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# Scale-specific order parameter fluctuations of seismicity before mainshocks: Natural time and Detrended Fluctuation Analysis

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**Abstract** – The order parameter fluctuations of seismicity are investigated upon considering a natural time window of fixed length sliding through the consecutive earthquakes that occurred in California. We previously found that when this length corresponds to a time period of the order of a few months, the fluctuations exhibit a global minimum before the strongest mainshock. Here, we show that in California, during the twenty five year period 1979–2003, minima of the fluctuations are identified 1 to 5 months before four out of five mainshocks with magnitude $M = 7.0$ or larger as well as before the $M = 6.9$ Northridge earthquake. These minima are accompanied by minima of the exponent $\alpha$ of the Detrended Fluctuation Analysis (DFA) of the earthquake magnitude time series, which since $\alpha < 0.5$ indicate anticorrelated behavior. These results of DFA alone cannot serve for prediction purposes, but do so when combined with the aforementioned minima in the fluctuations of the order parameter of seismicity identified in natural time analysis.



**Introduction.** – Earthquakes exhibit complex correlations in time, space and magnitude. This has been the objective of a number of recent studies [1–12]. The opinion prevails (*e.g.*, see ref. [4] and references therein) that the observed earthquake scaling laws [13] indicate the existence of phenomena closely associated with the proximity of the system to a *critical* point. Making use of the order parameter $\kappa_1$ of seismicity defined in natural time (see below), in a previous study [14] we investigated the period before and after significant mainshocks. Time series for various lengths of $W$ earthquakes that occurred before or after a mainshock have been studied. The natural time analysis of these time series revealed the following challenging finding: The probability distribution function $P(\kappa_1)$ *vs.* $\kappa_1$ exhibits a bimodal feature for $W \approx 10^3$ when approaching a mainshock. In an attempt to quantify this feature, we considered the *variability* of $\kappa_1$, which is just the ratio $\beta \equiv \sigma(\kappa_1)/\mu(\kappa_1)$, where $\sigma(\kappa_1)$ and $\mu(\kappa_1)$ stand for the standard deviation and the mean value for $\kappa_1$ (see also below). The bimodal feature reflects that upon approaching the mainshock with the number $W$ of the earthquakes before mainshock decreasing, the variability of $\kappa_1$ may exhibit an increase.

In a subsequent investigation [15], we extended the study of ref. [14] based on the following grounds: Since in ref. [14], we analyzed time series for various lengths of $W$ earthquakes before the mainshock, in ref. [15] we focused on the *complementary* case [16,17], *i.e.*, we considered a natural time window of fixed length (that means comprising a fixed constant number $W$ of consecutive seismic events) sliding through the seismic catalog. The results became exciting upon using a *crucial* scale, *i.e.*, when these $W$ consecutive events extend to a time period comparable to the lead time [17–19] of the precursory Seismic Electric Signals (SES) activities. These are series [18,19] of low frequency ($\leqslant 1$ Hz) electric signals that precede [17,20] major earthquakes and are emitted when the future focal region enters the critical stage. Employing such a fixed natural time window sliding through the California seismic catalog over a twenty five year period (1979–2003), we found that the $\kappa_1$ fluctuations of the order parameter of seismicity exhibited a *global* minimum value well before (*i.e.*, somewhat less than five months) the strongest earthquake, *i.e.*, the Landers 7.4 earthquake (EQ) in 1992.

The scope of the present letter is twofold. First, we extend the study of ref. [15] in order to investigate whether, beyond the aforementioned case of Landers

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EQ, minima in the order parameter fluctuations appear before the other major EQs with magnitude 7.0 or larger in California during the period 1979–2003. Second, to further shed light on the nature of these minima, we employ Detrended Fluctuation Analysis (DFA) [21], which has become the standard method when studying long-range correlated time series and can also be applied to real world non-stationary signals [22–27], in order to investigate temporal correlations in the earthquake magnitude time series at the same natural time window length scale as the one mentioned above that was found of crucial importance to identify the minimum in the order parameter fluctuations of seismicity in ref. [15].

The latter DFA study was motivated by the following findings resulted from the analysis of other complex time series like the case of electrocardiograms: Several applications of DFA established the existence of long-range correlations in the healthy heart rate variability, *e.g.* see refs. [28,29] and references therein (cf. additional studies [30,31] showed that healthy dynamics exhibits even higher complexity characterized by a broad multifractal spectrum, see also sects. 9.2.1 and 9.5.1 of ref. [17]). For individuals at high risk of sudden cardiac death, however, the fractal physiological organization (long-range temporal correlations) breaks down and this is often accompanied by emergence of *uncorrelated randomness*, see ref. [28] and references therein. This has been verified by means of DFA as well as by using the two types of complexity measures in natural time that consider fluctuations either on fixed time scales or take into account fluctuations on different time scales [16,32]. Quite interestingly, an analogous behaviour is reported here for the case of seismicity. In particular we find that, while in the regimes of stationary seismic activity long-range temporal correlations exist [6] between earthquake magnitudes with a DFA exponent $\alpha \approx 0.6$, these correlations break down in the regimes during which the fluctuations of the order parameter minimize and then the value of the exponent $\alpha$ becomes even lower than 0.5, thus showing anticorrelated behavior (cf. the value $\alpha = 0.5$ corresponds to uncorrelated random signals, *i.e.*, white noise).

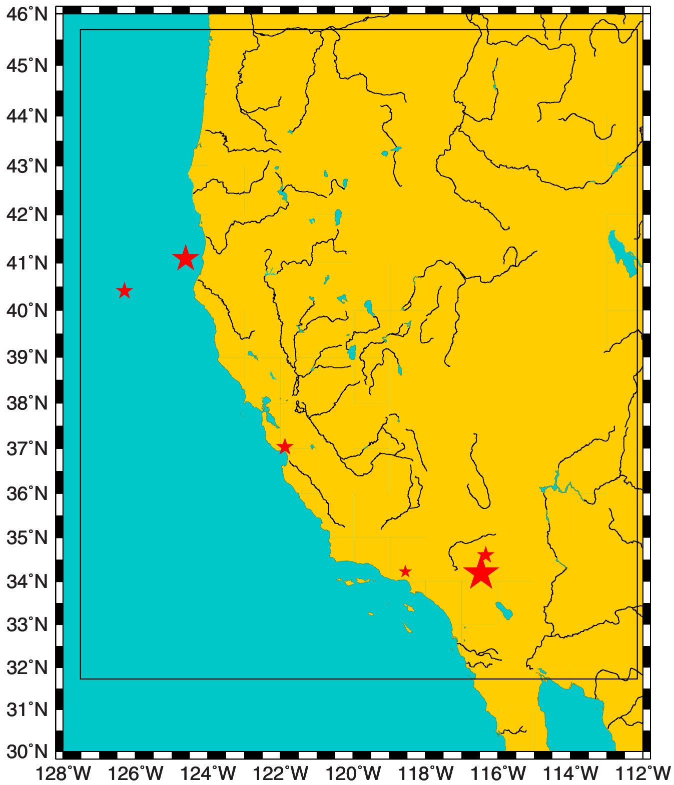


Fig. 1: (Color online) Map showing the area, surrounded by the black rectangle, the seismicity of which has been analyzed in natural time during the period 1979–2003. The red stars mark the epicenters of the six major earthquakes of table 1.

**Natural time analysis. The procedure followed. –** For a time series comprising $N$ events we define [33,34] the natural time for the occurrence of the $k$-th event by $\chi_k = k/N$. Thus, we ignore the time intervals between consecutive events, but preserve their order and energy $Q_k$. We then study the evolution of the pair $(\chi_k, Q_k)$ where $p_k = Q_k / \sum_{n=1}^{N} Q_n$ is the normalized energy released during the $k$-th event. The approach of a dynamical system to criticality is identified by means of the variance [17,33–36] $\kappa_1 (\equiv \langle \chi^2 \rangle - \langle \chi \rangle^2)$ of natural time weighted for $p_k$ where $\langle f(\chi) \rangle = \sum_{n=1}^{N} p_k f(\chi_k)$. In the frame of natural time analysis it has been suggested [35] that the order parameter of seismicity is just the quantity $\kappa_1$.

Let us take a natural time window length comprising $W$ consecutive events. Starting from the first earthquake, we calculate the $\kappa_1$ values using say $N = 6$ to 40 consecutive events. We next turn to the second earthquake, and repeat the calculation of $\kappa_1$. After sliding, event by event, through the whole natural time window, the computed $\kappa_1$ values enable the calculation of their average value $\mu(\kappa_1)$ and the standard deviation $\sigma(\kappa_1)$ that correspond to this natural time window of length $W$. We then determine the variability of $\kappa_1$, *i.e.*, the quantity $\beta = \sigma(\kappa_1)/\mu(\kappa_1)$. Here, we apply the following procedure [15]: for each earthquake $e_i$ in the seismic catalog, we calculated the $\kappa_1$ values resulting when using the *previous* 6 to 40 consecutive earthquakes. Then, the hitherto obtained $\kappa_1$ values for the earthquakes $e_{i-W+1}$ to $e_i$ were considered for the estimation of the variability $\beta$ for a natural time window length $W$. The resulting $\beta$ value, labeled $\beta_i$, was attributed to $e_i$, the data of which was obviously *not included* in the $\beta_i$ estimation. In addition, for each earthquake $e_i$ we proceed, by following the standard procedure [21,29,37], to the DFA of the magnitude time series of the preceding $W$ events and the resulting exponent is labelled $\alpha_i$. By the same token, we also clarify that although the resulting $\alpha_i$ value was attributed to $e_i$ whose data *were not included* in the $\alpha_i$ estimation.

**The data analysed and the results obtained. –** The following seismic catalog has been used: the United States Geological Survey Northern California Seismic Network catalog available from the Northern

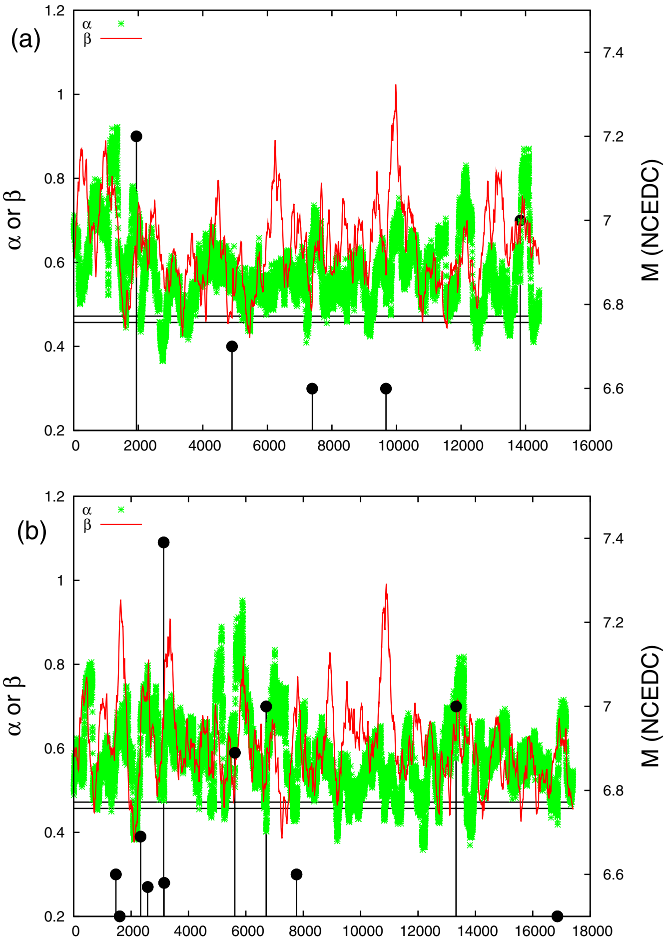


Fig. 2: (Color online) The variability of $\kappa_1$ (red, left scale) and the DFA exponent $\alpha$ (green asterisks, left scale) *vs.* the number of events (earthquakes) for a natural time window of length $W = 300$ events during the period: (a) 1 January 1979 to 1 January 1990 and (b) 1 January 1990 to 1 January 2004. The earthquakes with $M \geqslant 6.5$ are shown with vertical bars ending at solid circles. The horizontal lines correspond to the values $\beta = 0.472$ and $\alpha = 0.458$ that refer to the minima of the variability of $\kappa_1$ and the DFA exponent observed before Mendocino fault EQ (see the text).

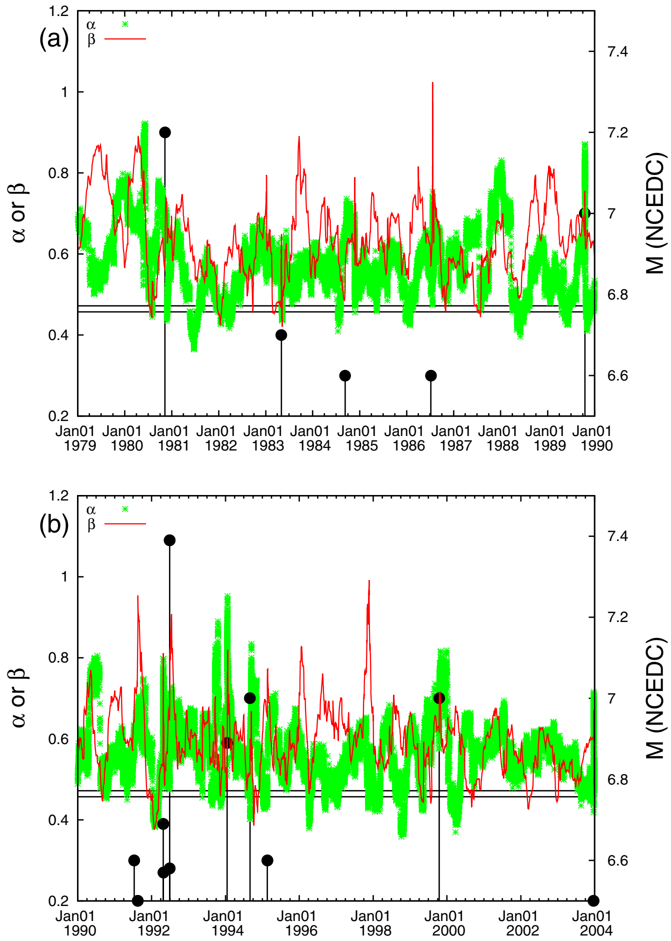


Fig. 3: (Color online) The same as in fig. 2, but the relevant quantities here are plotted *vs.* the conventional time.

California Earthquake Data Center, at the http address: `www.ncedc.org/ncedc/catalog-search.hmtl`, hereafter called NCEDC. The earthquake magnitudes reported in this catalog are labelled with $M$ (NCEDC) or simply $M$. The seismic moment, which is proportional to the energy release during an earthquake and hence to the quantity $Q_k$ used in natural time analysis, is calculated [17] from the relation $\log_{10}(M_0) = 1.5M + \text{const.}$

Following ref. [15], we consider all earthquakes with $M \geqslant 2.5$ reported by NCEDC, within the area $\mathrm{N}^{45.7}_{31.7}\mathrm{W}^{112.1}_{127.5}$ see fig. 1, during the period from January 1, 1979 to January 1, 2004 and analyzed them in natural time. Since we have on average $\sim 10^2$ earthquakes per month (cf. 31832 earthquakes for the 25 year period), by taking into account that the lead time of SES activities is around a few months (with an upper limit [17] of around 5 months), we focus hereafter on the natural time window length $W = 300$.

Figures 2(a), (b) show, for $W = 300$, the variability of $\kappa_1$ (red, left scale) and the DFA exponent $\alpha$ (green asterisks, left scale) as a function of the number of events (EQs) during the whole period, 1 January 1979–1 January 2004, investigated. In addition, in the same figures, we also plot (black vertical bars ending with solid circles, right scale) the EQs with $M \geqslant 6.5$ that occurred during the same period. Figures 3(a), (b) depict the same results as in figs. 2(a), (b) for the variability of $\kappa_1$ and the exponent $\alpha$, but here they are plotted *vs.* the conventional time for the sake of the reader's convenience.

In what remains, we focus on the major EQs with $M \geqslant 7.0$ that occurred during the aforementioned period with epicenters inside the area investigated. These five EQs are inserted in table 1 by adding in italics the Northridge EQ on 17 January 1994 which although was of a somewhat smaller magnitude (*i.e.*, $M = 6.9$) it arose a high interest in view of its destructive consequences. To better visualize what happened before each of these six EQs, we show in figs. 4(a), (b), (c), (d), (e) and (f) the corresponding excerpts of figs. 3(a), (b) but in an expanded (conventional) time scale. An inspection of

Table 1: All major EQs with $M \geqslant 7.0$ within $N_{31.7}^{45.7}W_{127.5}^{112.1}$ during the period 1979–2003. The $M = 6.9$ Northridge earthquake is also included in italics. The values of minima observed for the variability $\beta$ of $\kappa_1$ and the DFA exponent $\alpha$ together with the dates of their observation, in parentheses, are also inserted. The lead time $\Delta t$ for each case is shown in the last column.

| EQ Date | LAT | LON | $M$ (NCEDC) | EQ Name | $\beta$ | $\alpha$ | $\Delta t$ (months) |
|---|---|---|---|---|---|---|---|
| 1980-11-08 | 41.08 | −124.62 | 7.2 | Eureka | 0.444 (1980-08-01) | 0.445 (1980-08-01) | $\approx 3$ |
| 1989-10-18 | 37.04 | −121.88 | 7.0 | Loma Prieta | – | – | – |
| 1992-06-28 | 34.19 | −116.46 | 7.4 | Landers | 0.378 (1992-01-28) | 0.383 (1992-02-02) | $\leqslant 5$ |
| *1994-01-17* | *34.23* | *− 118.55* | *6.9* | *Northridge* | *0.459 (1993-11-14)* | *0.431 (1993-11-14)* | $\approx 2$ |
| 1994-09-01 | 40.41 | −126.30 | 7.0 | Mendocino fault | 0.472 (1994-08-01) | 0.458 (1994-08-09) | $\approx 1$ |
| 1999-10-16 | 34.60 | −116.34 | 7.0 | Hector Mine | 0.444 (1999-05-14) | 0.422 (1999-05-15) | $\approx 5$ |

these figures reveals that in five (out of six) cases, a few months before each EQ occurrence (this lead time is designated by $\Delta t$ in table 1) a pronounced minimum appears in the variability $\beta$ of $\kappa_1$ accompanied by an almost simultaneous minimum in the $\alpha$ value, which is lower than 0.5, thus pointing to an anticorrelated behavior in the earthquake magnitude time series. All these results are inserted in table 1. In other words, we find that the long-range correlations during the stationary regimes of seismicity (recall that $\alpha \approx 0.6$ as found in ref. [6]) *break down* well before the occurrence of a major EQ and turn to anticorrelated behavior almost during the observation of the minimum in the variability $\beta$ of the order parameter of seismicity $\kappa_1$.

**Discussion of the results.** – An inspection of table 1 shows that the values of the minima observed in the variability of $\kappa_1$ before the five (out of 6) EQs lie between 0.378 and 0.472. Quite interestingly, the *lowest value* (*i.e.*, 0.378) —which we recall that it solely stems from *earlier* seismicity— precedes the *strongest* EQ, *i.e.*, the Landers EQ, that occurred on 28 June 1992 with $M = 7.4$, thus confirming the main conclusion of ref. [15]. As for the $\alpha$ values of the corresponding minima observed in the DFA exponent before these five EQs, they vary between 0.383 and 0.458 and in addition we observe that the *lowest* $\alpha$ value (among these five minima) is observed before the Landers EQ which is the *strongest* event.

Despite the above similarity between the two types of minima, however, we draw attention to the following important difference: While the lowest value 0.378 (before Landers EQ) among the minima observed in the variability of $\kappa_1$ is also the *lowest* $\beta$ value during the whole period studied (*i.e.*, *global* minimum) —see figs. 2(a), (b)— this does *not* hold for the $\alpha$ values. In other words, a careful inspection of figs. 2(a), (b) show that there are cases, see for example the dates 22 June 1981, 6 October 1998, 26 March 2000 where the corresponding minima in the $\alpha$ values are $\alpha = 0.365$, 0.359 and 0.370, *i.e.*, lower than the aforementioned minimum value $\alpha = 0.383$ observed before the Landers EQ, without having been followed by major EQs. Hence, we may conclude that the *global minimum* in the variability of $\kappa_1$, which is actually followed by the *strongest* EQ, is *not* accompanied by the *global* minimum of the DFA exponent. This reflects that the observation of the latter *global* minimum alone cannot serve for prediction purposes, while the former global minimum does so.

In order to further investigate the usefulness of the present findings we mark with two horizontal lines in figs. 2–4 the largest values among the minima of $\beta$ and among the minima of $\alpha$, respectively, that have been observed to precede major EQs (see table 1). These are the values $\beta = 0.472$ and $\alpha = 0.458$ before the Mendocino fault EQ. We now examine how many minima (appearing almost simultaneously, *i.e.*, differing by no more than 10 days) obeying the limits $\beta \leqslant 0.472$ and $\alpha \leqslant 0.458$, have been observed during the whole 25 year period studied. Discarding cases —there exists just a single such case here during late December 2003— of large variations of the DFA exponent caused by aftershocks immediately after (within one day or so) a significant mainshock, we find eight cases obeying the limits. These include the five minima that correspond to the major EQs reported in table 1 and three others (around 13–15 January 1982, 9 May 1983 and 7–8 April 1996) which are false alarms since they are not followed by major EQs (within a time window of around five months, which is the maximum lead time for the SES activities as mentioned above). These results could be alternatively seen as follows: Among the eight "predictions" emerged on the basis of the above limits, five turned out to be successful. In addition, the three false "predictions" cover a false alarm period of only $3 \times 5$ months (out of a 25 year period, *i.e.*, $25 \times 12$ months). Following ref. [38], these results convincingly show that the "predictions" achieved are far beyond chance. In a forthcoming study a distinction of the true precursory changes from false alarms is achieved based on the following two

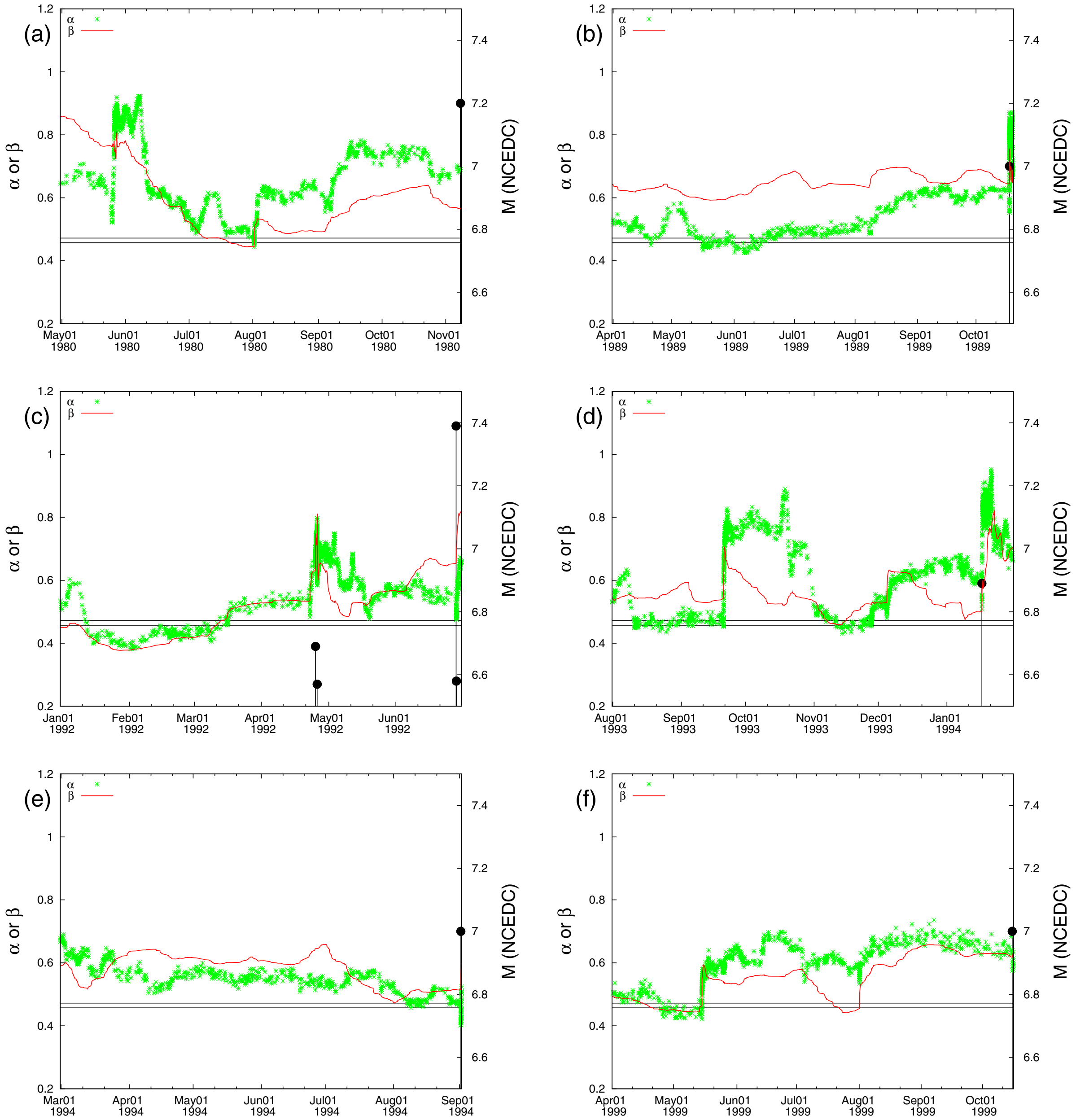


Fig. 4: (Color online) Excerpts of fig. 3, but given here in expanded time scale. They show what happened several months before each one of the following earthquakes (see table 1): (a) Eureka on 8 November 1980, (b) Loma Prieta on 18 October 1989, (c) Landers on 28 June 1992, (d) Northridge on 17 January 1994, (e) Mendocino fault on 1 September 1994 and (f) Hector Mine on 16 October 1999.

conditions. First, during the time when the DFA exponent indicates anticorrelated behavior, the $\beta$ values for $W=200$ should predominate those for $W=300$. Second, the date at which the $\beta$ values for $W=300$ minimize cannot delay more than 40 days from that for $W=200$.

The present findings are currently investigated in other regions like Japan, where the EQ mechanism (subduction) is usually different than that in California (strike-slip). Preliminary results are encouraging showing, however, that in Japan, probably due to the aforementioned difference in the EQ mechanisms, the dates of the minimum in the variability of $\kappa_1$ and the subsequent minimum in the DFA exponent differ more than in the case of California.

Finally, we comment on the Loma Prieta EQ. This is the only case (out of six) in table 1 for which although a clear minimum in the DFA exponent was observed (almost four months before its occurrence, see fig. 4(b)), this was not accompanied by an almost simultaneous clear minimum in the $\kappa_1$ variability. The exact reason for this behavior is not clear. We note, however, that natural time analysis has been already successfully applied [39] in order to determine the occurrence time for this EQ as follows: In general, *if* SES data are available, when the $\kappa_1$ value resulting from the natural time analysis of the seismicity subsequent to the SES recording becomes approximately equal to 0.070, the mainshock occurs within a time window of the order of one week [33]. Thus, we analyzed in natural time all the earthquakes within the area $N_{36.2}^{38.5}W_{122.7}^{120.7}$ after the initiation of the precursory magnetic-field variations recorded by Fraser-Smith and coworkers [40,41]. We found [39] that the $\kappa_1$ value became approximately $\kappa_1 = 0.070$ almost 4.5 days before the Loma Prieta EQ.

**Conclusions. –** Natural time analysis of the seismicity in California from 1 January 1979 to 1 January 2004 revealed that the variability $\beta$ of the order parameter of seismicity exhibited clear minima 1–5 months before the occurrence of five out of six major earthquakes (*i.e.*, except Loma Prieta). These minima are accompanied by minima of the DFA exponent $\alpha$ of the earthquake magnitude time series, which since $\alpha < 0.5$ point to anticorrelation. The calculations should be carried out at a specific natural time scale $W = 300$ events selected on the basis of the lead time of SES activities. We showed that the almost simultaneous appearance of these two types of minima, in the variability of $\kappa_1$ and in the DFA exponent, may serve for "prediction" purposes.

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