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RESEARCH PAPER

Identifying the occurrence time of an impending mainshock: a very recent case

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Abstract The procedure by means of which the occurrence time of an impending mainshock can be identified by analyzing in natural time the seismicity in the candidate area subsequent to the recording of a precursory seismic electric signals (SES) activity is reviewed. Here, we report the application of this procedure to an M_W 5.4 mainshock that occurred in Greece on 17 November 2014. This mainshock (which is pretty rare since it is the strongest in that area for more than half a century) was preceded by an SES activity recorded on 27 July 2014, and the results of the natural time analysis reveal that the system approached the critical point (mainshock occurrence) early in the morning on 15 November 2014.

Keywords Seismic electric signals · Natural time analysis · Earthquake prediction · Critical phenomena

1 Introduction

Earthquakes (EQs) in general exhibit complex correlations in time, space, and magnitude M, which have been investigated by several authors (Sornette 2000; Corral 2004; Davidsen and Paczuski 2005; Holliday et al. 2006; Saichev and Sornette 2006; Eichner et al. 2007; Lennartz et al. 2008, 2011; Lippiello et al. 2009, 2012; Sarlis et al. 2009, 2010; Telesca and Lovallo 2009; Bottiglieri et al. 2010; Telesca 2010; Sarlis 2011; Huang and Ding 2012; Sarlis and Christopoulos 2012; Varotsos et al. 2011c, 2012). The observed earthquake scaling laws (Turcotte 1997) indicate the existence of phenomena closely associated with the proximity of the system to a critical point, e.g., see Holliday et al. (2006), since scaling is a hallmark of criticality (Stanley 1999). Here, we take this view that mainshocks are (non-equilibrium) critical phenomena.

Major EQs are preceded by transient changes of the electric field of the Earth termed seismic electric signals (SES) (Varotsos and Alexopoulos 1984a, b). A series of such signals recorded within a short time are called SES activities (Varotsos and Lazaridou 1991; Varotsos et al. 1993, 2009; Varotsos 2005), the average leading time of which is of the order of a few months (Varotsos et al. 2011a). It has been suggested that SES are emitted when the stress in the focal area of the impending mainshock reaches a critical value (Varotsos and Alexopoulos 1984a, b, 1986; Varotsos et al. 2011b). This suggestion is strengthened by the recent finding (Varotsos et al. 2013) that the fluctuations of the order parameter of seismicity defined in the frame of natural time analysis (see the next section) minimize upon the initiation of an SES activity exhibiting long-range temporal correlations (Varotsos et al. 2014). Such minima of the fluctuations of the order parameter of seismicity have been identified before all major ($M \geq 7.6$) EQs in Japan (Sarlis et al. 2013, 2015).

The identification of the occurrence time of an impending mainshock within a short time window is a challenge. This becomes possible when employing a procedure that combines SES data and natural time analysis of the seismicity (Varotsos et al. 2001, 2002a, b, 2005, 2008, 2011a; Sarlis et al. 2008; Sarlis 2013). In short, the initiation of the SES activity marks the time when the system enters the critical stage, and then the natural time analysis of the subsequent seismicity in the candidate area (which is

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determined on the basis of SES data, e.g., see Varotsos 2005) identifies when the system approaches the critical point, i.e., the mainshock occurrence, e.g., see Fig. 1 of Huang (2015). It is the scope of this paper to report a characteristic application of this procedure, which refers to an SES activity that was followed by a pronounced M_W 5.4 mainshock in Greece on 17 November 2014, which is pretty rare as explained later.

2 Summary of the procedure to identify the occurrence time of an impending mainshock

Let us first summarize the natural time analysis (Varotsos et al. 2002a) in the case of seismicity: In a time series comprising N EQs, the natural time $\chi_k = k/N$ serves as an index for the occurrence of the k-th EQ. The combination of this index with the energy Q_k released during the k-th EQ of magnitude M_k, i.e., the pair (χ_k, Q_k), is studied in natural time analysis. Alternatively, one studies the pair (χ_k, p_k), where $p_k = Q_k \Big/ \sum_{n=1}^{N} Q_n$ stands for the normalized energy released during the k-th EQ. It has been found that the variance of χ weighted for p_k, designated by κ_1, which is given by (Varotsos et al. 2001, 2002a, b, 2003a, b, 2011a):

$$\kappa_1 = \langle \chi^2 \rangle - \langle \chi \rangle^2 = \sum_{k=1}^{N} p_k \chi_k^2 - \left(\sum_{k=1}^{N} p_k \chi_k \right)^2 \qquad (1)$$

plays a prominent role in natural time analysis. In particular, κ_1 may serve as an order parameter for seismicity (Varotsos et al. 2005), and it has been empirically observed (Varotsos et al. 2001, 2002b, 2005, 2008, 2011a; Sarlis et al. 2008; Sarlis 2013) that κ_1 of the seismicity in the candidate area when considering all EQs with magnitude equal to or larger than a magnitude threshold M_{thres} subsequent to an SES activity becomes equal to 0.070 when approaching the critical point (mainshock occurrence). Note that Q_k, and hence p_k, for EQs is estimated through the usual relation (Kanamori 1978): $Q_k \propto 10^{1.5 M_k}$.

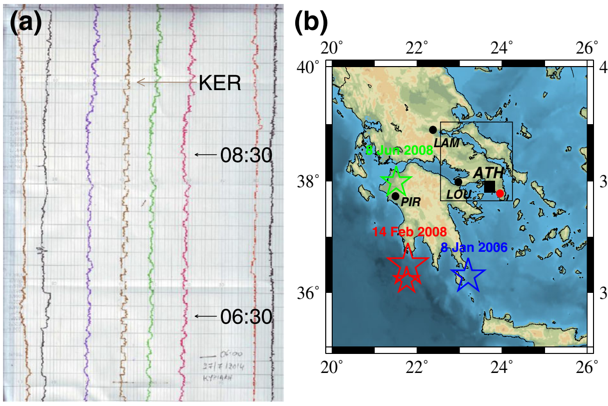

Fig. 1 **a** The SES activity of dichotomous nature recorded at the Keratea (KER) geoelectrical station of the SES telemetric network. **b**The predicted epicentral area designated by the *rectangle* on a map in which the location of the KER station (*red bullet*) is shown along with that of other geoelectrical stations Lamia (LAM), Loutraki (LOU) and Pirgos (PIR) (*black bullets*). The epicenters of the strongest EQs in Greece ($M_W \geq 6.5$) during the last decade are also shown with stars. The central station of the SES telemetric network is located at Athens (ATH, *black square*)

Upon the recording of an SES activity, one can estimate an area A within which the impending mainshock is expected to occur. The magnitude M of the expected EQ is estimated through the relation $\log_{10}\left(\frac{\Delta V}{L}\right) \approx 0.3\, M + \text{const.}$, e.g., see Varotsos and Lazaridou (1991), where for a given measuring dipole of length L and a given seismic area the SES amplitude $\Delta V/L$ is found from the anomalous variation ΔV of the potential difference between the corresponding two electrodes. When area A reaches criticality, one expects in general that all its subareas have also reached criticality simultaneously. At that time, therefore, the evolution of seismicity in each of its subareas is expected to result in κ_1 values close to 0.070. Assuming equipartition of probability among the subareas (Sarlis et al. 2008), the distribution Prob(κ_1) of the κ_1 values of all subareas should be peaked at around 0.070 exhibiting also magnitude threshold invariance. This usually occurs a few days to around 1 week before the mainshock, thus it enables the prediction of the occurrence time of major EQs with time window of the order of a week or less.

3 Application to a recent pronounced seismic activity in Greece

The SES activity shown in Fig. 1a was recorded on 27 July 2014 at Keratea (KER) geoelectrical station, the location of which is depicted with the red bullet in Fig. 1b. On the basis of the selectivity map of this station [i.e., the map showing all seismic areas in the past that gave rise to SES recorded at this station, e.g., see Varotsos and Lazaridou (1991)] and the ratio of the SES components, the candidate area was determined (Sarlis et al. 2014). This is depicted here by the rectangle in Fig. 1b as was designated in the uppermost right part of Fig. 2 of the paper uploaded by Sarlis et al. (2014) on 7 August 2014.

We now proceed to the natural time analysis of the seismicity subsequent to the aforementioned SES activity at KER within the candidate area 37.7°N–39.0°N, 22.6°E–24.2°E. The EQ catalog of the Institute of Geodynamics of the National Observatory of Athens available on 2 February 2015 at http://www.gein.noa.gr/services/current_catalogue.php was used, e.g., see Chouliaras et al. (2013); Mignan and Chouliaras (2014). Figure 2a depicts Prob(κ_1)

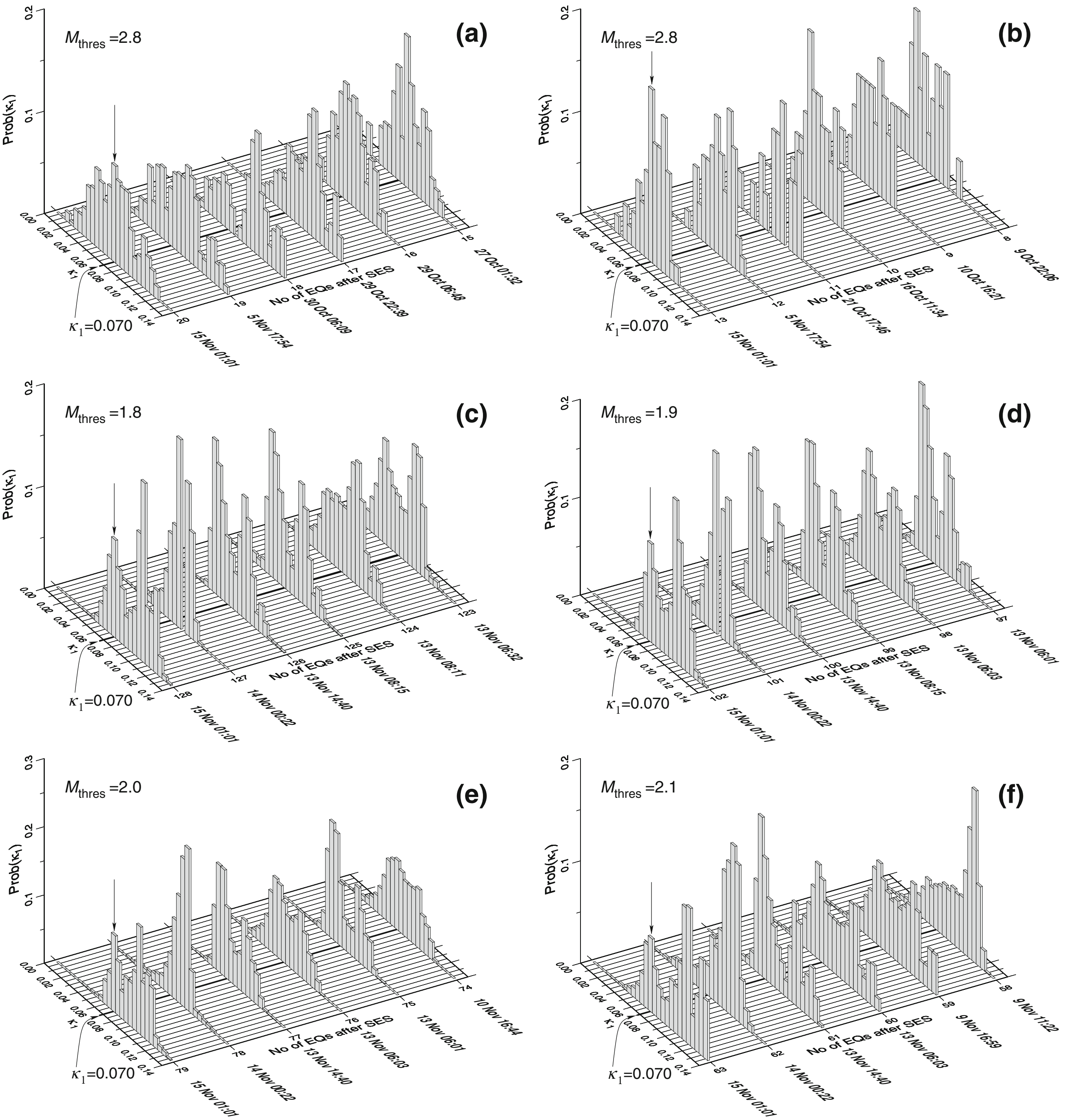

Fig. 2 How the histograms of Prob(κ_1) versus κ_1 evolve event by event in the natural time analysis of the seismicity subsequent to the initiation of the SES activity depicted in Fig. 1a. In each panel, the magnitude threshold (M_{thres}) used in the calculation is also depicted. For details on the exact (sub) areas within the *rectangle* of Fig. 1b considered in each panel, see Sect. 3

versus κ_1 of seismicity for $M_{\mathrm{thres}} = 2.8$ (the data used are compiled in Table 1) for the period after 27 October 2014, i.e., almost three weeks before the mainshock occurrence on 17 November 2014. During this period, six smaller EQs occurred and we observe that Prob(κ_1) maximizes at $\kappa_1 = 0.070$ upon the occurrence of the last EQ, i.e., the M_{L} 2.8 EQ at 01:01 UT on 15 November 2014. It is remarkable that the same behavior is observed in Fig. 2b, where in the computation of the κ_1 values, we discarded from the seismicity of the candidate area 37.7°N–39.0°N, 22.6°E–24.2°E the EQs that occurred within the subarea 37.7°N–38.3°N, 22.6°E–23.3°E. This is consistent with the fact that the latter subarea constitutes the preliminary selectivity map of the LOU station, see Fig. 1b, which however did not show any SES activity simultaneously with the one initiated on 27 July 2014 at KER station (alternatively, the area resulting from the subtraction of the above two areas could have been announced as a candidate area for the

Table 1 All EQs with $M_L \geq 2.8$ that occurred after the initiation of the SES activity on 27 July 2014 within the area 37.7°N–39.0°N, 22.6°E–24.2°E, as they were reported on 2 February 2015 by the Institute of Geodynamics of the National Observatory of Athens

Orignal time		Lat. (°N)	Long. (°E)	Depth (km)	M_L
Date (a-mo-d)	Time (h:min:s)				
2014-07-30	00:55:04	38.04	24.12	19	3.6
2014-08-01	22:36:46	38.95	24.15	24	3.0
2014-08-02	23:00:04	38.04	24.11	14	3.0
2014-08-08	00:29:42	38.92	23.10	19	2.9
2014-08-08	00:30:23	38.92	23.09	14	3.4
2014-08-25	03:40:13	38.09	22.74	15	2.9
2014-09-18	07:24:25	37.70	23.09	25	3.6
2014-09-24	16:05:31	38.73	22.58	11	2.8
2014-10-06	02:29:51	38.96	23.22	21	2.8
2014-10-09	22:06:28	38.25	24.11	18	2.8
2014-10-10	16:21:09	38.80	23.10	11	2.8
2014-10-11	01:53:35	37.88	22.55	19	3.2
2014-10-16	11:34:17	38.75	23.38	24	2.8
2014-10-21	17:46:25	38.59	22.99	23	3.2
2014-10-27	01:32:24	38.14	22.63	14	3.1
2014-10-29	06:48:12	38.13	22.63	17	3.1
2014-10-29	22:39:37	38.14	22.64	15	3.4
2014-10-30	06:09:08	38.14	22.63	15	3.7
2014-11-05	17:54:39	38.65	23.95	24	3.0
2014-11-15	01:01:23	37.79	23.96	186	2.8
2014-11-15	08:11:31	38.99	23.70	24	3.7
2014-11-17	23:05:55	38.64	23.40	24	5.2
2014-11-17	23:09:03	38.64	23.41	23	5.2

Table 2 All EQs with $M_L \geq 1.8$ that occurred after the initiation of the SES activity on 27 July 2014 within the area 37.7°N–39.0°N, 22.6°E–24.2°E excluding those (see the text) within the subarea 37.7°N–38.3°N, 22.6°E–23.3°E, as they were reported on 2 February 2015 by the Institute of Geodynamics of the National Observatory of Athens

Orignal time		Lat. (°N)	Long. (°E)	Depth (km)	M_L
Date (a-mo-d)	Time (h:min:s)				
2014-07-30	00:55:04	38.04	24.12	19	3.6
2014-07-30	09:14:12	38.82	23.30	22	2.1
2014-07-31	04:18:24	38.93	24.12	12	1.8
2014-07-31	08:02:16	38.14	23.52	10	1.8
2014-07-31	12:22:06	38.66	23.58	3	1.8
2014-07-31	15:12:24	38.58	23.58	16	2.2
2014-08-01	01:46:54	38.72	22.74	13	1.9
2014-08-01	21:06:38	38.89	23.53	17	1.9
2014-08-01	22:32:32	38.94	24.13	11	2.2
2014-08-01	22:36:46	38.95	24.15	24	3.0
2014-08-02	07:32:40	38.94	24.12	16	1.9
2014-08-02	23:00:41	38.04	24.11	14	3.0
2014-08-02	23:02:36	38.04	24.11	11	2.6
2014-08-05	16:18:27	38.74	22.57	10	1.9
2014-08-07	03:38:12	38.27	24.13	20	2.7
2014-08-07	06:00:09	38.26	24.15	11	2.2

Table 2 continued

Orignal time		Lat. (°N)	Long. (°E)	Depth (km)	M_L
Date (a-mo-d)	Time (h:min:s)				
2014-08-07	06:09:57	38.27	24.14	11	1.9
2014-08-07	13:44:07	38.76	23.87	13	1.9
2014-08-07	20:28:32	38.27	24.16	22	2.6
2014-08-08	00:29:42	38.92	23.10	19	2.9
2014-08-08	00:30:23	38.92	23.09	14	3.4
2014-08-08	00:36:13	38.92	23.09	11	1.8
2014-08-08	00:36:59	38.92	23.09	13	1.8
2014-08-08	01:13:03	38.91	23.10	16	2.2
2014-08-08	12:03:30	38.76	23.48	11	1.8
2014-08-08	14:05:13	38.26	24.15	12	2.5
2014-08-08	14:06:05	38.26	24.14	12	2.3
2014-08-08	14:28:59	38.27	24.15	12	2.2
2014-08-08	17:03:06	38.38	23.97	15	2.3
2014-08-10	01:54:07	38.90	23.06	19	2.3
2014-08-10	07:31:10	38.27	24.13	22	2.4
2014-08-14	05:31:15	38.70	22.82	13	2.6
2014-08-14	08:51:11	38.56	23.64	18	1.8
2014-08-14	11:43:06	38.71	22.79	10	2.1
2014-08-14	15:13:27	38.56	23.28	20	1.8
2014-08-15	09:56:59	38.80	23.52	25	1.8
2014-08-20	21:44:19	38.67	22.63	18	2.3
2014-08-23	16:26:48	38.55	24.11	15	2.2
2014-08-26	07:45:48	38.15	23.52	11	1.9
2014-08-26	16:39:17	38.74	22.76	10	2.6
2014-08-28	18:00:27	38.74	22.76	7	1.9
2014-08-31	09:16:52	38.95	23.02	15	1.9
2014-09-01	15:00:55	38.87	23.57	16	1.9
2014-09-02	11:48:54	37.79	23.86	13	2.1
2014-09-02	13:00:44	38.88	23.57	25	2.3
2014-09-02	21:33:56	38.72	22.80	12	2.5
2014-09-03	15:10:55	38.60	22.66	19	1.8
2014-09-03	16:56:34	38.45	23.72	15	1.9
2014-09-05	00:46:08	38.47	22.56	18	1.8
2014-09-06	02:49:22	38.82	23.12	11	1.8
2014-09-06	23:40:45	38.88	24.14	7	1.8
2014-09-07	05:47:43	37.80	23.87	9	2.3
2014-09-07	06:05:55	39.02	23.53	25	2.3
2014-09-08	08:46:39	38.73	22.57	17	2.1
2014-09-08	16:05:48	38.82	23.12	13	2.2
2014-09-10	16:51:54	38.71	22.73	21	2.6
2014-09-12	19:22:00	37.80	23.87	8	2.6
2014-09-13	13:26:51	38.72	22.77	13	1.8
2014-09-14	12:40:30	38.70	22.74	16	2.1
2014-09-14	16:11:42	38.23	24.05	19	2.0
2014-09-14	16:35:40	37.89	23.58	15	2.7
2014-09-15	05:05:09	38.73	23.92	22	2.5
2014-09-15	07:09:11	37.89	23.55	15	1.9
2014-09-16	15:32:53	38.76	23.94	17	2.0

Table 2 continued

Orignal time		Lat. (°N)	Long. (°E)	Depth (km)	M_L
Date (a-mo-d)	Time (h:min:s)				
2014-09-17	07:40:18	38.58	23.20	13	2.2
2014-09-20	19:18:57	39.03	23.29	15	1.9
2014-09-22	03:00:50	38.73	22.59	11	2.0
2014-09-23	01:51:40	38.36	23.80	19	2.1
2014-09-24	16:05:31	38.73	22.58	11	2.8
2014-09-24	16:29:10	38.72	22.74	12	1.8
2014-09-24	16:33:38	38.73	23.91	11	2.1
2014-09-25	03:07:58	38.67	23.08	12	2.1
2014-09-27	05:25:33	38.73	23.91	15	2.5
2014-09-29	00:16:07	38.99	23.24	16	1.8
2014-09-30	09:00:08	38.12	23.52	9	1.8
2014-09-30	10:17:15	37.88	23.66	12	2.0
2014-10-01	08:31:01	38.93	24.07	15	1.9
2014-10-02	06:00:33	37.80	23.88	9	2.0
2014-10-04	04:43:17	38.96	23.21	14	1.9
2014-10-06	02:29:51	38.96	23.22	21	2.8
2014-10-06	15:39:03	38.71	22.79	12	2.2
2014-10-06	18:00:10	39.02	24.07	15	2.3
2014-10-07	09:07:14	38.18	23.53	11	1.8
2014-10-08	18:41:31	38.67	22.66	15	1.9
2014-10-09	08:48:54	38.15	23.53	14	1.8
2014-10-09	21:31:09	38.95	24.13	27	2.6
2014-10-09	22:06:28	38.25	24.11	18	2.8
2014-10-10	02:05:37	38.92	22.96	10	1.8
2014-10-10	16:21:09	38.80	23.10	11	2.8
2014-10-11	14:47:39	38.69	22.80	10	2.1
2014-10-13	02:07:14	38.40	23.96	22	1.8
2014-10-16	11:34:17	38.75	23.38	24	2.8
2014-10-16	17:31:39	39.02	23.27	14	1.8
2014-10-17	09:24:40	38.68	23.10	8	1.9
2014-10-19	20:06:03	38.60	23.30	14	2.0
2014-10-21	11:30:48	38.36	23.99	17	2.1
2014-10-21	17:46:25	38.59	22.99	23	3.2
2014-10-21	18:04:26	38.59	22.97	15	2.0
2014-10-24	00:19:54	38.34	23.54	14	1.9
2014-10-25	17:54:53	38.36	23.82	20	2.0
2014-10-26	12:06:05	38.74	22.57	9	1.9
2014-10-27	17:37:07	38.56	24.10	8	1.9
2014-10-30	03:02:01	38.77	23.53	25	2.1
2014-11-01	16:59:53	38.71	22.56	13	2.0
2014-11-01	21:51:13	38.08	23.61	17	2.0
2014-11-02	00:45:05	38.78	23.31	15	2.0
2014-11-03	05:09:28	38.08	23.61	18	2.2
2014-11-03	08:28:52	39.01	23.33	21	1.9
2014-11-05	16:52:38	38.65	23.94	22	2.4
2014-11-05	17:54:39	38.65	23.95	24	3.0
2014-11-06	02:52:05	38.81	23.50	15	1.8
2014-11-07	11:58:18	38.64	23.92	13	2.0

Table 2 continued

Orignal time		Lat. (°N)	Long. (°E)	Depth (km)	M_L
Date (a-mo-d)	Time (h:min:s)				
2014-11-08	21:00:55	38.73	22.58	7	2.2
2014-11-09	02:13:07	38.21	24.07	12	2.0
2014-11-09	11:22:31	39.02	23.42	25	2.3
2014-11-09	16:59:54	38.64	23.91	13	2.2
2014-11-10	16:44:19	38.63	23.92	12	2.0
2014-11-10	16:44:42	38.64	23.94	13	2.0
2014-11-12	02:48:58	39.04	23.54	14	1.9
2014-11-12	19:15:54	38.82	23.38	16	1.8
2014-11-13	06:01:31	38.72	22.58	10	2.0
2014-11-13	06:03:04	38.36	23.55	14	2.4
2014-11-13	06:32:59	38.87	23.55	15	1.8
2014-11-13	08:11:04	38.47	24.10	11	1.8
2014-11-13	08:15:49	38.67	22.67	18	1.9
2014-11-13	14:40:13	38.70	22.70	8	2.4
2014-11-14	00:22:20	39.00	24.15	21	2.1
2014-11-15	01:01:23	37.79	23.96	186	2.8
2014-11-15	08:11:31	38.99	23.70	24	3.7
2014-11-17	23:05:55	38.64	23.40	24	5.2
2014-11-17	23:09:03	38.64	23.41	23	5.2

impending mainshock). To assure that this behavior exhibits also magnitude threshold invariance, we repeated the calculation that resulted in Fig. 2b, but for low magnitude thresholds (so that to have a large number of EQs). In particular, Fig. 2c–f depict the corresponding results for $M_{\rm thres} = 1.8$, 1.9, 2.0, and 2.1, respectively, which do show that Prob(κ_1) versus κ_1 exhibits local maximum at $\kappa_1 = 0.070$ upon the occurrence of the aforementioned EQ on 15 November 2014 (the seismic data used in order to obtain Fig. 2b–f are given in Table 2). Actually, almost three days later, i.e., at 23:05 UT on 17 November 2014, the $M_{\rm W}$ (USGS) = 5.4 EQ occurred with an epicenter at 38.67°N, 23.39°E (followed by a smaller $M_{\rm W}$ (USGS) 5.1 EQ at 23:09 UT with epicenter at 38.68°N, 23.24°E). It should be mentioned that EQs of such magnitude occur there very rarely. In particular, no EQ with $M_{\rm W}$ (USGS) $\geq$ 5.4 took place within the coordinates 38.3°N–39.0°N, 23.0°E–23.8°E since 1965. In view of this very rare occurrence, it is interesting to study this case in the future by employing an approach (Moustra et al. 2011) which uses SES and a neural network (trained by relevant data of earlier cases) to predict the magnitude and the occurrence time of the forthcoming EQ.

4 Conclusion

A pronounced $M_{\rm W}$ (USGS) = 5.4 EQ was strongly felt at Athens, Greece, on 17 November 2014. This is pretty rare since it is the strongest EQ that occurred in that area since 1965. The procedure based on natural time analysis of the seismicity subsequent to an SES activity recorded on 27 July 2014 at the KER station close to Athens revealed that the system approached the critical point (mainshock occurrence) just a few days before, i.e., on 15 November 2014.

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