations (e.g., KAN-Turkey, INGV-Italy) gave preliminary EQ source characteristics that differ from those reported by USGS and Harvard. The solutions of INGV-Italy, for example, indicate a strike slip component considerably larger than that determined by USGS or Harvard.

Analysis in natural time to determine the time window of the 6.9 earthquake. In order to achieve this goal, we follow the procedure developed in Refs. 5, 7, 12. We set the natural time for seismicity zero at the initiation time of the disturbances recorded at PIR on Sept. 17, 2005, and form time series of seismic events in natural time for various time windows as the

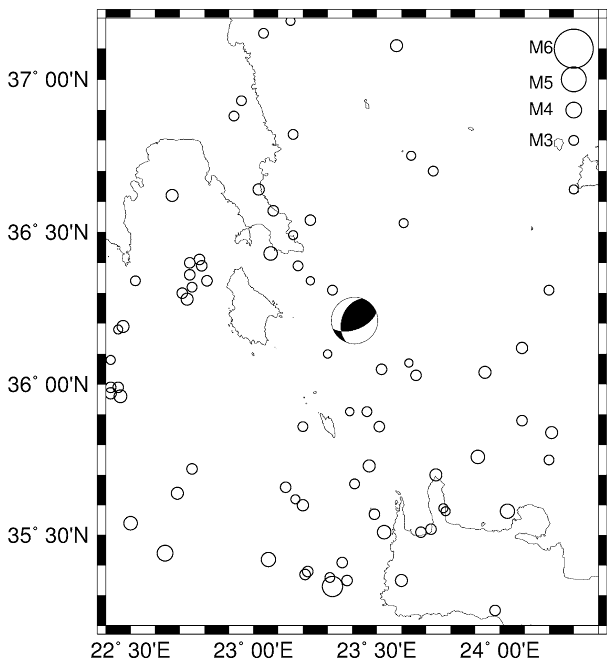

Fig. 4. Map showing the epicentral locations of all EQs that occurred after the geoelectric disturbances at PIR on Sept. 17, 2005 within the shaded region of Fig. 1, i.e., 2 degrees X 2 degrees around the epicenter of the 6.9 EQ on January 8, 2006. The source mechanism of the 6.9 EQ is also shown.

number of consecutive (small) EQs increases. We consider all the small EQs that occurred before the mainshock after the natural time zero, within the region (35.2° to 37.2°)N, (22.4° to 24.4°)E surrounding the epicenter (see Fig. 1). The epicentral distribution shown in Fig. 4 is based on the EQ catalogue of GI-NOA (http://www.gein.noa.gr/services/monthly-list.html on Jan. 10, 2006). For each of the time windows, the following quantities have been computed: κ_1, S and S_-. The results, plotted in Fig. 5A, show that κ_1 approaches the value 0.070 from *above* (which corresponds to a critical state[4),5)]) at 12:46 UT on January 6, 2005, i.e., almost two days before the occurrence of the mainshock. Both S and S_- values, are smaller than the value $S_u = 0.0966$, as they should[9)] in a critical system. These results support the view that the observed disturbances were real SES activities.

If we make the same calculation, but by imposing a magnitude threshold M_L (or M_D) ≥ 3.0 (where M_D stands for the so called "duration" magnitude), we obtain the results depicted in Fig. 5B showing that the critical point is approached a week before the mainshock (cf. no EQ with $M_L \geq 3.0$ occurred during this week). The difference in the results of the two calculations is understood in the following context: if higher magnitude threshold is used, the description of the real situation approaching criticality would become less accurate due to *coarse graining*[4)] when the number of events is finite.

In summary, the study in natural time of the seismicity after the disturbances at PIR reveals that the time window of the 6.9 EQ can be determined with a narrow range of around 2 days up to 1 week. Although expost facto in this case, similar operation could be performed in advance if the probable focal area, in which the natural time analysis of seismicity should be conducted, had been estimated independently with the help of selectivity map of the concerned station.

Discussion. Concerning the SES activities recorded at MYT, the relevant results confirmed[1)] that they were most probably correlated to the sequence of the three magnitude 6.0 EQs in the Aegean Sea during Oct. 17-20, 2005. As for the results related to the disturbances at PIR on Sept. 17, 2005, they show that at least one of the two disturbances of Fig. 3 is most probably correlated with the 6.9 EQ of Jan. 8, 2006.

We are left with the following open questions. 1) Were the recordings in Fig. 3 real SES activities? If so, are they two separate SES activities or constitute a single SES activity? These questions cannot be answered at present, because the feature of the whole signal in Fig. 3 is too complicated to perform the natural time analysis so far developed for a sequence of dichotomous pulses. If signals are simpler and dichotomous, we can provide an answer by following a procedure similar to that indicated in Ref. 1. If they were two separate SES activities, one of them may be correlated with the 6.9 EQ in southern Greece and the other may be with the 6.1 EQ in western Greece. If we exclude the latter correlation, the remaining disturbance in Fig. 3 would imply a future strong EQ.

2) Why was the shape of the disturbances at PIR so complicated? We do not have the answer to this question either. The possible answer might be related to the fact that the depth of the 6.9 EQ was ≈ 67 km which was much deeper than other Greek EQs preceded by SES activities. If this was the case, the possible correlation of one of the disturbances with the shallow 6.1 EQ would be excluded.

3) An additional question refers to the four SES activities recorded at MYT. The three magnitude 6.0 EQs that occurred in the Aegean Sea had almost the same

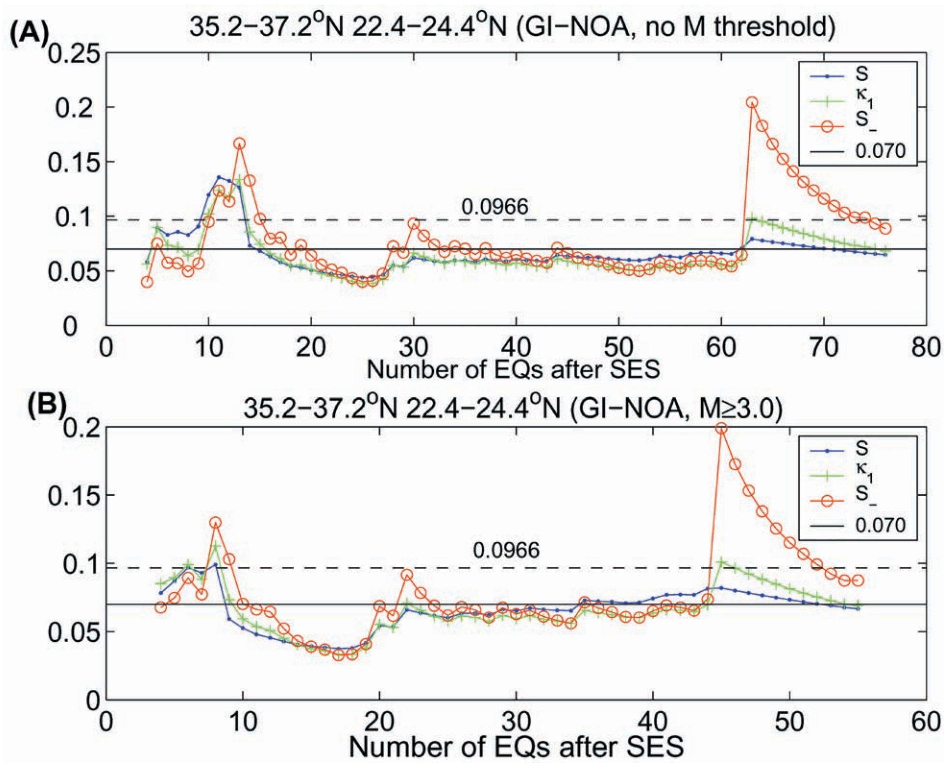

Fig. 5. The variance κ_1, the entropy S and the entropy under time reversal S_- of the seismicity within the shaded region of Fig. 1, as it evolves event by event after the geoelectric disturbances recorded at PIR on September 17, 2005. (A): For all small EQs reported (see Fig. 4); (B): For EQs with a magnitude threshold M_L(or M_D) ≥ 3.0. The horizontal solid line corresponds to κ_1 = 0.070 while the broken to S_u = 0.0966.

source mechanism characteristics and hence they are most likely correlated with the first three SES activities which had the same polarity. But what about the fourth SES activity of opposite polarity? In principle, this SES activity could be related to the EQ in southern Greece, but the epicentral distance is unusually large (≈ 400 km).

Main conclusions. Five EQs with magnitude 6.0 or larger occurred in Greece during the last few months. Three of them occurred in the Aegean Sea close to the western coast of Turkey and have been preceded by a series of intense SES activities at MYT on Lesvos island. Two others, which occurred in western and southern Greece, the last being the strongest EQ in Greece during the last twenty years, were preceded by two intense geoelectric disturbances at PIR located in western Greece. The study, in natural time, of the small EQs that occurred after these geoelectric disturbances at MYT and PIR, led to the determination of narrow time window(s) of around a few days, for the occurrences of the first strong EQ in the Aegean Sea and the EQ in southern Greece, respectively. These are the facts, but a few questions still remain open.

Note added on the proof. Two intense electric disturbances were recorded at PAT station (38.32 °N, 21.90 °E) near Patras City; on February 2, and 13, 2006. Since they were recorded only at three long dipoles, the criteria to distinguish SES from noise could not be applied. However, the natural time analysis on the Feb. 13 disturbance suggested that it could not be attributed to artificial source, but to an SES activity.[13] The Feb. 2 disturbance had too few (i.e., 7) pulses to make natural time analysis. Determination of the parameters of the impending EQ is difficult, because the selectivity map and calibration (p. 311 of Ref. 4) have not been established yet for PAT station. Assuming that the calibration of PAT is more or less comparable to IOA, and taking into consideration that the disturbances were not recorded at other VAN stations, the EQ epicenter may be inferred to: Either lie at a distance **r** of a few tens of km from PAT (i.e., in the Patraikos Gulf) and the magnitude may be M_s(ATH)~5.0 or an appreciably stronger EQ may occur, but at a significantly larger epicentral distance, e.g., M_s(ATH)~6.5 at **r** ~200 km, possibly within $N_{36.2}^{38.7}$ $E_{21.5}^{23.5}$ excluding the regions surrounding Pirgos and Kalamata as well as that close to Athens. In order to specify, the occurrence time of the impending EQ, natural time analysis of small EQs that occur after the aforementioned electric disturbance(s) is in progress.

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