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Distinguished seismological and electromagnetic features of the impending global failure: Did the 7/9/1999 M5.9 Athens earthquake come with a warning?

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Clear VLF electromagnetic (EM) anomalies were detected prior to the Athens earthquake (EQ). We attempt to establish the hypothesis that these emissions were launched from the pre-focal area during micro-fracturing process. The spectral analysis in terms of fractal dynamics reveals that distinquished alterations in the associated scaling parameters emerge as the EQ is approached. These alterations suggests that the evolution of the Earth's crust towards the "critical point" takes place not only in the seismological sense but also in the pre-fracture EM sense. VAN-signals and space-time TIR-signals were also detected prior to the Athens EQ. These anomalies, as well as the fault modeling of the Athens EQ obtained by interferometric combinations of ERS2 SAR images bring further support for the confidence in the reliability of our conclusions.

Key words: Earthquake prediction, wavelet analysis, intermittent criticality, electromagnetic emissions, Athens earthquake, fracture, scaling laws, fault nucleation

1. Introduction

An outstanding problem in material science and in geophysics is to undrestand, and more importantly to predict, macroscopic defects or shocks. When a heterogeneous material is strained, its evolution toward breaking is characterized by the nucleation and coalescence of micro-cracks before the global instability. Both acoustic as well as EM emissions, in a wide frequency spectrum ranging from very low frequencies (VLF) to very high frequencies (VHF), are produced by micro-cracks, which can be considered as the so-called precursors of general fracture.

We view the earthquakes (EQs) as large scale fracture phenomena. Our main tool is the monitoring of the micro-fractures, which occur before the final break-up in the pre-focal area, by recording their VLF-VHF EM emissions. Sufficient experimental and theoretical evidence indicates that as the final failure in the disordered media is approached the underlying complexity manifests itself in linkages between space and time, generally producing fractal patterns. Thus, a lot of work on complexity focuses on statistical power laws that describe the scaling properties of fractal processes and structures. Herein, we concentrate on the fundamental question whether distinguished alterations in associated scaling dynamical parameters emerge as EQs are approached, which could be used as diagnostic tools for Earth's crust failure.

Most aspects of a new class of models of fracture are encompassed by a concept called "Intermittent Criticality" (IC) (Sornette and Sammis, 1995; Saleur *et al*., 1996a,b; Sammis *et al*., 1996; Heimpel, 1997; Sornette, 2004). IC bridges both the hypothesis of an underlying self-organized complexity and the occurrence of precursory phenomena (e.g. Huang *et al*., 1998; Grasso and Sornette, 1998; Hainzl *et al*., 2000; Newman and Turcotte, 2002; Al-Kindy and Main, 2003). It is a further purpose of this paper to investigate the suggestion that not only the precursory seismic activity but also the pre-fracture EM activity may reveal the "critical" rearrangements that occur as the external field drives the heterogeneous pre-focal area from one meta-stable local free-energy minimum to another towards the global instability.

2. The EM Pre-fracture Phenomenon Associated with the Athens EQ

Aiming at recording VLF-VHF EM precursors, since 1994 a station was installed at a mountainous site of Zante island (37.76°N–20.76°E) in western Greece (Fig. 1) with the following configuration: (i) six loop antennas detecting the three components (EW, NS, and vertical) of the variations of the magnetic field at 3 kHz and 10 kHz respectively; and (ii) three vertical $\lambda/2$ electric dipoles detecting the strength of the electric field at 41 MHz, 54 MHz, and 135 MHz respectively. The frequencies 3 kHz, 10 kHz, 41 MHz, 54 MHz, and 135 MHz were selected because of the low background activity at these frequencies at this location. All the EM time-series were sampled at 1 Hz.

In the present study we focus on the case of the Athens EQ (Fig. 1). The basic argument for this choice is that very

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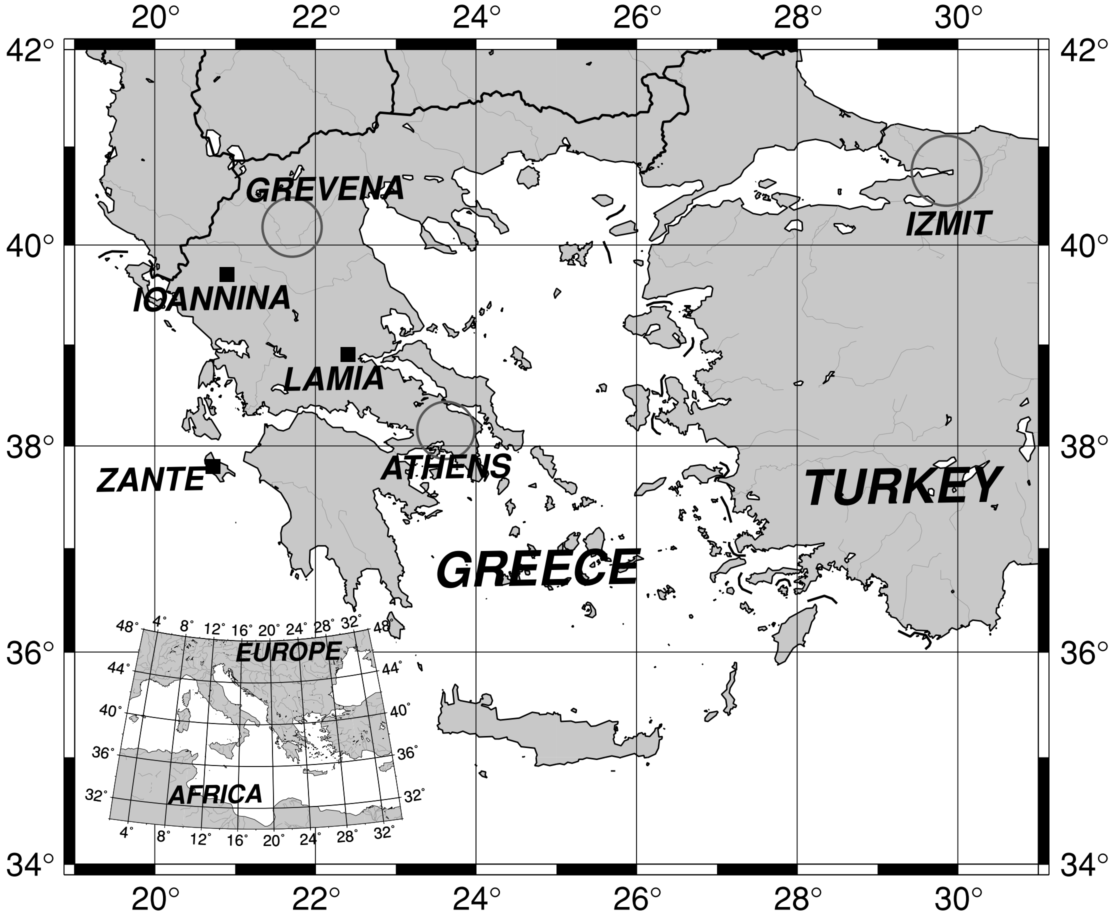

Fig. 1. A map demonstrating the location of the Zante RF station and the location of the Ioannina VAN station. The circles indicate the epicentres of the Athens, Kozani-Grevena and Izmit earthquake.

clear EM anomalies have been detected in the VLF band (Figs. 2 and 3), i.e., at 3 kHz and 10 kHz, before the Athens EQ (Eftaxias *et al.*, 2000, 2001a). We note the simultaneous detection of anomalies at the three components (EW, NS, vertical) (see Fig. 3). These accelerating anomalies are embedded in a long duration quiescence period concerning the detection of EM disturbances at 3 kHz and 10 kHz. Characteristically, Figure 2 shows the 10 kHz (EW) time series between 4 July and 11 September. These emissions have a rather long duration, i.e., approximately a few days, thus it provides sufficient data for statistical analysis. The Athens EQ ($M_s = 5.9$) occurred on 7 September 1999 at 11:56 GMT at a distance of about 20 km from the center of the city of Athens, the capital of Greece.

Geomagnetic activity as expressed by the planetary three-hour-range K_p index (hhtp://www.gfz-potsdam.de/pub/home/obs/kp-ap/) is depicted in the visualization of the K_p values utilizing the Bartels musical diagram (Fig. 4). One can recognize that the recorded sequence of VLF EM emission before the Athens EQ was observed during quiet magnetic conditions. Note that the 6 September 1999 is referred as one of the quietest days of the month. Additionally, we have investigated, in detail, the meteorological activity indicating that it is unlikely the observed anomaly to have any relation to meteorological effects.

The damaging Athens EQ arrived very shortly after the major 17/8/1999 $M_w = 7.4$ EQ of Izmit, Turkey, which occurred approximately 650 km to the NE of Athens (Fig. 1). Although it is possible that the occurrence of these local EQs was coincidental, the timing strongly supports the hypothesis that the two seismic events might be causally related. Sufficient seismological measurements encourage the former hypothesis.

3. Relation of the Dynamics between the Athens and Izmit Earthquakes

Seismological evidence of *dynamically* triggered regional seismicity following the Izmit EQ was independently presented by (Brodsky *et al.*, 2000; Papadopoulos, 2002; Tzanis and Makropoulos, 2002). Their results suggest a link between the activity in Greece and the Turkish event, i.e., demonstrates interactions between EQs over large distances.

3.1 Brodsky, Karakostas, and Kanamori's approach

Brodsky *et al.* (2000) report that the Izmit EQ was followed *immediately* by small EQs throughout much of continental Greece. The daily seismicity maps before and after Julian day 229 reveals a peak in seismicity on day 229 (see figure 1 and 2 in their article). The observation of long range events immediately after the largest amplitude shaking is consistent with the dynamic stress triggering the EQs

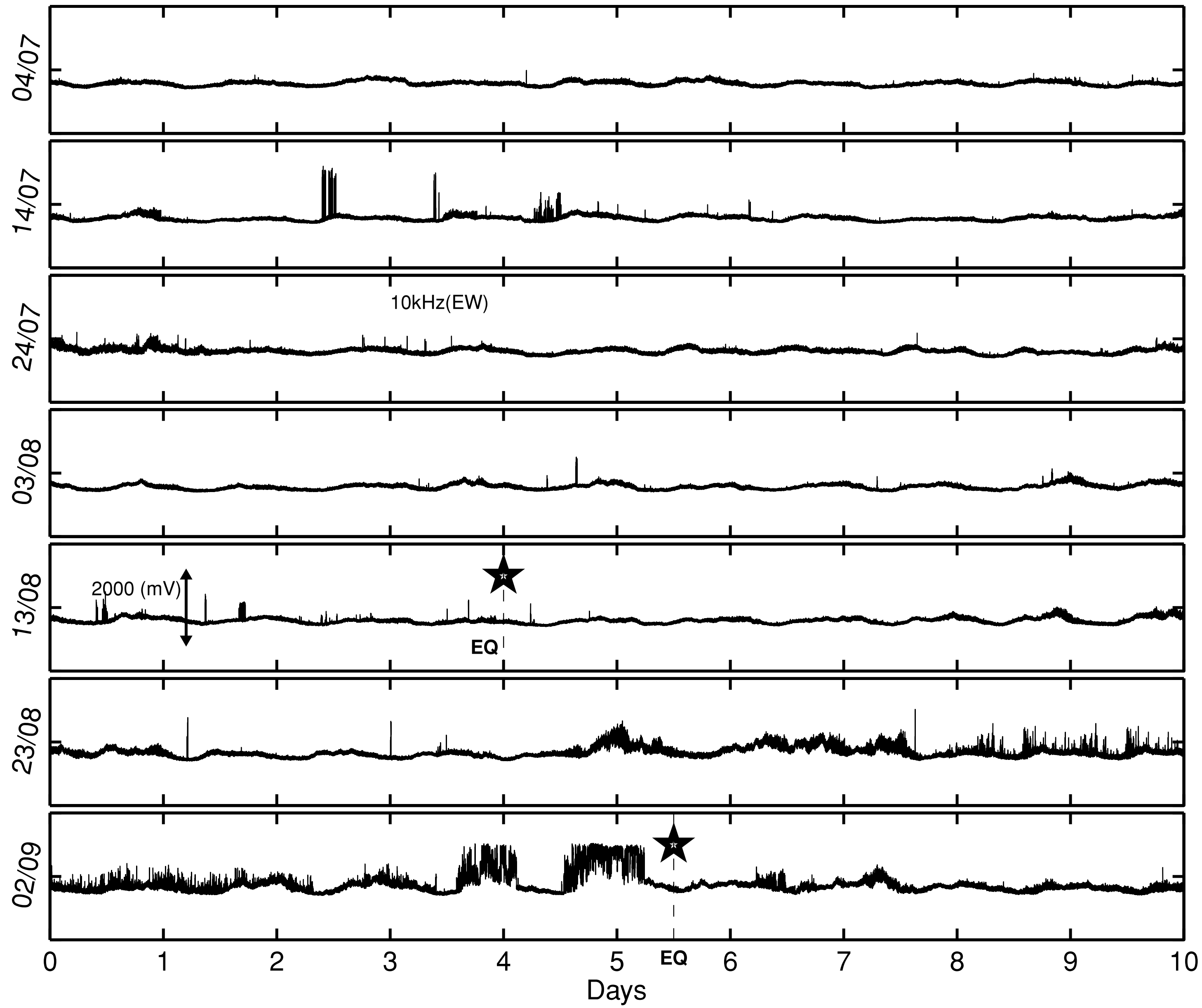

Fig. 2. Electromagnetic time series at Zante station at 10 kHz (EW). The left vertical line indicates the origin time of the 17/08/99 Izmit event and the right vertical line the same for the 7/09/99 Athens event.

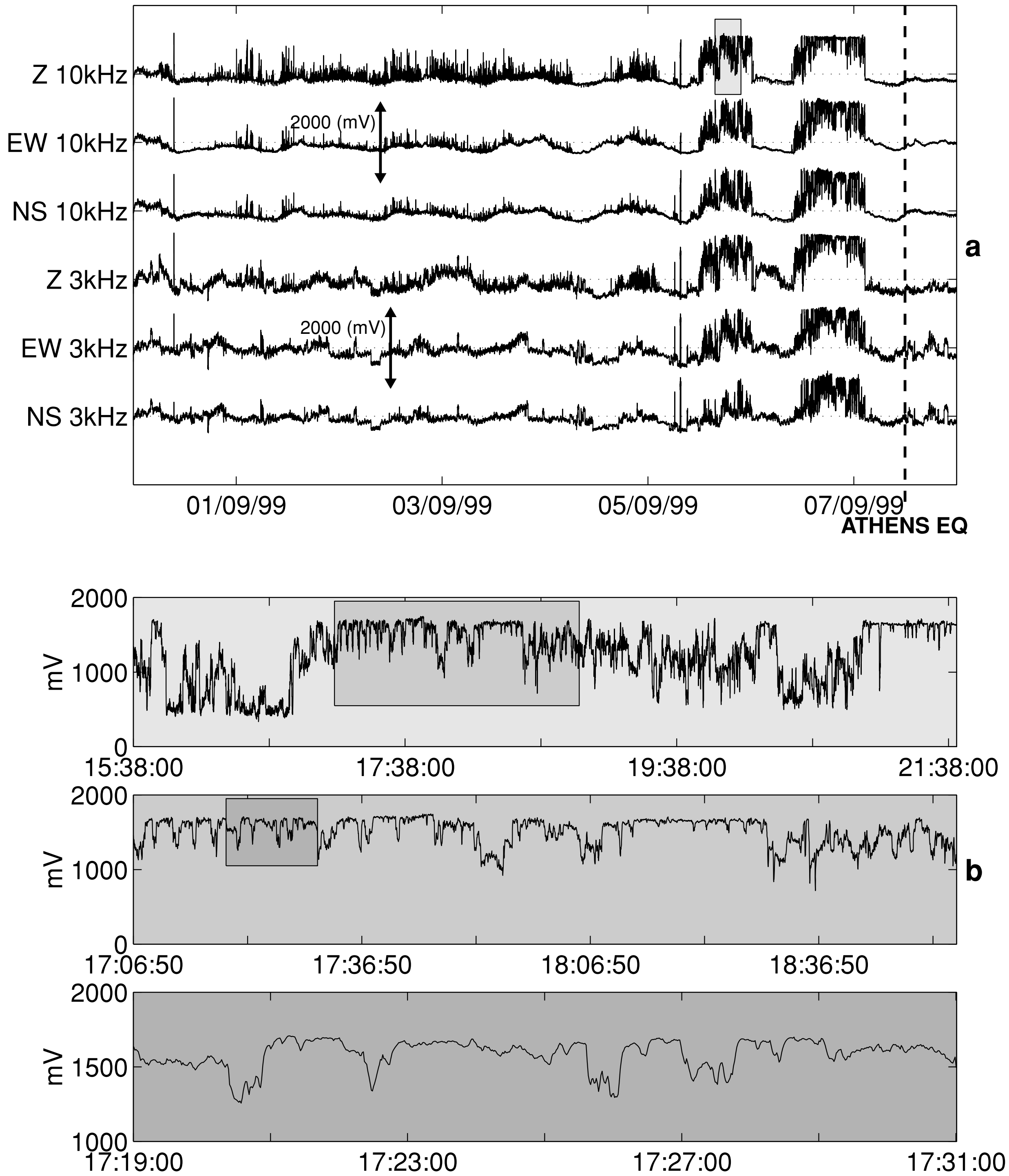

Fig. 3. (a) Anomalies recorded at Zante station by six loop antennas detecting the three components (EW, NS, and vertical) of the variation of the magnetic field at 3 kHz and 10 kHz. The vertical line indicates the time of the Athens EQ occurrence. The two detected strong multi-peaked signals on the 5th and 6th September, with sharp onsets and also sharp ends, show a surprising correlation in the energy domain with the two faults activated in the Athens EQ. (b) Detailed portions of the EM anomaly in progressive decrease of the time window marked in shaded frames. Notice that the avalanches in the EM time series have a very ragged shape. There are avalanches of all size while each avalanche is always finely balanced between continuing and dying out. We also note the pattern of fast, slow, and intermediate range fluctuations.

(Brodsky *et al.*, 2000; Stein, 1999; Gomberg *et al.*, 1998).

It is worth mentioning that laboratory evidence supports the emergence of a positive feedback between the Izmit EQ and the Athens EQ. Krysac and Maynard (1998) have shown that during the fracture of a brittle material, the breaking of a bond launches a propagating stress wave which may trigger the breaking of other bonds. Such a process might be important just prior to an avalanche of bond-breaking events when there would be a relatively high density of bonds on the verge of breaking. Lei *et al.* (2000) used a new rapid data acquisition system to examine the role of pre-existing crack density in determining the mechanical properties of crystalline rock. Their results demonstrate that pre-existing, particularly large, cracks are the most dom-

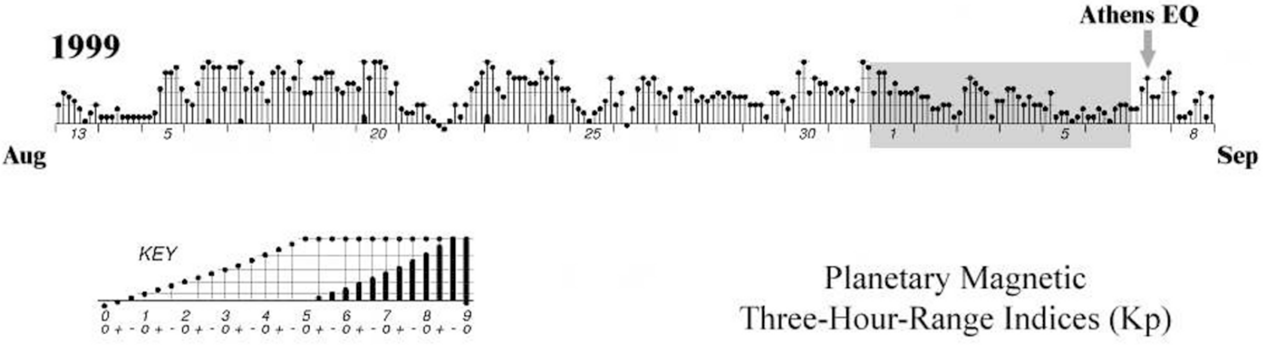

Fig. 4. The temporal evolution of the geomagnetic activity as expressed by the planetary three-hour-range K_p index (http://www.gfz-potsdam.de/pub/home/obs/kp-ap/). The shaded frames indicate the time windows of the precursory EM activities recorded before Athens earthquake. One can recognize that the precursory electromagnetic phenomena have been detected during low geomagnetic activity.

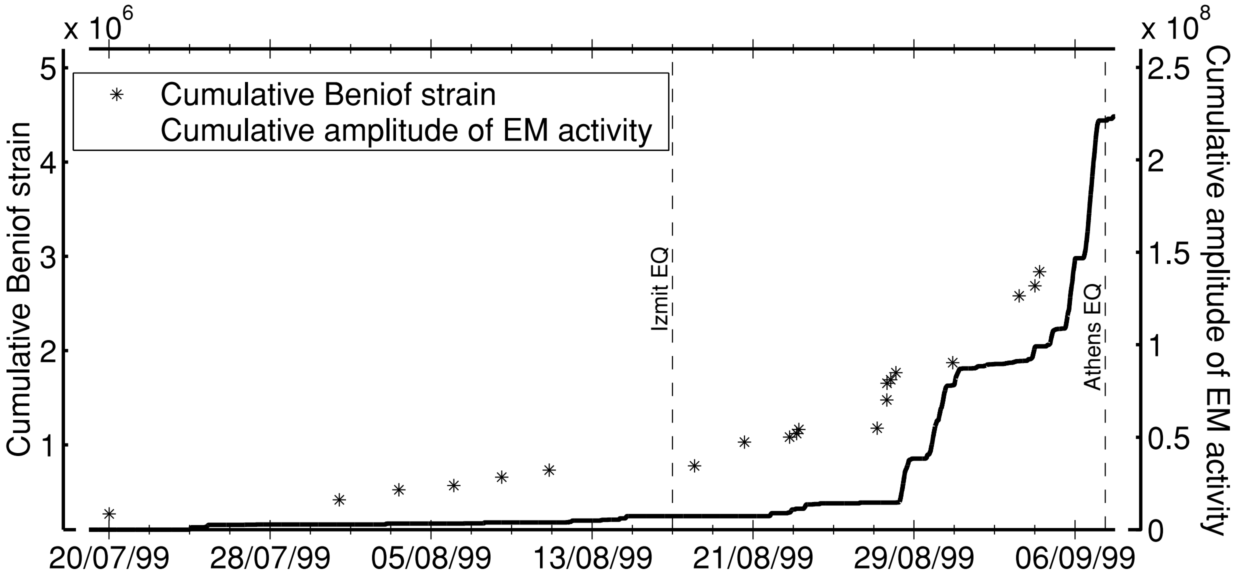

Fig. 5. The Benioff cumulative strain release as a function of time (denoted by) along with the "Beniof" cumulative electromagnetic energy release in arbitrary units as a function of time (denoted by solid line) both computed over circle (R = 110 km) on the epicentre of the Athens earthquake. The strong similarity of the temporal evolution of both the seismic and the EM energy release approaching the main event is pronounced.

inant factor of all heterogeneities that govern the faulting process, especially the nucleation. The pre-existing cracks lead to a precursory micro-seismicity that is an important feature of fault development in rocks. The authors suggest that this makes the failure predictable. A reasonable mechanism for the dominant role of pre-existing crack is that the stress concentration at a crack tip is generally much higher than that caused by the other kind of heterogeneity.

3.2 Tzanis and Makropoulos' approach

Tzanis and Makropoulos (2002) have detected precursory power-law acceleration of seismic release rates in the case of Athens EQ. The authors find that the apparent onset of precipitous power-law behavior began immediately after the 17/8/1999 $M_w = 7.4$ Izmit EQ and culminated with the Athens event, disappearing soon afterward (Fig. 5). Their analysis indicates that prior to 17/8/99, seismic release rates either were quasi-constant, or any power law dependence was subtle and could not be clearly detected. This experimental evidence also hints at a causal connection between the two events and raises the issue of the spatial distribution and temporal behaviour of their process. More precisely, they found that prior to the Athens EQ, regional seismic energy release has exhibited a power-law increase, of the form $\Omega(t) = \sum \sqrt{E_i} = K + A(t_c - t)^n$, where t_c is the time of the culminating event. The authors have established a critical radius of 110 km from the epicentre, however, a few days prior to the main event the process of foreshoks generation was centred at the epicentre area.

3.3 Papadopoulos' approach

A time-to-failure analysis performed by Papadopoulos (2002) showed that the process of small EQs generation, at a distance of about one source dimension (∼30 km) from the Athens EQ epicentre, started accelerating very slowly from the beginning of 1994. However, only immediately after the Izmit EQ the process culminated with a clear short-term acceleration similar to the classic foreshock seismicity increase.

The observed long-range correlations can be understood by analogy to the statistical mechanics of a system approaching a critical point for which the correlation length

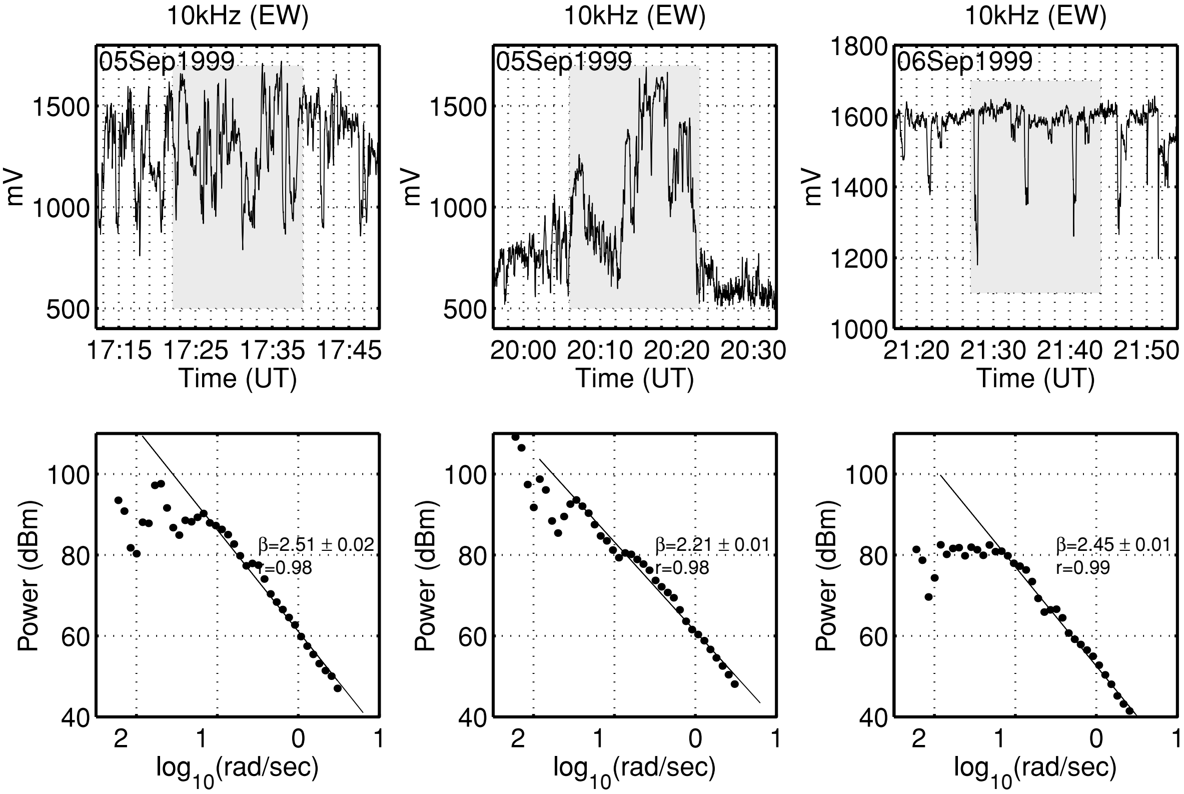

Fig. 6. Excerpts of the VLF EM emission recorded on 5th and 6th of September, 1999, i.e., before the Athens EQ (upper part). The corresponding power spectrum density of the signals versus frequency, in a $\log S(f) - \log f$ representation, is presented in the lower part. We observe a deviation of the β-values from the main part of the power-law in the range of lower frequencies. The low frequency range is not consistent with criticality because the corresponding time scales are beyond the scale-free evolution of the perturbations. For higher frequencies, we observe a characteristic decay of spectral density following a critical power-law.

is only limited by the size of the system (Bowman *et al.*, 1998).

4. Features Combining the Pre-fracture EM Emission and the Last Stage of EQ Preparation Process

In this section we try to demonstrate that the observed sequence of EM pulses prior to the Athens EQ could be considered as a hallmark of the last stage of the EQ preparation process.

4.1 Damage localization and the sensitivity of energy release

We recall that a few days prior to the Athens event, the seismicity was centred at the epicentral area, i.e. at a distance of about one source dimension (~30 km) from the Athens EQ epicentre (Tzanis and Makropoulos, 2002; Papadopoulos, 2002). Simultaneously, the rate of the seismic energy release was exhibited a significant increase. It may be concluded that the main event have been preceded by a process of damage localization and critical sensitivity of energy release corresponding to micro-cracking. This result meets the international experience (Shaw *et al.*, 1992; Dodze *et al.*, 1996; Reasenberg, 1999). Theoretical (Shaw *et al.*, 1992) and laboratory (Li *et al.*, 2002) studies also suggest that the damage localization and sensitivity of energy release characterize the fracture surface formation, and thus provide two cross-checking precursors for the prediction of rupture.

4.2 On the short lead-time of the detected EM anomaly

Immediate foreshocks have been defined as local instabilities that occur in the process of the ensuing overall dynamic instability. Typical immediate foreshocks that are concentrated close to its hypocentral region begin to appear a few days before the main shock. Morgounov (2001) have proposed the "relaxation creep model of impending EQ". The order of the lead-time (from a few days to a few of hours) and duration (of the order of a few hours) of the observed strong precursory signals support their association with the tertiary stage of creep in terms of the "relaxation creep model of impending earthquake" (Morgounov, 2001). Notice that changes in creep, such as episodes of rapid creep called *creep events*, have been suggested as possible EQ precursors (e.g. Thurber, 1996, and references there in). Thurber (1996) found that the time interval between the *creep events* and the subsequent EQs on the creeping portion of the San Andreas fault ranged from 1 to 5 days. These empirical facts may give a suggestion for the time window to identify immediate precursors. The EM precursor under investigation was emerged during the last few days before the main shock. The short lead-time of the detected EM anomaly bolsters up the hypothesis that the observed VLF EM anomaly might reflect the nucleation phase of the Athens EQ.

4.3 On the morphology of the EM precursor

An important characteristic is the multi-peaked episodic character of the VLF EM activity (Fig. 3). In nonlinear systems with many degrees of freedom, such as the heterogeneous crust of the earth, there are large numbers of metastable states. The impulsive emission may reflect the rearrangements that occur as the system shifts from one metastable state to another (Sethna *et al.*, 2001).

In general, it has been experimentally observed and theoretically suggested that the response (acoustic or electromagnetic emission) of stressed disordered media takes place in bursts of widely distributed intensity, indicative of an internal avalanche dynamics (Diodati *et al.*, 1991; Petri *et al.*, 1994; Anifrani *et al.*, 1995; Dahmen and Sethna, 1996; Zapperi *et al.*, 1997; Kuntz and Sethna, 2000; Sethna *et al.*, 2001). The "relaxation creep model of impending earthquake" also predicts that an avalanche-like EM anomaly correspond to the final, tertiary stage of creep (Morgounov, 2001).

An inspection in Fig. 3 reveals that the detected two strong multi-peaked signals on the 5th and 6th September emerged with sharp onsets and also sharp ends. This characteristic has been also observed in the pattern of the VLF EM activity recorded just before the Kozani-Grevena EQ (Eftaxias *et al.*, 2002; Kapiris *et al.*, 2002). Numerical (e.g. Lockner and Madden, 1991) and laboratory (e.g. Reches and Lockner, 1994) results support the relation of the abrupt launch of the burst-like VLF EM anomalies to the abrupt initiation of the nucleation phase. The observed surprising correlation between these two impulsive signals and two faults of the Athens EQ (see Section 4.5) in the energy domain further support the above mentioned relation. The possible connection of the two signals with the nucleation phase of the Athens EQ, may also point to the persistent mode of the process at this stage, when due to the high level of clustering of defects, even a small crack, if it connects large clusters, may generate a large event (Chelidze, 1986; Kapiris *et al.*, 2004b). It is remarkable that the fractal spectral analysis reveals an underlying persistent behaviour within these two strong EM bursts (see Section 6.4).

4.4 A possible EM trace of the Kaizer effect

Figure 3 reveals the strong intermittent character in the last stage of the precursory EM emission. We focus on this point.

Irreversible deformation of rocks is accompanied by the Kaizer effect: "if the heterogeneous material is loaded, then unloaded before fracture, and loaded again, only a small number of micro-fractures are detected before attaining the previous load. Micro-fracturing activity increases dramatically as soon as the largest previously experienced stress level are exceeded indicating the beginning of further damage in rocks (Chelidze, 1986; Garcimartin *et al.*, 1997)". In a recent review article Lavrov (2003) discusses experimentally established features of the Kaizer effect, including mechanism and theoretical models of the phenomenon.

We suggest that the observed intermittency could be considered as a signature of a non-monotonous tectonic stress variation combined with the Kaizer effect, i.e., as an EM hallmark of the Kaizer effect in the geophysical scale. This behavior could be also considered as a hallmark of the log-periodic law of energy release (Sornette and Sammis, 1995) again combined with the Kaizer effect.

4.5 On the accelerating emission rate

The observed significant divergence of the energy release constitutes a fundamental signature of the progressive ordering of the a fault network under the influence of many small-scale changes (Jaume and Sykes, 1999).

The whole EM precursor was emerged from August 31 to September 7, 1999 (Fig. 2). It is characterised by a clear accelerating emission rate (Figs. 2 and 3(a)), while, this radiation is embedded in a long duration quiescence period concerning the detection of EM disturbances at the VLF frequency band. The significant acceleration of EM energy release rates during the last days before the Athens EQ hints at a causal connection between the two events.

The subsequent fact strongly supports the former suggestion. The accelerating precursory EM phenomenon ends in two very strong signals (Figs. 2 and 3). The first EM signal contains approximately 20% of the total EM energy received and the second the remaining 80% (Eftaxias *et al.*, 2001a). On the other hand, the fault modelling of the Athens earthquake, based on information obtained by radar interferometry (Kontoes *et al.*, 2000), predicts two faults. The main fault segment is responsible for 80% of the total energy released, with the secondary fault segment for the remaining 20%. It is worth noticing that a recent seismic data analysis carried out by M. Kikuchi, using the now standard methodology (Kikuchi and Kanamori, 1990) indicates that a two-event solution for the Athens EQ is more likely than a single event solution (Eftaxias *et al.*, 2001a). According to Kikuchi, there was probably a subsequent ($M_w = 5.5$) EQ after about 3.5 s of the main event ($M_w = 5.8$). This surprising correlation in the energy domain between the two strong pre-seismic kHz EM signals and two faults of the Athens EQ, strongly supports the hypothesis that a part of the energy released during the opening of cracks in the formation of these two faults was transformed to the captured VLF EM energy.

In order to gain deeper understanding of the above mentioned correlation we compare the temporal evolution of the mechanical energy release along with the temporal evolution of the EM energy release. The seismicity data are taken from the raw catalogue of the Geodynamics Institute of the National Observatory of Athens (http://www.gein.noa.gr/services/cat.html) and span the period 10/5/99–7/9/99. Figure 5 shows the cumulative Benioff strain release $\Omega(t)$ as a function of time, computed over circle ($R = 110$ km) on the epicentre of the Athens EQ, along with the cumulative amplitude of EM events exceeding a threshold (in arbitrary units) as a function of time. One recognizes a striking similarity in the morphology of the temporal evolution of both the seismic energy release and the captured EM.

We pay attention to the fact that the precursory accelerating EM activity has been detected in a time window from few days to few hours prior to the Athens event, i.e., when the seismicity rates attain there the largest values (Fig. 5) and while the region of the correlated accelerating seismic release was centred at the epicentral area (Papadopoulos, 2002; Tzanis and Makropoulos, 2002). We also bear in mind that the accelerating pre-seismic EM radiation is embedded in a long duration quiescence period concerning the

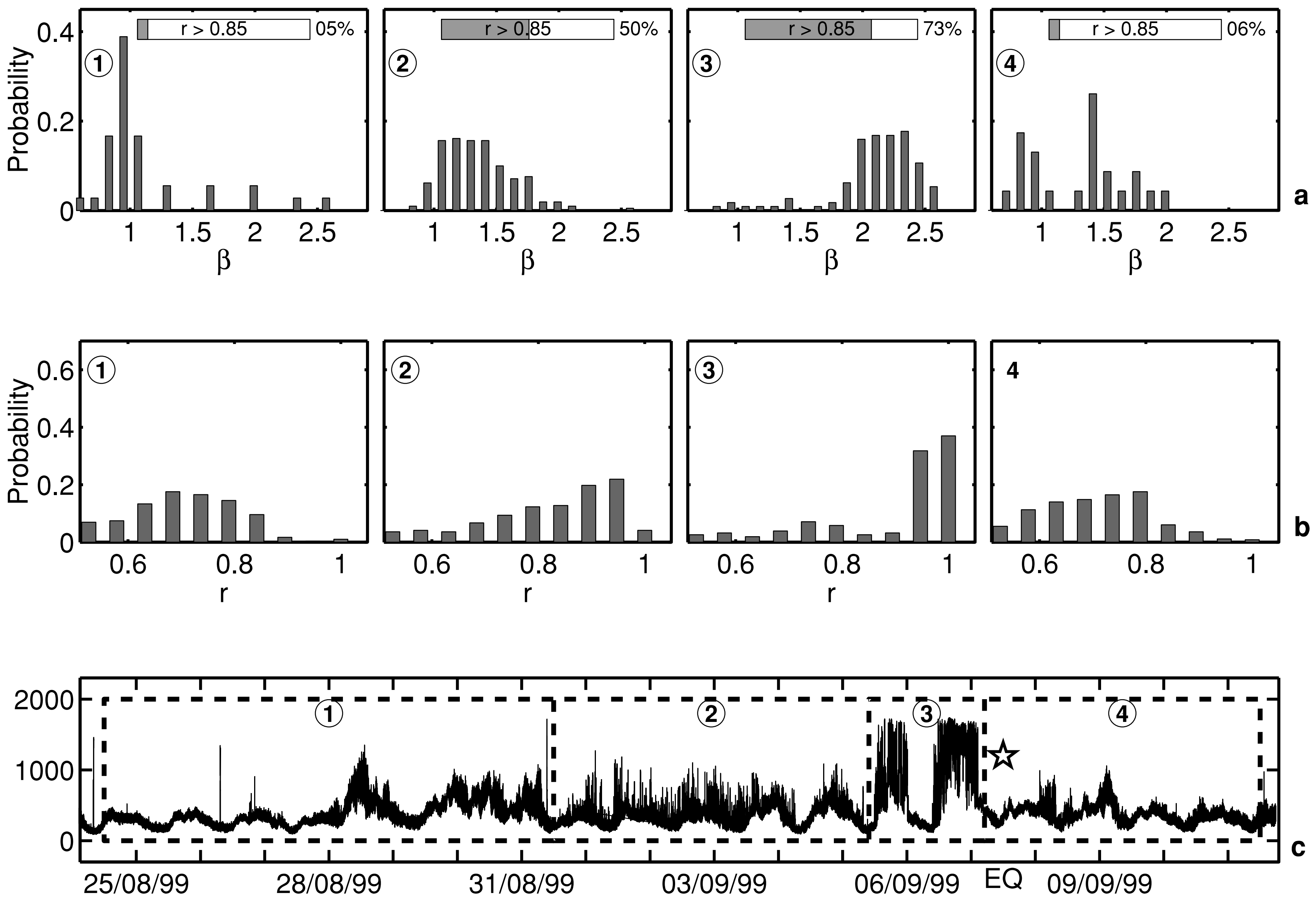

Fig. 7. (a) Histograms of distribution of probability of the power-law exponent β calculated on segments of 1024 measurments for four consecutive intervals in the 10 kHz (EW) time-series as marked in (c). The power law fits the region $\omega = 3.142$ down to 0.048 rad/sec (see Fig. 6). (b) Histograms of distribution of probability of the correlation coefficient for the same consecutive intervals as in (a).
(c) The 10 kHz (EW) time-series sampled at 1 Hz.

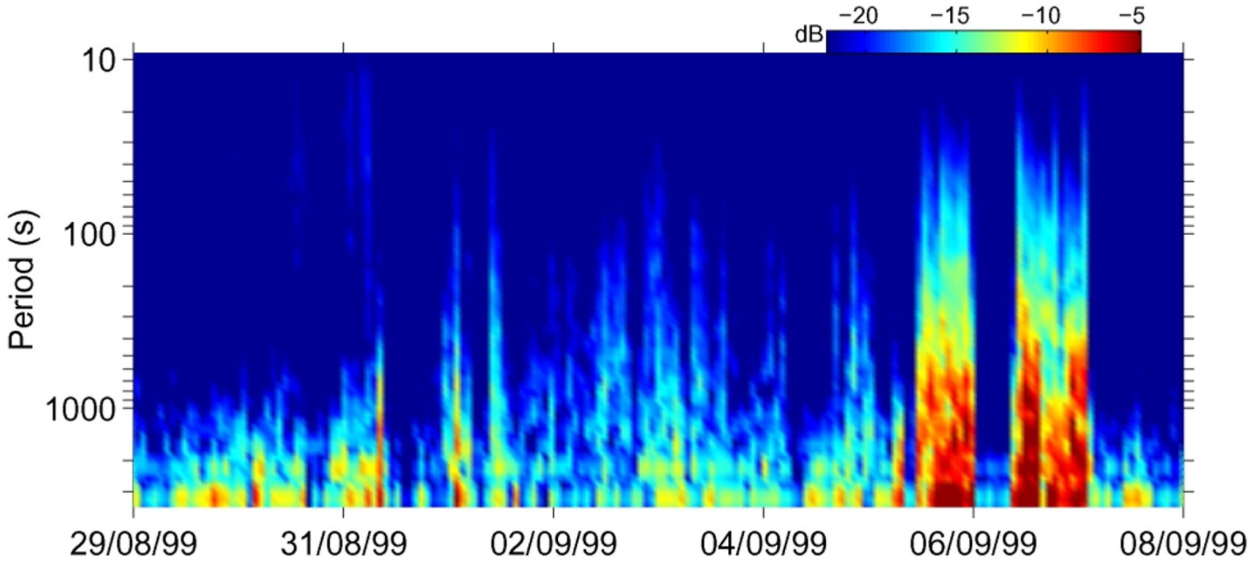

Fig. 8. The wavelet power spectrum of the 10 kHz (E-W) electromagnetic time series between 29/08/1999 and 8/09/1999. The intensity scale on the top shows colour corresponding to the values of the square spectral amplitudes in arbitrary units. The spectrum reveals both, new higher frequencies with low amplitudes are progressively added with time, while, the amplitude in each frequency (emission rate) increases as the earthquake is approached mainly in lower frequencies (see text).

detection of EM disturbances at the VLF frequency band (Fig. 2).

The above mentioned experimental findings suggest that the accelerating VLF EM activity could be related to the precursory accelerating seismicity associated with the Athens EQ.

5. Fractal Analysis of the Pre-fracture EM Time-series

A well accepted qualitative physical picture for the progressive damage of a heterogeneous system leading to global failure is the following: “First, single isolated defects and micro-cracks nucleate which then, with the increase of load or time of loading, both grow and multiply leading to an increase of the density of defects per unit volume”. Thus, as the damage increases, a new “phase” appears where micro-cracks begin to merge leading to screening and other cooperative effects. Finally, the main fracture is formed leading to global failure”. The challenge is to determine the time interval (window) during which the “short-range” correlations evolve to “long-range”. In this section we attempt to identify this critical epoch in the pre-seismic time series.

Any given time-series may exhibit a variety of autocorrelation structures. For example, successive terms may show strong (“brown noise”), moderate (“pink noise”) or no (“white noise”) correlation with previous terms. The strength of these correlations provides useful information about the “memory” of the system (Miramontes and Rohani, 2002). One approach for estimating this effect is to estimate the value of the scaling exponent β in the power spectrum of the time series. Power spectral analysis is generally used to examine an irregular time series, especially when a power spectral density, $S(f)$, shows a coloured-noise type of behaviour, approximated by a power-law spectrum:

$$S(f) \sim f^{-\beta} \qquad (1)$$

where coloured-noise means that the power spectrum manifests more power at low frequencies than at high frequencies, i.e., $\beta > 0$. The values $\beta \approx 0$, $\beta \approx 1$, and $\beta \approx 2$ correspond to white, pink and brown noise, respectively. In this context, the power-law index β is one of the quantities describing the irregularity (the time-clustering) of the time series. More specifically, if the process is Poissonian, the occurrence times are uncorrelated; for this memoryless process $\beta = 0$, and the interevent-interval probability density function $p(t)$ behaves as a decreasing exponential function $p(t) = \lambda e^{-\lambda t}$, for $t \geq 0$, with λ the mean rate of the process. On the other hand, $\beta \neq 0$ is typical of point process with self-similar behavior. Self-similarity means that parts of the whole can be made to fit to the whole in some way by scaling. This class of processes has a decreasing power-law interevent-interval probability density function $p(t) = kt^{-(1+\beta)}$. Consequently, if the time-series of amplitudes of the detected precursory EM emission $A(t)$ is *a temporal fractal* then a power law spectrum of the recorded time-series is expected (Turcotte, 1992). The slope of the line fitting the log-log plot of the power spectrum by a least square method in the linear frequency range gives the estimate of the spectral index. The associated linear correlation coefficient r is a measure of the quality of fit to the power law (1).

A Continuous Wavelet Transform (CWT) was used for decomposition of our transient, non-stationary signals. The wavelet transform constitutes as a tool for the manipulation of self-similar or scale invariant signals as the Fourier transform does for translation-invariant signals such as stationary, and periodic signals (Wornell, 1996). We have chosen the wavelet analysis based on the Morlet mother wavelet (Torrence and Compo, 1998). As there is a number of different wavelets which could be, in principle, employed, the question arises what are the reasons for this particular choice. This is discussed in detail by Torrence and Compo (1998), who showed that this choice of complex wavelet transform is useful for time series analysis, where smooth, continuous variations in wavelet amplitude are expected due to oscillatory behaviour of investigated time series.

In Fig. 6 we show a few examples of fitting of Eq. (1). We observe a deviation of the β-values from the main part of the power-law in the range of lower frequencies. The low frequency range is not consistent with criticality because the corresponding time scales are beyond the scale-free evolution of the perturbations. For higher frequencies, we observe a characteristic decay of spectral density following a critical power-law.

5.1 Focus on the temporal evolution of spectral fractal indexes

In order to assess the use of EM signals as signatures of EQ generation, the basic question to address is if associated parameters are able to reveal dynamical characteristics of the associated active tectonics. In this sense, we investigate the temporal evolution of the dynamical fractal parameters of the detected precursory EM emission. More precisely, we calculate the characteristic parameters β, r associated with successive intervals of 1024 samples each prior to failure and study the time evolution of these parameters (sampling rate 1 Hz). The recorded VLF EM time series has been divided into 4 periods, as presented in Fig. 7(c).

5.2 Study of the temporal evolution of the linear correlation coefficient *r*

Fig. 7(b) illustrates the histograms of the distribution of the coefficient r for the four time windows that presented in Fig. 7(c). It is clear that as the main event is approached r (using high frequencies (see Fig. 6)) shifted to higher values (periods 1, 2, 3 on Fig. 7(c)): a region with r close to 1 is approached during the last hours of the precursory emission (period 3 on Fig. 7(c)).

The fact that the data follow the power-law (1) suggests that the pre-seismic EM emission could be ascribed to a multi-time-scale cooperative activity of numerous activated cracks in which an individual units activity is dominated by its neighbours so that all units simultaneously alter their behaviour to a common fractal pattern. The temporal evolution of r is reasonable if we accept that stress and strain become non-linear at the end of the loading cycle, producing rapidly accelerating effects. Thus, we can expect the prevalence of the pre-failure EM signals over the background noise just before the main event.

5.3 Study of the temporal evolution of the β-scaling exponent

In Fig. 7(a) we illustrate the histograms of the distribution of the spectral exponent β for the four consecutive time windows that presented in Fig. 7(c). The included β-values (>1) corroborate to the presence of memory in the underlying fracto-EM process, i.e., the system refers to its history in order to define its future (non-Markovian behavior). The EM fluctuations show strong correlations with previous ones. We focus on the fact that the distribution of β-values is shifted to higher values with time. This behaviour signify a gradual increase in the spatial correlation as the main shock is approached (Turcotte, 1992), i.e., a higher degree of organization with time. The increase in the spectrum slope with time also reveals the gradual enhancement of lower frequency fluctuations (see Section 6.1), which indicates that cracks interact and coalesce to form larger fractal structures in the pre-focal area. Note that the power law behaviour described above breaks down just after the cessation of the VLF EM activity ∼9 hour before the failure (period 4 on Fig. 7(c)).

The aforementioned features of the pre-fracture EM time-series seems to determine the epoch during which the short-range correlations evolve to long-range, namely, themselves constitute a physically solid argument to distinguish the dynamics in a heterogeneous medium close to the global rupture instability (or "critical point").

6. Candidate Precursory Behaviours

6.1 The gradual predominance of of the lower frequencies

The EM precursor under study is characterized by a clear accelerating emission rate (see Section 4.5 and Fig. 5). Herein, we attempt a more detailed study of this behavior. Wavelet spectral analysis permits quantitative monitoring of the evolution of the transient signals. Figure 8 shows the wavelet spectrum of the EM time series under investigation. We discriminate a progressive shift to higher frequencies. It is remarkable that these new components are launched with small amplitudes. This figure also shows increase of amplitude in each emission rate as the main event is approached. The former behaviour mainly characterizes the lower frequencies (emission rates). The question to be answered is whether the system transmits more power at lower frequencies. We recall that the power spectral density, $S(f)$, shows a coloured-noise type of behaviour, namely, the power spectrum manifests more power at lower frequencies. The observed shift of β to higher values with time (Fig. 7(a)) reveals that the system selects to transmit more power at lower frequencies as the main event is approached; consequently,their amplitudes increase significantly. Finally, the lower frequencies relatively dominate in the power spectrum.

6.2 The predominance of larger EM events

Recently, using EQ terminology, we have focused on a possible EM Gutenberg-Richter type distribution in the detected EM time series prior to the Athens EQ (Kapiris *et al.*, 2004a). This emission has a rather long duration, thus it provides sufficient data for statistical analysis.

The statistical analysis has shown that the cumulative number $N(>A)$ of EM events (the number of EM events having amplitudes larger than A) vs EM pulse amplitude A follows the power-law

$$N(>A) \sim A^{-b} \tag{2}$$

where $b = 0.62$ (Kapiris *et al.*, 2004a). Hence, the cumulative amplitude distribution of the EM events is consistent with a Gutenberg-Richter-type law with a b value of 0.62. Note that physically, the value $b = 0.62$ indicates a preponderance of large EM events in the precursory EM time series. Moreover, the power law observed here could be interpreted as an additional strong EM indication that the system evolves without characteristic length scale; this evidence is also a fundamental hallmark of criticality.

6.3 The Hurst exponent

A first pioneer approach to studying the characteristics of irregular time series was presented by Mandelbrot (1977): the time-series $A(t)$ can be viewed geometrically as a curve, which can be considered to be self-affine when each part of it is a reduced scale image of the whole. The increment function $[A(t+h) - A(t)]h^{-H}$, where $h > 0$, has a probability distribution independent of t, where H (Hurst exponent) is an index describing the characteristics of the self-affine curve. In terms of spectral analysis, the power spectral density of such a curve follows a power-law form, $S(f) \sim f^{-\beta}$, where $\beta = 2H + 1$ (Turcotte, 1992). H lies anywhere in the range of $0 < H < 1$ and characterizes the persistent / anti-persistent properties of the signal according to the following scheme: (i) $H = 0.5$ ($\beta = 2$) suggests no correlation between the process increments, that is the system is characterised by random fluctuations. (ii) The range $0.5 < H < 1$ ($2 < \beta < 3$) suggests persistence of the signal (Feder, 1989), i.e., if the amplitude of electromagnetic fluctuations increase in one time interval, it is more likely to continue increasing in the period immediately following. (iii) The range $0 < H < 0.5$ ($1 < \beta < 2$) suggests a clustering or anti-persistence of the signal, i.e., if the system increases in one period, it is more likely to continue decreasing in the period immediately following, and vice versa.

6.4 A candidate precursor: the transition from anti-persistent to persistent properties

Concerning our data, the values of the spectral exponents β calculated for the precursory EM signal provide the following interpretation of the underlying fracto-EM mechanism. In the first stage of the pre-seismic EM activity, the EM events evolve with anti-correlated increments, typical of processes regulated by stabilizing negative feedback mechanisms. In other words, this implies a set of fluctuations tending to induce a stability of the system, namely a non-linear feedback system that “kicks” the opening rate away from extremes. The observed systematic increase of the H-exponent during the pre-seismic stage indicates that the fluctuations become less anti-correlated with time. This implies that the nonlinear negative feedback mechanism gradually loses its ability to “kick” the system away from extremes.

We would like to stress the appearance of persistent properties within the characteristic two EM bursts in the tail of the VLF EM precursor, i.e., just before the EQ (Fig. 7(a)). This means that increases in the value of the associated time series are likely to be followed by increase.

It is remarkable that this behavior of Hurst exponent confirms the analogous experience associated with the EM anomalies detected just before the Kozani-Grevena EQ. Indeed, on May 13, at 08:47 UT, a magnitude M_s (GREV) = 6.6 EQ struck the Grevena in NW Greece (Fig. 1). VLF-VHF EM emissions have been observed before this destructive EQ at Zante station with the following order (see Fig. 2 in Kapiris *et al.*, 2002): (i) a few tens of hours prior to the main event anomalies were recorded at 41 MHz and 54 MHz respectively, with increasing EM emission rate. These anomalies ceased approximately one hour before the EQ occurrence; (ii) very strong multi-peaked EM signals with sharp onsets and ends at 3 kHz and 10 kHz, lasting about half hour, emergred approximately one and half hour before the main shock. The VHF precursory component becomes less anti-persistent as the main shock is approached (Fig. 9(a)). The VLF precursor that emerged just before the global failure also shows strong persistent behavior (Fig. 9(b)).

The existence of persistent properties may indicate that the process acquires the self-regulating character and to a great extent the property of irreversibility, one of the important components of prediction reliability (Morgounov, 2001). It is worth mentioning that laboratory experiments by means of acoustic and EM emission also show that the main rupture occurs after the appearance of persistent behaviour (Ponomarev *et al.*, 1997; Alexeev and Egorov, 1993; Alexeev *et al.*, 1993). Recently, Sammis and Sornette (2002) presented the most important mechanisms for such positive feedback.

The underlying physics Heterogeneity governs the fracture in disordered materials. The interplay between the heterogeneities in the pre-focal area and the stress field might be responsible for the observed pattern of the EM time-series, and in particular, for the temporal evolution of the Hurst exponent (Kapiris *et al.*, 2004b; Eftaxias *et al.*, 2004). Indeed, in a highly disordered medium there are long-range anti-correlations, in the sense that a high value of threshold for breaking is followed by a low value, and vice versa. The anti-persistent character of the EM time series may reflect the fact that areas with a low threshold for breaking alternate with much stronger volumes. Crack growth continues until a much stronger region is encountered. When this happens, crack growth stops and another crack opens in a weaker region, and so on. The observed decrease of the anti-persistent behaviour can be understood if we accept that the micro-heterogeneity of the system becomes less anti-correlated with time.

On the other hand, in the case of a homogenous medium, the stress is enhanced at its tip and therefore the next microcrack almost surely develops at the tip. Thus, one expects to see long-range positive correlations, i.e., persistent behaviour, $0.5 < H < 1$, in the associated EM emission. As a result, the bound $H = 0.5$ may signal the transition from a heterogeneous to a more-or-less homogeneous regime.

The mentioned physical pictures seem to explain why the gradual decrease of heterogeneity leads to a decrease in the ability to drive the system away from a persistent mode, namely, an irreversible phase transition.

Based on the behavior of the H exponent we have attempted to establish the following scenario: the initial anti-persistent part of the precursory EM radiation is triggered by micro-fractures in the highly disordered medium that surround the backbone of asperities. The persistent radiation is, in turn, thought to be clue to the fracture of these large high strength asperities that sustain the system (Kapiris *et al.*, 2004b; Eftaxias *et al.*, 2004). The observed suprising correlation in the energy domain between the two strong EM bursts in the tail of the pre-seismic activity and two faults of the Athens EQ (see Section 4.5) strongly sup-

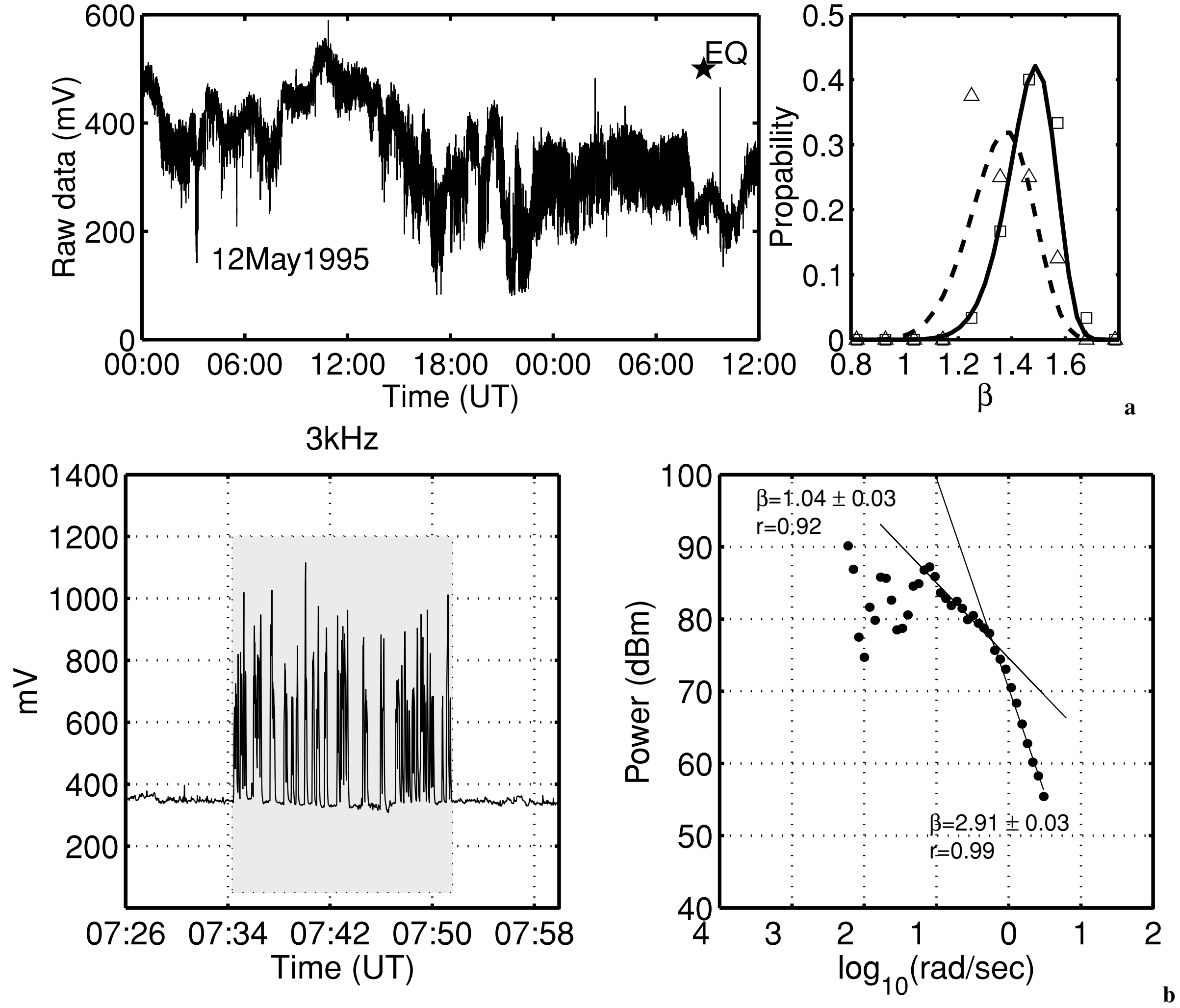

Fig. 9. (a) 41 MHz VHF EM signal detected prior to the 13/05/95 Kozani-Grevena EQ (Eftaxias *et al.*, 2002; Kapiris *et al.*, 2002) (left). The curves demonstrate the distribution of probability of the power law exponent β calculated on 1024 bit segments for two consecutive time periods: (i) from 12-May-1995, 00:00 up to 12-May-1995, 16:00 approximately ($\triangle$) , and (ii) the next 16 hours up to the end of the precursory signal ($\sim$13-May-1995, 8:00) ($\square$). One can recognize the gradual shift towards greater values of the dynamical exponent β as the Kozani Grevena EQ is approached.
(b) The 3 kHz EM emission recorder on May 13th 1995 before the Kozani-Grevena EQ that occurred on the same day at 08:47 UT. The power spectral density of the signal versus frequency is presented in a $\log S(f) - \log f$ representation. The two solid straight lines may indicate that the VLF activity exhibits a power law behavior with two different branches, one at the lower ($\beta = 1.04$, $r = 0.92$) and another at the higher frequencies ($\beta = 2.91$, $r = 0.99$). In this case the power law at higher frequencies may reflect the dynamics within the bursts while the one at lower frequencies may indicate the correlation between the bursts. We pay attention to the fact that the critical exponent $\beta = 2.91$ indicates strong persistent behavior within the bursts.

ports the former hypothesis.

Such a statement has to be supported on to become solid ground by a further detail field and laboratory investigation. Importantly, recently Lei *et al.* (2000, 2004) have studied how an individual asperity fractures, how coupled asperities fracture, and the role of asperities in fault nucleation and as potential precursors prior to dynamic rupture. The observations reveal a strong similarity between the fracture of asperities in laboratory-scale experiments and tectonic-scale events. The authors suggest that: (i) intense microcracking may occur in the strong asperity when the local stress exceeds the strength of the asperity. This feature is in agreement with our results. (ii) The self-excitation strength, which expresses the strength of the effect of excitation associated with the preceding event on succeeding events, or equivalently, the degree of positive feedback in the dynamics, reaches the maximum value of $\sim$1 during the nucleation phase of the fault. We recall that the H-exponent, which also indicates the degree of the positive feedback in the dynamics, approaches the maximum value 1 in the tail of the precursory EM radiation as well.

6.5 A possible hint indicating the approach of the critical point: the increase of the correlation length

The Athens EQ occurred right after the maximum of the variation of the critical exponent β (Fig. 7(a)). The former result corroborates analogous behavior on the VHF EM anomalies detected prior to the Kozani-Grevena EQ (Eftaxias *et al.*, 2002; Kapiris *et al.*, 2002; Eftaxias *et al.*, 2003) (Fig. 9). Laboratory experiments by means of acoustic and EM emission also show that main rupture occurs right after the maximum of the variation of the critical exponent β (or H) (Ponomarev *et al.*, 1997; Alexeev and Egorov, 1993; Alexeev *et al.*, 1993).

The underlying question is: What is the physics involved

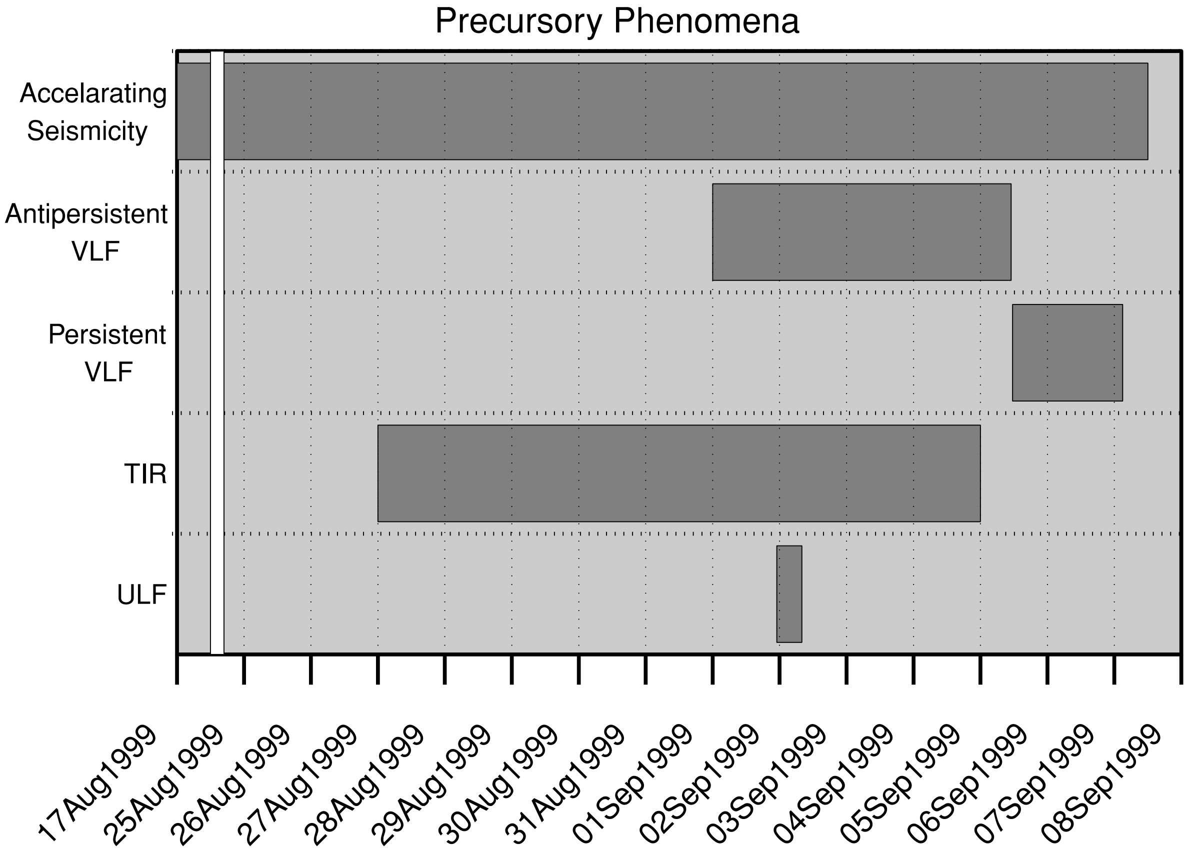

Fig. 10. Prior to the Athens earthquake, the following candidate precursors have been reported: (i) an accelerating seismic energy release in the area around the epicentre of the Athens event, (ii) an accelerating Very Low Frequency electromagnetic emission. The first part of this activity shows antipersistent behavior, while, the tail of this EM precursor exhibits persistent character (iii) a sequence of TIR signals that exhibits a progressive increase of its intensity in the area around the pre-focal zone, and finaly (iv) a SES activity (Ultra Low Frequency—geoelectric potential differences).

with this possible precursor criterion?

Maslov *et al.* (1994) have formally established the relationship between spatial fractal behaviour and long-range temporal correlations for a broad range of critical phenomena. By studying the time correlations in the local activity, they show that the temporal and spatial activity can be described as different cuts in the same underlying fractal. Laboratory results support this hypothesis: Ponomarev *et al.* (1997) have reported in phase changes of the temporal and spatial Hurst exponents during sample deformation in laboratory acoustic emission experiments. Consequently, the observed increase of the temporal correlation in the preseismic time-series may also reveal that the opening-cracks are gradually correlated at larger scale length with time. Generally, the important feature of spatially extended systems exhibiting a critical behaviour is that the growth of the spatial correlation length obeys a power law with a singularity in the critical point (Bowman *et al.*, 1998; Main, 1999; Zoller and Hainzl, 2002; Zoller *et al.*, 2001); the corresponding main event occurs when the stresses are correlated over all length scales up to the size of the network. The simultaneously reported significant divergence of the energy release furter supports the former hypothesis.

7. The EM Quiescence Just before and after the Earthquake.

An interesting characteristic of the VLF-VHF EM precursors is the systematically observed EM quiescence at all frequency bands before the earthquake (Nagao *et al.*, 2000). Importantly, the phenomenon of quiescence has been reported by a number of researchers to occur close to the global failure in laboratory studies on rocks (Meredith *et al.*, 1990; Meredith, 1990; Morgounov, 2001).

Eftaxias *et al.* (2000, 2001b) have attempted to explain this effect based on a model for the micro-fracture of granular media which consists of rigid grains separated by interstices filled with a brittle elastic material. This model assumes a Gaussian distribution of variance σ of the elastic properties of the brittle elastic material. Such structures are typical of a wide class of geophysical media. The analysis of this model indicates that the maximum rate of cracking, i.e., the maximum intensity of the emitted acoustic/electromagnetic emission, appears well prior to global instability, while, the cracking rate in the “tail” of the fracture process is very low and its minimization is expected just before the event (exception is the theoretical situation $\sigma = 0$).

More recently, we have suggested (Kapiris *et al.*, 2004b) that the observed precursory EM quiescence can be explained in terms of a catastrophic decrease in the elastic modulus M close to mechanical percolation threshold:

$M \sim |x - x_c|^f$, where $f \sim 3.6$ for $3d$ systems (Sahimi and Goddard, 1986). The sudden drop of M means that the amount of elastic energy that can be released during crack nucleation (merging) decreases abruptly at $x \to x_c$; consequently, the amplitudes of acoustic and EM emissions may decrease before the final rupture. If we accept this hypothesis, the EM quiescence could give a hint of a considerable probability for a forthcoming EQ in the following few hours.

Our field experience does not reveal any precursory EM activity for aftershock sequences. The catastrophic decrease in the elastic modulus may rationalize this observation as well. The Kaizer effect (see Section 4.4) also explains this quiescence: "if the sample is loaded and unloaded before fracture and loaded again, only a small number of micro-fracturing are detected before attaining the previous load". In this sense, a potential explanation is that the stress required for an aftershock to occur does not exceed the stress needed for the main shock.

8. Discussion and Conclusions

We show that not only the precursory seismic activity but also the precursory EM activity reveals the rearrangement that occurs as the external field drives the pre-focal area from one meta-stable state to another towards global instability. The measurements indicate a strong connection between the evolution of both the pre-fracture accelerating seismic energy release around the epicentre of the Athens event and the pre-fracture accelerating EM emission captured by the loop antennas.

We view the EQ as a large scale fracture phenomenon. Many recent theories for the rupture in heterogeneous media rely on concepts borrowed from statistical physics and non-linear dynamics. The school of "Intermittent Criticality" considers large EQs as a "critical phenomenon", culminating in a large event that is analogous to a kind of "critical point" (Sornette and Sammis, 1995; Saleur *et al.*, 1996a,b; Sammis *et al.*, 1996; Bowman *et al.*, 1998; Zoller *et al.*, 2001; Sornette, 2004). This approach bridges both, the hypothesis of an underlying critical state and the occurrence of precursory phenomena.

The analysis of the EM precursor in terms of fractal dynamics seems to offers the possibility for a systematic monitoring of the Athens EQ generation. Indeed, this analysis reveals that the underlying fracto-EM complex mechanism manifests itself in linkages between space and time producing fractal processes and structures. By monitoring the fractal characteristic of the pre-fracture EM emissions in consecutive segments, we found distinguished alterations in the associated scaling dynamical parameters, which could be used as diagnostic tools for earth's crust failure. These observations find an explanation within the school of the "Intermittent criticality": the observed scaling alterations can indicate that the pre-focal area intermittently reach criticality in the form of a single large EQ when longer stress correlations are established on all scale lengths up to and including the largest possible event for the given fault network. Namely, seismic cycles represent the approach to and retreat from a "critical" state of a fault network.

We suggest that the evolution of the anti-persistent / persistent properties with time could be understood in the framework of this scenario: the initial anti-persistent part of the precursory EM radiation is triggered by micro-fractures in the highly disordered system that surrounds the, more-or-less, homogeneous backbones in the pre-focal area. The gradual decrease of the anti-persistent behavior can be understood if we accept that the micro-heterogeneity becomes less anti-correlated with time. On the other hand, we think that the appearance of persistent properties within the two strong EM bursts that have been launched in the tail of the precursory emission may indicate the fracture of the large high strength asperities in the pre-focal area.

The systematically observerd period of EM quiescence just before the EQ may indicate the expected catastrophic decrease in the elastic modulus M close to mechanical percolation threshold. In this framework, the emergence of EM quiescence might considered as a further "hint" of a considerable probability for a forthcoming EQ in the following few hours.

It is worth mentioning that clear TIR signals over the area around the Athen's EQ epicentre has been detected from satellites during the last days prior to the Athens EQ (Filizzola *et al.*, 2003). Moreover, on September 1 and 2, 1999, a series of ULF seismic electric signals (VAN-signals) has been recorded in Lamia station with duration ~9 hours (Varotsos *et al.*, 1999). The recorded SES activity exhibits the following peculiarity: this lasts several hours, but its last portion has a larger amplitude and also changes polarity (see Fig . 3 in Varotsos *et al.*, 1999). Thus, the SES activity could be interpreted as consisting of two separate SES activities, coming from two different sources (Varotsos *et al.*, 1999). This observation is in agreement with the fault modeling of the Athens EQ (see Section 4.5) and the pattern of the pre-seismic VLF EM radiation. It might be argued that the information for the impending two faults activation had imprint in the detected VAN-signals as well. These two anomalies bring further support for the confidence in the reliability of our conclusion.

In summary, a set of physical peculiarities has been emerged prior to the Athens EQ, namely, an accelerating seismic energy release, an accelerating VLF EM radiation, a SESs-activity (VAN-signals), a clear sequence of TIR signals. Figure 10 describes these precursors that have been emerged during the last few days prior to the Athens EQ. Moreover, a radar interferometry analysis leads to the fault modeling of the Athens EQ. All these various observations lead to converging results. This observation suggests that it is useful to combine various field measurements to enhance the understanding behind the generation of EQs. The achievement of converging estimations, as in the case under investigastion, would definitely improve the chances for an EQ prediction. Maybe, the Athens EQ is a particular case in this direction.

There still remains a problem of explaining a VLF wave propagation from ~10 km depth to the surface. One of the possible mechanisms is the effective radiation in the inhomogeneous crust using fractal geoantenna (Eftaxias *et al.*, 2004). The idea is that as the "critical point" is approached, an array of "radiating elements" having a fractal distribution can form a fractal-geo-antenna. The creation of rupture fault lengths, i.e. fracto-electromagnetic emitters, without characteristic length scale is in agreement with the observed power law distribution of the amplitudes of EM pulses. We have explored this idea in terms of fractal electrodynamics, which combines fractal geometry with Maxwell's equations. The fractal tortuous structure can significantly increase the radiated power density, as compared to a single dipole antenna. The tortuous path increases the effective dipole moment, since the path length along the emission is now longer that the Euclidean distance.

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