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Seismic and Electrical Precursors to the 17-1-1983, M7 Kefallinia Earthquake, Greece: Signatures of a SOC System

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Abstract. Prior to the 17-1-1983 event, the seismicity of the broader area of the Ionian islands and western Greece exhibited several phenomena interpretable in the context of a self-organised critical system with long range interactions. The regional seismic energy release exhibited power law acceleration towards the time of rupture, the numerical modelling of which yields a time-to-failure of 1983.1±0.2. Time dependent changes were also observed in the b-values, assuming the form of monotonic increase that promptly reversed after the earthquake. This indicates the induction of instability to the region due to the earthquake preparation process, which is consistent with the critical point earthquake model. The critical point model predicts that failure is a co-operative effect occurring at small scale, and cascading from the microscopic to the macroscopic scale. This involves a crack propagation avalanche at the terminal phase of the seismic cycle, the time function of which has been modelled with a limited class of characteristic transient bay-like shapes, featuring a corner frequency and inverse power energy distribution law. Electrification processes due to crack propagation may generate an electrical precursor with similar characteristics. Such a potential precursor has been observed independently on 15-1-1983, approx. 120km from the epicentre. In consequence of our observations, we discuss a model relating seismicity and electrical precursors.

1 Introduction.

In the last several years, a mounting body of evidence indicates that the earthquake generation process is a critical phenomenon, culminating to a large event that corresponds to some critical point (CP)- (Allègre and LeMouël, 1994; Keilis-Borok, 1990; Saleur et al., 1996; Sornette and Sornette, 1990; Sornette and Sammis, 1995; Bowman et al., 1998). It has also been demonstrated that rupture in heterogeneous media is a critical phenomenon (Herrmann and Roux, 1990; Sornette et al., 1992). According to the CP hypothesis, large earthquakes only occur when the fault system is in a critical state, were the term "critical" describes a metastable system balancing at the verge of disorder and characterised by both extreme susceptibility to external factors and strong correlation between its different parts. The critical state and the postulated Self-Organised Criticality (SOC) of the earth's crust (Bak and Tang, 1989; Sornette and Sornette, 1989; Scholz, 1991) describe properties of the crust at different time scales. Critical rupture occurs when the applied force reaches a value, beyond which the fault system moves globally and abruptly, while SOC needs a slow driving force and describes the jerky steady state of the system at large time scales: the critical state of large earthquakes is only a fraction of the long-term condition described by self-organised criticality.

Bowman et al., (1998) provide a thorough conceptual review of the CP earthquake hypothesis, one a fundamental prediction of which is that before it reaches the critical point , a *regional* system of faults goes through a characteristic period of accelerating seismicity. Previous work (Bufe and Varnes, 1993; Bufe et al., 1994; Saleur et al., 1996; Sornette and Sammis, 1995) has attempted to predict the time of the ensuing mainshock by quantifying the accelerating seismic release, while Bowman et al., (1998) have demonstrated the CP concept for Californian seismicity. Varnes (1989) and Bufe and Varnes (1993) have found that seismic release prior to a large event can be described by a power law time-to-failure relation of the form

$$\sum \Omega(t) = K + A(t_c - t)^n \qquad (1)$$

where Ω is any quantity estimated from the earthquake magnitude using an expression of the form $\log\Omega = cM + d$, including earthquake count when c=0, $\sum\Omega$ is the cumulative seismic release as a function of time, t_c is the time of the culminating event, A is negative and $n<1$ of the order of 0.3. K is the value of $\sum\Omega$ when $t=t_c$. These authors justified the law in terms of damage mechanics, but as Sornette and Sammis (1995) point out, a power law increase in the cumulative seismic release can also be expected for heterogeneous materials if the rupture process is analogous to a critical phase transition.

Towards the end of the earthquake cycle, the material surrounding the fault zone of the culminating event experience

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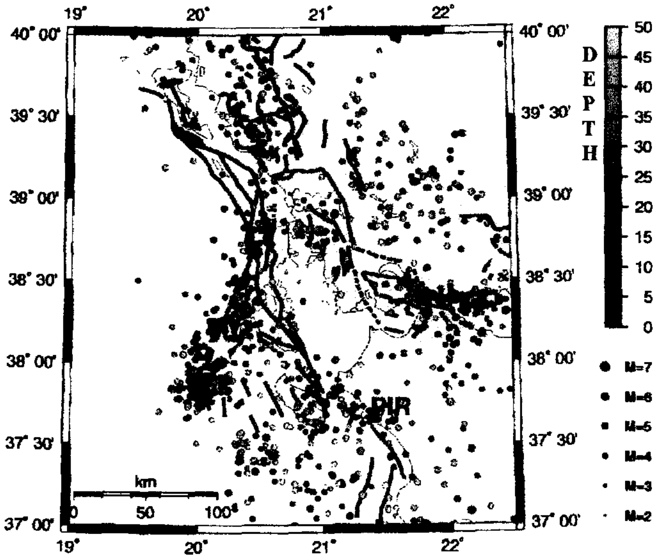

Figure 1. The seismicity of the Ionian region and neighbouring areas during the period 1972.0-1983.0. The white star indicates the epicentre of the 17/1/1983 earthquake. PIR is approximately the location of the station where the postulated ULF electric transient precursor was recorded by Varotsos and Alexopoulos (1984).

dilatancy, pronounced non-linear deformation and gradual loss of load bearing capacity and, finally, failure. The onset of non-linear deformation near the end of the cycle coincides with the commencement of *microfracturing* (micro-crack propagation). The natural interactions between crack populations of different sizes result in rapid stress drop and in a progressively more breciated zone, which forms some incipient macroscopic shear fracture. By the end of this stage stress is determined by friction on the shear zone and strain is caused by an avalanche of fusing cracks leading to irreversible instability and rupture. Rupture can be understood as a co-operative failure occurring at small scale, and cascading from the microscopic to the macroscopic scale (e.g. Sornette and Sornette, 1990). Since the nucleation of rupture is controlled by the volumetric concentration of microcracks and microfaults, the CP is attained when their density reaches some critical threshold value. Thus, the CP earthquake model also predicts the appearance of different scales in the construction of the macroscopic rupture of a large earthquake and an increasing density of microcracks.

Rupture may not nucleate immediately on reaching the CP. For instance, residual friction may prevent its immediate commencement. Alternatively, many patches along and across the fault zone may have attained the CP, but the heterogeneous distribution of stress, (e.g. a barrier), prevents the nucleation of a rupture at the highest level of the crack hierarchy. In both these cases the system has gone through a pre-seismic crack propagation phase and as it is extremely susceptible to external and internal factors, a small additional event may easily tip the balance towards rupture nucleation.

Now, consider that laboratory experiments clearly suggest that microscopic failure (microfracturing) is associated with electrification, i.e. the appearance of spontaneous charge production and transient electric and electromagnetic emission (E-EME) during the opening of microcracks. Some authors have also provided quantitative estimates of charge production rates and currents associated with microfracturing: 10^{-3} C/m^2 are reported by Warwick et al. (1982) from current spikes of individual cracks, 10^{-3} C/m^2 are estimated by Enomoto and Hashimoto (1990) and 10^{-2} C/m^2 are reported by Ogawa et al. (1985). A younger generation of experiments, (e.g. Fiffolt et al., 1993; Chen et al., 1994; Enomoto, et al, 1994; Hadjicontis and Mavromatou, 1996; Yoshida et al., 1997), observe simultaneous Acoustic and E-EME signal, confirming that electrification effects arise during microfracturing. Finally, Bella et al., (1994) observe simultaneous Acoustic and E-EME in field conditions inside caves. Several electrification mechanisms have also been proposed, the simplest being piezoelectricity (Nitsan, 1977; Warwick et al., 1982; Yoshida et al., 1997). Inasmuch as electrification has been observed in non-piezoelectric materials, additional mechanisms may be contact or separation electrification (Ogawa et al., 1985) and the motion of charged dislocations both for the case of elastic rock deformation (Slifkin, 1993; Hadjicontis and Mavromatou, 1996) and for the case of non-elastic deformation, when dislocations move and pileup to form and propagate cracks (Ernst et al., 1993; Vallianatos and Tzanis 1998, 1999a). Cress et al., (1987) also suggest that the ionisation of the void space within the crack and the acceleration of unbounded electrons may intensify charge production.

It follows that the generation of an Electrical Earthquake Precursor (EEP) is probable at the terminal stages of the earthquake cycle, during the crack avalanche stage and concurrently with attaining the CP. This should appear very shortly before the time of the earthquake, the lag between the precursor and rupture being variable, but most probably in the range of hours to days.

The sequence of events described above is a plausible physical context for the explanation of two very different types of precursory effects. It should be noted however, that due to the very different nature of seismic and electromagnetic phenomena, such effects are usually investigated by scientists of different disciplines who have not as yet established a protocol for exchanging ideas and expertise, let alone a common theory to interpret them. The international literature does not contain examples of seismicity and electric or magnetic precursory effects, that may be jointly interpreted in terms of the same physical causes. In a first attempt to fill the gap, we report the case of the M=7.1 earthquake that occurred on 12:41 GMT of 17 January 1983, SW of Kefallinia island (Ionian sea, Greece) at the co-ordinates 38.09°N, 20.19°E (ISC) and focal depth of 9 km (see Baker et al., 1997, for a review). The main shock was preceded by seismicity changes strongly suggestive of a CP system evolving towards instability, as well as a probable electrical precursor appearing 2 days before the earthquake and reported by Varotsos and Alexopoulos (1984). The possible EEP is critically discussed and interpreted in terms of a theory of electric signals due to crack propagation.

2 Seismicity precursors

The seismicity data used in this study are taken from the catalogue of Makropoulos et al., (1989). In effect, this is the ISC catalogue with magnitude m_b converted to M_S, complete and homogeneous for M≥4 as of 1975. However, due to the

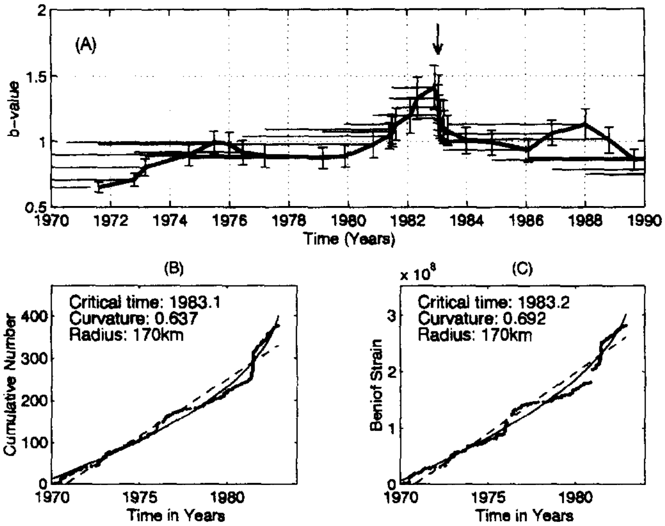

Figure 2. **(a)** The time dependence of b-values in a regional scale. **(b)** illustrates the event count and **(c)** the cumulative Benioff strain, within a radius of 170km around the epicentre of the 17/1/1983 earthquake. In the latter two cases, the continuous solid line represents a power law relation of the form (1) and the best fitting (dashed) straight line the null hypothesis of constant seismic release rate.

high seismicity of the Ionian region where Kefallinia is located, the threshold of completeness and homogeneity for M≥4 recedes to 1972, as verified using both the methods of Stepp (1971) and Habermann, (1983). Herein, we use the entire set of events with focal depth ≤50 km and M≥4, that occurred in the Ionian region and neighbouring areas during the period 1972.0-1983.0; this comprises a total of 1030 events and is illustrated in Fig. 1.

Time dependent b-values. This interesting phenomenon is illustrated in Fig. 2a and was detected with standard weighted LS along a series of time windows comprising the latest 100 events prior to the instant at which a b-value was calculated. The interval spanned by each window is indicated with a thin horizontal line. The changes clearly stand above the 2σ level. They begin by the late months of 1979 and increase almost monotonically until the time of the earthquake, promptly reversing afterwards.

Accelerating seismic release. The measures of seismic release used herein include the cumulative number of earthquakes $\Sigma N(t)$, and cumulative Benioff strain. Benioff strain is defined as $\varepsilon_i(t)=E(t)^{1/2}$ where $E_i(t)$ is the energy of the i^{th} event at time t, calculated after Kanamori and Anderson (1975) as $\log_{10}E_i(t)=4.8+1.5M_S$. The cumulative Benioff strain is, then, $\varepsilon(t)=\sum_{i=1}^{N(t)}\sqrt{E_i(t)}$ where $N(t)$ is the number of events at time t.

The seismic release rates within a radius of 170km around the epicentre of the earthquake are shown in Fig. 2b (cumulative event count) and Fig. 2c (cumulative Benioff strain). Both curves have been modelled with a power law relation of the form (1). The former is best described with the parameters K=442, A=-121.17, n=0.4921 and t_c=1983.1, and the latter by $K=3.43\times10^8$, $A=-8.35\times10^7$, n=0.5398, and t_c=1983.2. Following Bowman et al., (1998), we quantify the performance of the power law fit against the null hypothesis of constant seismic release rate, by defining a curvature parameter

$$C = \text{Power law fit RMS/Linear fit RMS},$$

such that when the data are best described by a power law curve, the RMS error will be small compared to the RMS error of the linear fit and C will also be small. We obtain $C_{N(t)}$=0.637, for the cumulative event count and C_{BS}=0.692 for the Benioff strain. In both cases, the power law model fits the data significantly better than a linear model, indicating that seismic release is indeed accelerating towards the time of the earthquake. The more significant deviation from the linear model becomes apparent by the very late 70's, almost concurrently with the observed increase of the b-value.

A brief discussion. The form of the time dependence observed in the b-values and the power law acceleration of seismic release can be understood in terms of the CP earthquake model. Thus, the low initial b-values and quasi-constant, low seismic release rate, quite possibly indicate a regional fault system functioning with a rough (heterogeneous) distribution of stress, short range stress-stress interaction and therefore localised activity and low seismicity rate. The almost concurrent onset of observable changes in the b-values and seismic release indicates a causal link between the two effects and may signify the onset of the processes causing the system to move towards the CP. The stress field on the regional scale is smoothed by progressively longer range interaction, generating an increasingly larger number of smaller earthquakes; accordingly, the increasing b-values reflect the progressively higher seismicity rate. It should be noted that the acceleration of seismic release becomes evident only a very few years prior to the culminating event and involves only small-intermediate magnitude events; it almost disappears when intermediate-large (M>5) earthquakes are considered. Thus, it appears that the longer stress-stress correlations can be established mainly across faults capable of producing small-intermediate magnitude events, apparently as a consequence of the regional tectonic peculiarities.

3 Electrical precursors.

The electrification of rocks during crack propagation has clearly been demonstrated by experiment. Note however that for common petrogenetic mineral and rock resistivies (ρ) and dielectric permitivities (ε_d), any charge and electromagnetic fluctuations with source dimension $l\approx10^{-4}$-10^{-1} m will disappear after a time $t_e\approx\varepsilon_d\cdot\rho\approx10^{-5}$-$10^{-7}$s (if no external sources are applied). This is comparable to the duration of crack opening t_c of 10^{-4}-10^{-7}s (assuming an opening velocity of 10^{-3}m/s). Charge production inside the crack is quickly destroyed by redistribution of the displacement currents and the current appears only while the crack propagates, vanishing as soon as it reaches its terminal size. If any long-lasting EEP is to be observed, it will have to be generated by the superposition of the signals from all simultaneously propagating cracks and evolve in time just like the crack propagation process. There are several arguments indicating that the electric field generated by individual cracks and/or crack ensembles, is dipole in nature (e.g. Slifkin, 1993; Molchanov and Hayakawa, 1994, 1995; Vallianatos and Tzanis, 1998, 1999a). The feasibility of observing long distance EEP due to crack propagation has been demonstrated by Vallianatos and Tzanis (1998, 1999a).

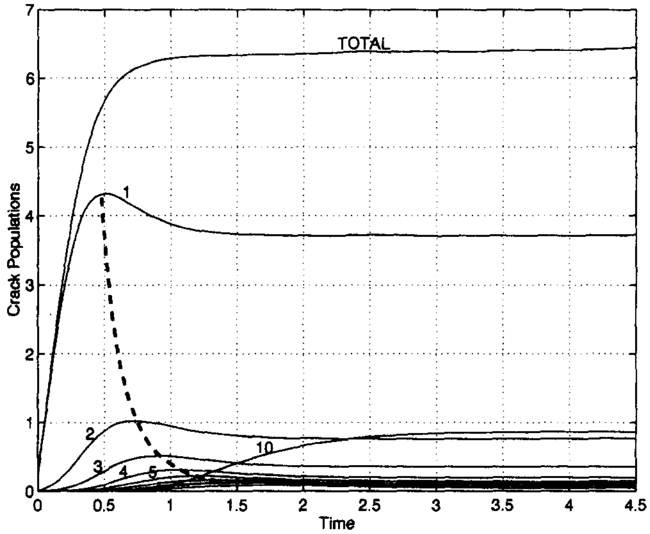

Figure 3a. The evolution of a crack ensemble discretised into ten populations with different sizes, following the kinetic theory of Czechowski, (1995).

Dynamics of crack propagation processes in large crustal volumes. Once crack propagation has began, it will develop with formation of new shear cracks, short and long range interaction between all cracks and as the crack density increases, fusion of smaller neighbouring cracks to form larger fractures of a size increasing according to the fractal law appropriate for the system. The duration of this process will be a function of the pace at which stress and strain evolve in the seismogenic zone and, more specifically, of the rate at which the stress level (hence the crack production rate) declines. Thus, the number of propagating cracks and the resulting electric field are first expected to increase, attain a maximum and then decline to a constant level and zero respectively. This may, conceivably, require any time interval between several seconds and a few hours, depending on the size, mechanical and thermal state of the deforming volume. In the following, we will attempt to construct a phenomenological description of the time function of the EEP source, which must be consistent with the phenomenology of brittle fracture, while accommodating a wide spectrum of permissible signal duration.

Cracks are organised in ensembles of distributed, interacting elements, therefore, a kinetic approach is most appropriate to describe their statistical mechanics and dynamic processes by which they propagate and fuse. This rather difficult problem has been addressed by only a handful of authors (Petrov et al., 1970; Newman and Knopof, 1982, 1983; Czechowski, 1991, 1995). We have found the most complete and comprehensive treatment of crack dynamics in the theory of Czechowski (1991, 1995), which expands on assumptions similar to those of Boltzman's kinetic theory and is based on the relationship

$$f(\mathbf{x}, l + p\upsilon\Delta t, t + \Delta t)\Delta\mathbf{x}\Delta l = f(\mathbf{x}, l, t)\Delta\mathbf{x}\Delta l + \left(\frac{\partial f}{\partial t}\right)_{fus}\Delta\mathbf{x}\Delta l\Delta t + N(l)\Delta\mathbf{x}\Delta l\Delta t \qquad (2)$$

where $f(\mathbf{x},l,t)$ is a size distribution function of cracks defined so, that $f(\mathbf{x},l,t)\ \Delta\mathbf{x}\Delta l$ is the number of cracks which exist at a time t within a volume element $\Delta\mathbf{x}$ around a point $\mathbf{x}$ and have sizes within Δl around size l, p is the probability and υ is the velocity with which cracks may propagate (both functions of an average stress field τ and the size of the crack). Thus, equation (2) describes the changes in the number of cracks within the element $\Delta\mathbf{x}\Delta l$ during Δt as resulting from the fusion of cracks $(\partial f/\partial t)\Delta\mathbf{x}\Delta l\Delta t$ and the nucleation of cracks $N(l)$. The fusion term in turn, describes the balance between 'gains', i.e. cracks changing from any other size to l in Δl, and 'losses', i.e. cracks changing their size from Δl to any other (larger) size : $(\partial f/\partial t)_{fus}=N_{gains}-N_{losses}$. In the limit $\Delta t\to 0$ the complete form of the kinetic equation is :

$$\frac{\partial f(\mathbf{x},l,t)}{\partial t} + \frac{\partial[\upsilon p f(\mathbf{x},l,t)]}{\partial l} = \frac{1}{2}\int_0^l f(\mathbf{x},l_1,t) f(\mathbf{x},l-l_1,t) s\upsilon p\,\mathrm{d}l_1 - f(\mathbf{x},l,t)\int_0^\infty f(\mathbf{x},l_1,t) s\upsilon p\,\mathrm{d}l_1 + N(l) \qquad (3)$$

The term $\upsilon p\partial f/\partial l$ in the right hand side of (3) represents the 'flow' of cracks in their size-space. The first term in the left hand side is the total number of gains, i.e. the number of binary interactions whereby cracks with sizes $l_1<l$ collide and merge with cracks with sizes $l-l_1$ to produce cracks with sizes l, and $s=s(l, l_1, \tau)$ is the cross section of collisions. The factor ½ prevents from counting a fusion twice. The second term in the left hand side is the number of losses, i.e. the number of binary interactions whereby cracks of any sizes l_1 forming a beam with flux density $\mathrm{d}I = \upsilon p f(\mathbf{x}, l, t)\mathrm{d}l_1$, collide with crack l and consume it. The kinetic equation describes how cracks propagate and join with probability depending on the total cross-section of collisions between cracks. The quantities s, υ, and p may be functions of the size of cracks, stress field and properties of the rock. We are particularly interested in an analysis which discretizes (3) in the size-space of cracks, according to

$$n_i(t) = \int_{L_{i-1}}^{L_i} f(l,t)\,\mathrm{d}l$$

so that the total number of cracks is divided into m populations n_i, i=1,2,…,m with respect to their size, in which case the integro-differential equation (3) reduces to a set of coupled, ordinary differential equations (Czechowski, 1991). The case m=10 has been studied in Czechowski (1995), subject to the constraints $0=L_0<L_1<\ldots<L_9<L_{10}=\infty$ and $L_i - L_{i-1}=1$ for i=1,2,…,9. Successive integrations of (3) over the intervals $(0,L_1]$, $(0,L_2]$, …, (L_9,∞), produce a set of coupled, ordinary differential equations describing the balance of gains and losses of any given group of cracks by fusion and by propagation. Assuming a constant production rate for the smallest crack population, in Fig. 3a we essentially reproduce the result of Czechowski (1995, figure 11.7.2a), but we also draw the total number of cracks propagating at any time. Observe that the successive crack population n_i appears with respect to n_{i-1} with a time delay t_d which follows some power law (dashed line) such, that the superposition of the successive populations n_1, n_2, n_3,…n_9 will produce a graph exhibiting sharp onset and saturation as early as possible. The shape of such a time function (the source

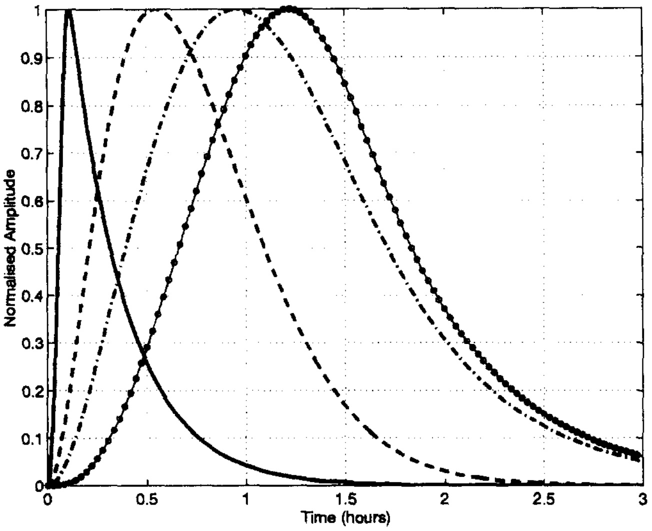

Figure 3b. Normalised time functions that may describe the evolution of the number of propagating cracks, for different parameters of Eq. 4. Solid line, $A=0.3\times10^{-2}$, $\beta=2$, $\alpha=-10^{-3}$; dashed line, $A=0.2\times10^{-3}$, $\beta=2$, $\alpha=-10^{-3}$; dash-dot, $A=0.2\times10^{-3}$, $\beta=2$, $\alpha=5\times10^{-4}$; open circles, $A=0.2\times10^{-3}$, $\beta=3$, $\alpha=5\times10^{-3}$. In all cases $\gamma=1$.

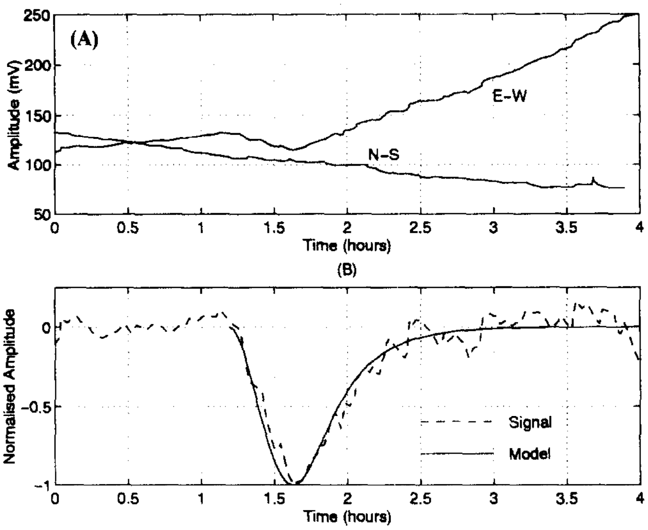

Figure 4. (a) The digitised signal recorded on 14:00 GMT of 15 January 1983 at Pyrgos, Greece, and reported by Varotsos and Alexopoulos (1984) as a precursor to the 17 January 1983 Kefallinia earthquake ($\Delta\approx120$km). **(b)** A model of the normalised long period E-W component of the signal, produced with equation 4 (after removing the background trend).

rise time) can be approximated with a half step function such as is the error function (for $t>0$) or the incomplete gamma function. Now, consider that in the pre-seismic case, if crack propagation does not cascade immediately to rupture, one should rather assume that as the deforming rock approaches its capacity of sustainable crack density, the process will decelerate and will stop when all possible cracks have been created and correlated at all lengths. The system will then have entered a metastable (CP) phase where rupture is imminent. Based on an ensemble of observational data such as will be shown shortly, we assume an exponential decay of crack production. Then, a complete time function describing the rise and decay of crack propagation processes could be given by

$$n(t) = \mathrm{erf}\left((At)^{\beta}\right)e^{-(\alpha t)^{\gamma}}\,u(t) \qquad (4)$$

where $u(t)$ is the Heaviside step function with $u(t)=1$ for $t>0$ and $u(t)=0$ for $t\leq0$. The constant β determines the slope of the rise time and A is a characteristic time of the crack production processes; they both should depend on material properties. Likewise, α is a characteristic relaxation time and the exponent γ determines the quickness of the decay. Examples of source time functions for different rise and relaxation time constants are shown in Fig. 3b.

The received electric signal : It is quite apparent that the electric signal generated by the electrification process accompanying microfracturing will be the convolution of the complete source time function and the waveforms of the entire ensemble of the simultaneously electrified cracks, which we denote as $\mathbf{E}_c(t)$. The time constant of $\mathbf{E}_c(t)$ is of the order of $t_c \sim 10^{-7}$ -10^{-4} s. Thus, $\mathbf{E}_c(t)$ may be approximated by a Dirac-δ type of function, with flat spectrum up to a corner frequency in the KHz-MHz range. It is therefore expected that when the source time function is much slower, i.e. with duration falling in the Hz-mHz range, its waveform will predominate and will determine the waveform of the resulting EEP. It follows that although several mechanisms may be involved in the electrification process of individual cracks, the *shape* of the eventual transient EEP signal will show minimal dependence on the particular mechanism. In consequence, only the long periods of the generated electric field are usually allowed to propagate.

A possible EEP to the 17/1/1983 Kefallinia earthquake. Varotsos and Alexopoulos (1984) claim to have recorded an electrical precursor to this earthquake, (SES in their terminology), which they illustrate in figure 7 of *their* paper. It comprises a long period signal beginning on approximately 14:00 of 15 January 1983, with a duration of 1½ - 2 hours and an bay-like shape, recorded at their PIR station, approximately 130 km SE of the epicentre (see Fig. 1). We have reproduced a digital version of the longer periods of the signal by scanning their figure 7, processing the image to enhance curvilinear features and digitising it on a high resolution monitor.

The digitised raw signal is shown in Fig. 4a. It comprises a transient superimposed on a very long period non-linear variation of the background. On removing the background variation, we obtain a very strong E-W component (25mV over 50m), but very weak N-S (below noise level). The E-W waveform (Fig. 4b) is asymmetric in shape, with faster rise time and a slower, exponential type decay, with total -duration no longer than 2 hours. The main part of the signal stands clearly above noise, the peak amplitude of which is approximately 20% of the peak signal amplitude. The later times of the signal, however, are obscured and there's no way of telling the shape or duration of the decay phase. The long period E-W components can be easily fitted with a function of the form (4). Since we do not have, as yet, any means for estimating the amplitude, we may only attempt to fit the signal and the model normalised with respect to their maximum values. In Fig. 4 we present a model with $\gamma=1$ and parameters $A\approx5.3\times10^{-4}$, $\beta\approx2.1$ and $\alpha\approx9.9\times10^{-4}$. Note that $2\pi/\alpha\approx6300$s (1.75 hours), which is approximately the duration of the model.

It is important to note that this signal belongs to the ensemble of anomalous transients used by Varotsos and Alexopoulos (1984) in the derivation of their amplitude - magnitude scaling law of the form $\log(\Delta V)=cM+d$, with $c=0.3$-0.4 and d different for different seismic regions, earthquake sequences and source-receiver paths. These authors attribute the almost universal slope to fundamental processes at the source, but cannot explain it. This was attempted by Sornette and Sornette (1990), on the basis of the CP earthquake model, long range correlation between the source and the observer and piezoelectricity as the fundamental electrification process. Vallianatos and Tzanis (1999b) have shown theoretically, that this type of scaling law and universal slope is to be expected from a fractal distribution of electric field emitters, and, moreover, in the case of dynamic crack propagation. Such characteristics are not likely to have been generated by anthropogenic noise and indicate that this signal may be a real EEP.

4 Discussion

The Critical Point earthquake model is a relatively new development in the understanding of the earthquake preparation process. Within the context of a Self-Organised Critical crust, it incorporates the inherent non-linearity of the Earth system, making specific predictions about the evolution of a fault network towards rupture. These include a crack propagation avalanche immediately prior to failure, involving spontaneous charge and electric field generation, by processes that have only recently began to be explored. Thus, the CP earthquake model provides a neat theoretical framework to account for such diverse kinds of precursory phenomena as are changes in the seismicity pattern and transient ULF electric events. Conversely, the observation of diverse phenomena that can be jointly considered under the same causative context and are consistent with theoretical predictions, leads to a robust set of complementary evidence, which can be telltale of an earthquake in preparation. We believe that such a complementary and robust set of precursors exists in the case of the 17/1/1983 Kefallinia Earthquake.

Recently, it has been suggested by several authors, (e.g. Geller et al., 1997; Leary, 1997 and others), that earthquakes cannot be predicted and precursors do not even exist because *"the Earth is in a state of self-organised criticality, where any small event has some probability of cascading into a large event"*. Bowman et al., (1998, p24365) have refuted such statements on the basis of the CP earthquake model. We simply note that the example of the 17/1/1983 Kefallinia earthquake is unique in demonstrating the possibility of obtaining deterministic signatures from a self-organised critical crust, in the literal sense of the notion (effects are determined by causes).

However, it should also be noted that although the theoretical framework discussed herein is plausible and testable, it is still incomplete. There exist several examples of precursory seismicity changes fitting the CP earthquake model around the world, but it is not as yet clear whether all major earthquakes comprise critical point processes and much effort is still needed before any definite conclusions can be drawn. An additional difficulty is that well constrained EEP signals such as presented in Section 3 are relatively rare in the literature. One major reason for this shortage could be the possibility that an electric signal is not always be generated during crack propagation, or it may be to weak to detect. For example, consider that if rock resistivity is low, the time constant of charge redistribution is much faster than crack opening times (for instance, $t_c \approx 10^{-9}$s when ρ=100Ωm); in this case there's simply no time for an observable macroscopic field to build up. Such problems make clear that a great deal of work and development is required, before one can claim a comprehensive theory of the earthquake preparation process.

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