4.1. *Local* versus *remote EEP generation*

The 'local EEP' school appeared at a time when the only verified electrification mechanisms were piezoelectricity and the EK effect, with the latter only producing weak electric fields, undetectable at long distances. Dobrovolsky *et al.* (1989) calculated the bulk strain before an earthquake, based on the model of rigid inclusion and theorised that precursory stress/strain propagation from the earthquake zone may generate a pressure gradient and a local electrokinetic field. Gershenzon and Gohberg (1993) advanced this idea on the basis of field data analysis. A very different line of arguments results from signal propagation studies (*e.g.*, Bernard, 1992; Honkura and Kuwata, 1993), source models and the analysis of field data (*e.g.*, Bernard and Le Mouël, 1996; Bernard *et al.*, 1997). On the basis of numerical models with simple dipole sources and without due consideration of EEP source physics, Honkura and Kuwata (1993) concluded that it is impossible to obtain a reasonable field amplitude without unreasonably powerful sources (in excess of 10^5 Am). Using such results as additional arguments and rejecting piezoelectricity and other solid state mechanisms, Bernard (1992) considered the EK effect as the only viable explanation of EEP (if any) and investigated the long range detectability of electrokinetic fields from kilometric length current filaments due to fluid flowing in narrow elongate conduits. He also concluded that this source is unlikely to give detectable EEP, even when he tried to focus the electric field with combinations of conductive and resistive layers, unless there was a local amplification mechanism of a hundredfold at least. Bernard (1992) also rejected the idea of EK currents driven directly by stress propagation from the source and provided calculations to demonstrate that this would be implausible. To remedy the situation, he proposed that precursory stress/strain propagation might destabilise small scale, metastable reservoirs, thus producing local fluid flow and electrokinetic potentials. This idea was further pursued by Bernard and co-workers, but does have an inherent disadvantage in requiring the ubiquitous presence of reservoirs at the verge of instability, without convincingly justifying why. The local EEP generation hypothesis neatly circumvents the 'selectivity' problem (see Section 4.2) and in one case, it has also been discussed in association with piezoelectricity (Sornette and Sornette, 1990).

The 'remote EEP' school accepts that the EEP is generated at the earthquake preparation zone and propagates as a transient field. The majority of the source models consider the EEP to be a macroscopic effect resulting from the superposition of many simultaneous small emitters. With very few exceptions (*e.g.*, Surkov, 1999), the source models presuppose some alignment of the individual emitters, so that they may interfere constructively. This cardinal prerequisite is extrapolated from small scale laboratory evidence, or is theoretically reasoned, but has not been conclusively documented for large rock volumes (also see Section 2). Several theoretical accounts of the plausibility and feasibility of long range fields *without* special earth structure, were given by Slifkin (1993), Mochanov and Hayakawa (1994, 1998), Vallianatos and Tzanis (1998, 1999a,b), Molchanov (1999), Surkov (1999) and Tzanis *et al.* (2000b). Analytical and numerical models attempting to demonstrate the feasibility of long range EEP *with* special earth structure, were presented by Sumitomo (1994), Varotsos *et al.* (1998) and Sarlis *et al.* (1999). These are all related to the 'selectivity' concept of VAN and will be discussed in Section 4.2, together with a number of related qualitative ideas.

At any rate, it is straightforward to demonstrate that the superposition of many tiny, distributed, quasi-aligned, simultaneous electric sources (cracks) can be a very efficient EEP generator. As an example, we calculate the expected electric field, due to a fractally distributed set of emitters. Figure 2a illustrates a horizontal section of a simulated 'fault zone' with dimensions 5×1.5 km, comprising an ensemble of cells, each $50 \times 15 \times 50$ m ($= 37\,500$ m^3). This is located at a distance of 50 km to the ENE of the observation point and the Earth is a half-space with resistivity of 100 $\Omega \cdot$m. Microfracturing has percolated parallel to the long axis of the ensemble, representing the strike of the incipient fault. The vertical dimension of the ex-

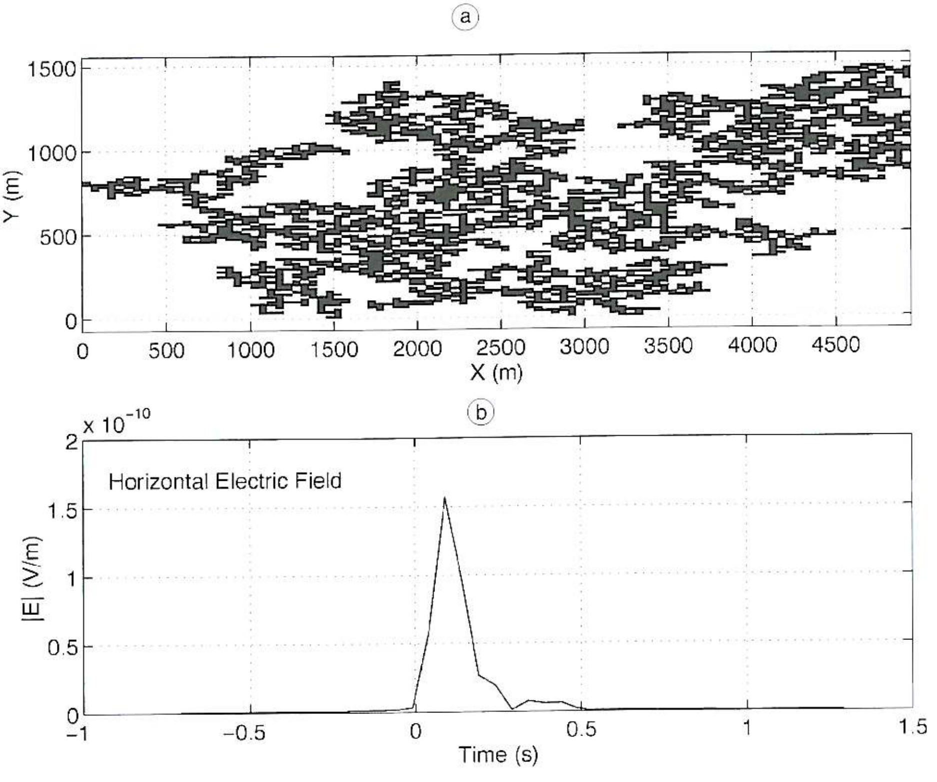

Fig. 2a,b. a) A horizontal slab model of a 5 × 1.5 × 2 km 'fault zone' comprising an ensemble of 100 × 100 × 40 cells, each with dimensions 50 × 15 × 50 m. Microfracturing has already reached the percolation threshold, parallel to strike. The structure is located 50 km ENE of the observer and the Earth is a half-space with $\rho = 100\ \Omega\cdot$m. b) The transient variation of the received horizontal electric field due to the instantaneous electrification of the structure in fig. 2a.

cited volume comprises a stack of 40 identical slices buried between 9-11 km. Electrification in each cell is represented by a horizontal electric dipole of current moment 10^{-6} Am, located at its centre of gravity. We have adopted this value based on laboratory measurements of average currents from individual cracks (*e.g.*, Warwick *et al.*, 1982), assuming a mean crack length of $l_c = 10^{-3}$ m. We suppose that the cells do not emit in perfect unison, but with a small advance or delay with respect to each other, simulated with a random perturbation of the phase of each emitter (cell) sampled from the interval [– 45°, 45°]. At this point, we assume that the time constant of the electrification process is of the order of $t_c = 10^{-6}$s, *i.e.* comparable to the opening time of cracks with $l_c = 10^{-3}$ m: the entire ensemble emits quasi-instantaneously, with a short Dirac-δ time function. The field is calculated using the complete analytic solution of King *et al.* (1992, pp. 155-159). Figure 2b shows the resulting transient variation with amplitude at peak, approx. 1.5×10^{-10} V/m. This result was obtained by the superposition of approx. 1.2×10^5 individual dipoles, each representing a cell of 37500 m^3 in volume. It follows that it is sufficient to have one 10^{-6} Am dipole per m^3 to obtain a variation of 5.6 mV/km at a distance of 50 km from the focus. The plausibility and possibility of much stronger fields is therefore apparent, when the source (crack) density increases, or the resistivity of the medium increases by a mere order of magnitude.

Source modelling should not be limited to feasibility studies, but should also aim at the prediction of the expected EEP signals properties (signal modelling). This, in turn, may allow the identification of true EEP and help to resolve the local or remote EEP conundrum. Work on this important topic is still early, but progress has been made and is reviewed below.

Gershenzon *et al.* (1989), Molchanov and Hayakawa (1994, 1998), Fenoglio *et al.* (1995), Patella *et al.* (1997) and Tzanis *et al.* (2000a,b) explored the conditions at the terminal stages of the earthquake cycle, during, or immediately following massive (micro)fracturing and dilatancy. It is apparent that independently of the electrification mechanism, any EEP signal generated during crack propagation will be determined by the properties of the microfracturing process. The work of Patella *et al.* (1997) indicates that electrokinetic fields due to the DDP process are at the noise level, a few tens of kilometers away from the source. The other authors assumed microfracturing electrification due to solid state mechanisms and developed intrinsically evolutionary models of the microfracturing processes from first principles. The model of Gershenzon *et al.* (1989) is partially relevant to the EEP case, but it still comprises one of the first poised attempts to develop a consistent theory of the source: they considered a model of cracking at the near surface parts of the seismogenic zone with a hierarchical, self-similar block structure. Molchanov and Hayakawa (1994) made a remarkable attempt to simulate the evolution of microfracturing and hence the spectrum of ULF precursors to the 8/8/1993, $M_s = 8$ Guam earthquake. Their model requires an increase in the nucleation of new cracks until, after a critical density, the production of new cracks declines while existing cracks grow by extension of their lengths in a non-linear fashion. Molchanov and Hayakawa (1998) presented an improved version, in which cracks are normally distributed in their size-space and undergo multistage redistribution with size development according to a sub-critical stress corrosion process. This model offers a reasonable description of the source spectrum shape, but is restrictive because it does not allow for the interaction and simultaneous evolution of hierarchical crack populations, which is intrinsic to microfracturing processes.

The approach of Tzanis *et al.* (2000a,b) accommodates these properties. On the premise that cracks are organised in ensembles of distributed, interacting elements, they argue that the dynamics of large scale microfracturing should rather be described by a kinetic approach and utilise the kinetic theory of Czechowski (1991, 1995). The model assumes that at any given level of the crack hierarchy, there is dynamic balance between the number of cracks introduced by the nucleation of new cracks and the fusion (mergence) of smaller cracks, and the number of cracks educed by fusing and changing to another larger size. Such multiple coupling across the crack hierarchy yields crack production rates exhibiting strong acceleration and clustering at the early times of the process, followed by rapid (exponential) decay. Their shape can be described with a generic time function of the form

$$\dot{n}(t) = dn(t)/dt = N_0 \gamma \alpha^{\gamma} t^{\gamma-1} e^{-(\alpha t)^{\gamma}} \qquad (4.1)$$

(in reality a Weibull probability density function), or an empirical time function such as

$$\dot{n}(t) = \mathrm{erf}\,((At)^{\beta}) e^{-(\alpha t)^{\gamma}} u(t), \qquad (4.2)$$

where $u(t)$ is the Heaviside step function with $u(t) = 1$ for $t > 0$ and $u(t) = 0$ for $t \leq 0$ assuring causality. Examples of (4.2) for different parameters A, α and β are shown in fig. 3. By virtue of eq. (2.3), the observed macroscopic electric signal will be $\bar{E}(\boldsymbol{r}, t) = \dot{n}(t) * E(\boldsymbol{r}, t)$. Since the time constant of $E(\boldsymbol{r}, t)$ is of the order of 10^{-7}-10^{-4} s, 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. For an example, consider the SES claimed by Varotsos and Alexopoulos (1984a) to have preceded the M 7.1 Kefallinia, Greece, earthquake of 17 January 1983, which was recorded at their PIR station, approximately 130 km SE of the epicentre. It comprises a transient begin-

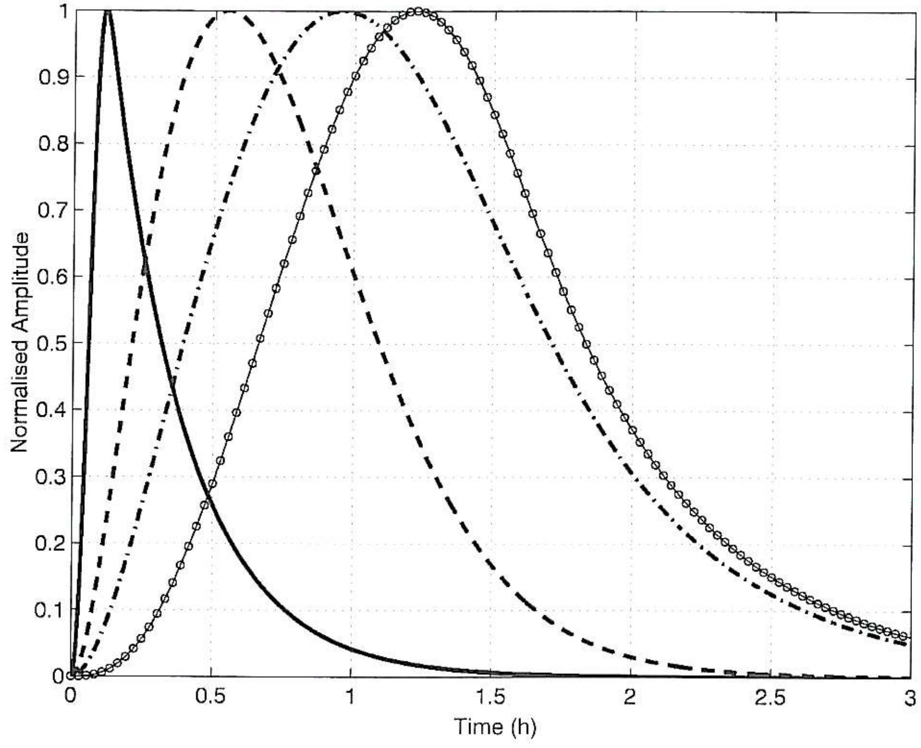

Fig. 3. Normalised time functions that may describe the evolution of the number of propagating cracks, for different parameters of eq. (4.2). Solid line: $A = 0.3 \times 10^{-2}$, $\beta = 2$, $\alpha = -10^{-3}$; dashed line: $A = 0.2 \times 10^{-3}$, $\beta = 2$, $\alpha = -10^{-3}$; dash-dot: $A = 0.2 \times 10^{-3}$, $\beta = 2$, $\alpha = 5 \times 10^{-4}$; open circles: $A = 0.2 \times 10^{-3}$, $\beta = 3$, $\alpha = 5 \times 10^{-3}$. In all cases $\gamma = 1$.

ning on approximately 14:00 of 15 January 1983 and lasting for 1½-2 h, superimposed on a very long period non-linear variation of the background (fig. 4a). On removing the background, one obtains a strong E-W component of 25 mV over 50 m, with an asymmetric bay-like shape (fig. 4b), but very weak N-S variation. A model of the normalised signal based on eq. (4.2) is also shown in fig. 4b, with $\gamma = 1$, $A \approx 5.3 \times 10^{-4}$, $\beta \approx 2.1$ and $\alpha \approx 9.9 \times 10^{-4}$. This signal belongs to the small ensemble of transients used by Varotsos and Alexopoulos (1984a) to construct their amplitude-magnitude empirical scaling law. A number of authors have independently argued, or shown, that this law derives from the fundamental fractal scaling of the electric field sources (Sornette and Sornette, 1990; Molchanov, 1999; Vallianatos and Tzanis, 1999b); such properties are not likely to have been generated by anthropogenic noise and indicate that this signal may be a real, long range EEP. It is apparent that albeit with crude models still requiring rigorous development and verification, certain classes of observed signals can indeed be described with generic theories of the source, which is more than could be claimed a very few years ago.

All the above studies assume that the EEP signal propagates in the crust. Huang and Ikeya (1998), however, considered propagation in the Earth-Ionosphere waveguide and demonstrated the feasibility of long range signals in the VLF-ELF bands with an analogue model that included a thin sheet conductor with irregular perimeter representing the sea. These results enhance the credibility of field observations in the

VLF-ELF band (*e.g.*, Fujinawa and Takahashi, 1998). The experiment could not scale down to the ULF band where transient EEP are expected, but only through theoretical extrapolation of the VLF results. Nevertheless, the authors interpreted transient EEP as the electric field of EM waves at ULF, as observed at the surface of the Earth. Interestingly enough, they observed a complex pattern of bright spots and shadows, with which they explain 'selectivity' (see below).

4.2. *'Selectivity'*

Related to the discussion above and a major incentive in begetting the 'local EEP' school, is the 'selectivity' concept of VAN. From the earlier days of their research, VAN claimed that in many cases, SES from a given source could be observed at a given station, but not at a nearby one (in the worst case example, the station farthest from the epicentre would 'feel' the EEP but the station nearest would not). In VAN's interpretation, there should be some mechanism 'deciding' which signal from which source will be observed at which destination. Selectivity was accordingly defined to be *«the sensitivity of a station to signals from a restricted number of seismic areas»* (Varotsos and Lazaridou, 1991), resulting from the co-operative effect of local geoelectric peculiarities that may block or enhance electric signals and/or regional structure comprising a network of narrow conductive channels (approx. 1000 m across), embedded in an insulating matrix and linked by other conductive channels to the surface (*e.g.*, Varotsos *et al.*, 1993, 1998; Sarlis *et al.*, 1999). VAN defined

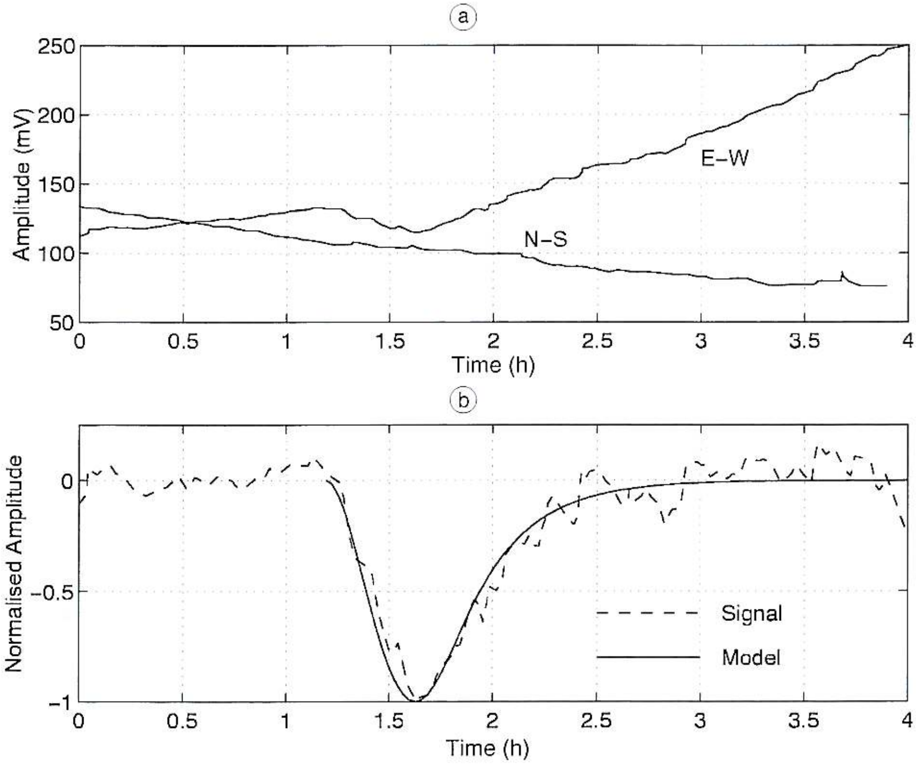

Fig. 4a,b. a) The digitised signal recorded on 14:00 GMT of 15 January 1983 at Pyrgos, Greece, and reported by Varotsos and Alexopoulos (1984) as a precursor to the 17 January 1983 Kefallinia earthquake ($\Delta \approx 120$ km). b) A model of the normalised long period E-W component of the signal, produced with eq. (4.2).

several 'observed characteristics' of selectivity (*e.g.*, Varotsos and Lazaridou, 1991; Varotsos *et al.*, 1993) and concluded that the careful compilation of a 'selectivity map' for each observation site is a fundamental prerequisite in determining the epicentral area of the impending event. The influence of *local* structure is *expected* (though not always easy to assess), but the concept of energy guided through an intricate network of tubular structures cannot be substantiated and provokes considerable criticism. One should also note the peculiar tendency of these channels to outcrop at the military installations, where VAN stations had been placed.

At the outset, and while not understanding the fundamental physics of the EEP signal, it should have appeared at least premature to speculate about preferential terrestrial propagation in special Earth structure. For instance, the inherent spatial properties of bipole or dipole fields may bar the signal from some inappropriately located stations, while Huang and Ikeya (1998) obtain analogous phenomena by means of propagation in a complicated Earth-Ionosphere waveguide. The VAN concept of terrestrial selectivity is not required to account for such effects. Nevertheless, an apparently compelling need to explain the 'observations' has led many authors to adopt it as a real phenomenon and contrive a number of alternative signal propagation paradigms. Just to mention a few, Lazarus (1993) requires the signal to propagate preferentially through regions of high dielectric constant (*e.g.*, pure water), linking 'preferred' epicentres and 'sensitive' regions, but he does not explain how these subterranean 'rivers' form, or why the field is not attenuated by the conductive crustal fluids. Utada (1993) favours the existence of planar conductive electric field guides, linking the earthquake epicentre with the observer; the field may be enhanced by near surface resistivity inhomogeneities of these planar features by galvanic effects. A numerical simulation of the concept was presented by Sumitomo (1994), but neither author specifies the geological nature of these (very long) continuous features which are not always active faults, given that sometimes the relative location between the earthquake epicentres and VAN observation sites in Greece is inconsistent with modern active tectonics (*e.g.*, the Kalamata region and Keratea station). In a final example, Hadjicontis and Mavromatou (1996) explain selectivity in terms of particular circuits between the source and the observer, involving conduction and displacement currents.

4.3. *Discussion and comments*

The concept of local electrokinetic EEP generation was developed on the premise that long range electric fields are implausible because they require unreasonably powerful sources, focusing of the electromagnetic energy at the sensitive sites with peculiar propagation paths and local amplification. The apparent absence of a magnetic field has been an additional argument. However, the plausibility of remote interaction with the earthquake source has not been fully appraised. The two main proponents of the concept (Bernard, 1992; Dobrovolsky *et al.*, 1999) disagree whether it is possible to have remote triggering of EK effects by direct stress/strain propagation, with the first author presenting a strong case against the idea, even though his own remedy (metastable reservoirs) is hardly testable. Of course, local EEP phenomena are expectable in the neighbourhood of the earthquake zone. Varotsos *et al.* (1993) provided a set of arguments against the local EEP concept, all deriving from VAN's experience with 'SES' type signals, supposedly recorded at the far field of the source. In part, these arguments are not consistent with observations (see Park, 1996, p. 499) and in terms of EEP physics, they can only be as good as the measurements on which they were based. At any rate, and barring problematic explanations involving selectivity and special propagation paths, it is difficult to deny the possibility of remote EEP. We know perfectly well that electric fields from anthropogenic or natural sources are clearly observable at long distances, as demonstrated by the references cited in Section 3 and also by the *ad hoc* experiments of Park and Fitterman (1990). If noise and artificial signals can propagate far enough, why not a natural EEP? It must also be noted that an efficient source (*i.e.* one generating a long range signal) is not necessarily a source of high current density or current moment, as assumed by Bernard (1992) or Honkura and Kuwata (1993). This has clearly been demonstrated in Section 4.1. The arguments and counter-arguments above do not answer whether one of the concepts is right or wrong, because the scientific knowledge required for decisive inference is still incomplete. It is also conceivable that there may be circumstances under which either local, or remote, or both types of EEP signals appear. We do emphasise, however, that the main arguments against remote EEP generation (implausibility of long range fields) are untenable.

5. Of things that mystify: lead times to earthquakes and statistical analysis

A factor of such outstanding importance as is the time lag between the EEP and the impending earthquake, is still a grey area, owing to the poorly understood physics of the source. The suspected or certain EEP phenomena presented in non-VAN international literature are reported to appear from months to minutes before the earthquake, but there is no hard evidence associating certain types of EEP signals with certain lead time windows. A possible exception is the case of VLF noise bursts which, according to the literature cited in Section 3, almost consistently appear a few to several days (but always less that two weeks) prior to the earthquake.

VAN is again the exception. For instance, according to Varotsos and Lazaridou (1991), the lead time is independent of earthquake magnitude and single SES exhibit a time lag between 7 h and 11 days, while «*small values of* [lead time] Δt*, of the order of 10 h, are usually related to aftershocks*». SES activity is more complicated because «*although the onset of electrical and seismic activity does not usually exceed 11 days, the time lag between the largest SES and the strongest earthquake may, however, be much longer, e.g. around 22 days*». The gradual variations of the electric field have a lead time of the order of 1 month (Varotsos *et al.*, 1996a). In addition to these signals, VAN's early work came up with 'short duration electric signals' 1-4 min prior to earthquakes, which in fact motivated their entire research effort, but were not further investigated (see Varotsos *et al.*, 1993, for a brief account).

Lead time considerations were at the heart of all the predictions issued by VAN. We re-iterate that all these observations were made on the basis of presumed but not proven EEP signals and were therefore susceptible to error. In the absence of additional physical constraints, they allow for too flexible a time window between the 'signal' and the earthquake, leading to liberal prediction statements of the general type «*... a time period of at least 3 weeks is elapsed between the initiation of SES activity and the occurrence of strong EQ (small shocks may start earlier). The strongest EQ usually occurs during the fourth week; otherwise smaller EQ(s) with magnitude around 5-units appear during this week and the strongest EQ occurs after an additional period of 2-3 weeks. The latter behaviour, seen for the first time in 1988* [the well advertised case of the 16/10/1988 $M_s = 6.0$ Pirgos earthquake] *has the advantage that the epicentre of the strongest EQ becomes known with good accuracy as it will lie in the vicinity of the preceding smaller EQ(s) which occurred a few weeks earlier*» (Varotsos *et al.*, 1996a, p. 35). This kind of 'prediction' has often caused considerable public concern, the culminating example being the anguish of the Athenians (Greece), after the 'prediction' of the large event which was supposed to occur in the Atalanti fault area, 70 km north of the city, right after the destructive 7/9/1999, *M* 5.9 earthquake (Varotsos *et al.*, 1999c).

Until comprehensive models of the EEP source are developed, only educated guesses of the lead times can be made. For instance, it would appear warranted to expect transient signals due to large scale microfracturing at the very terminal stages of the earthquake cycle, (hours to days prior to rupture), when greatly accelerated non-elastic deformation is expected by all theories and models of the earthquake source, as well as the corroborating laboratory and field evidence. Given also the non-linear nature of the seismogenetic processes, another good educated guess is that lead time data will probably not allow precise statements of the form «an earthquake will occur at exactly *X* time units after observing the *Y* type of EEP».

Rather, one should expect that in the future, electrical (and other) precursory signals may be conclusively identified on the basis of their properties, so that preparation and mitigation measures can be taken and vigilance exercised.

In the grand theme of EEP research, statistics was used as a tool of inference only for VAN predictions in Greece, since this is the only case that several 'official' predictions have been made and documented. The earlier method followed by VAN was to exchange telegrams between members of the team when a 'SES' was observed. At later times, telegrams or faxes were also dispatched to a number of institutions outside Greece. Following some earthquake to which the SES was attributed, the telegrams were produced as evidence of success. Subsequently, and in spite of the many physical uncertainties, statistics was used to validate the predictions, in the sense of establishing an *a posteriori* 'beyond chance' association between the presumed SES signals and the earthquakes with which they have been associated. This resulted in a long stream of papers including critical reviews of VAN methods and procedures (*e.g.*, Drakopoulos *et al.*, 1993 and Geller, 1996), and statistical appraisals that eventually led to the intense debate and controversy appearing in the Special Issue *Debate on «VAN», Geophys. Res. Lett.*, **23** (11), of May 1996, partly repeated in Sir J. Lighthill (ed.), «*A critical review of VAN*», World Scientific, Singapore.

In addition to VAN's own work, some results indicated that the method does significantly better than chance (*e.g.*, Hamada, 1993; Shnirman *et al.*, 1993; Nishizawa *et al.*, 1994; Aceves *et al.*, 1996, etc.), while many others concluded to exactly the opposite (Mulargia and Gasperini, 1992; Wyss and Allmann, 1996; Kagan, 1996; Rhoades and Evison, 1996; Burton, 1996, etc.). To a certain degree, the differences resulted from the different definitions of success adopted by different researchers. For instance, one definition of success may be the number of successful predictions divided by the total number of predictions. Alternatively, it may be the total number of successful predictions divided by the total number of earthquakes above a magnitude threshold. Clearly, the former (optimistic) definition is favourable, because it *presumes* that out of a (selectable) subset of the total number of earthquakes, some predictions have actually been made and some are false. Conversely, the latter definition is unfavourable because it *presumes* (without justification) that *all* earthquakes should have been predicted. The definition of success also depends on the lead time between the precursor and the earthquake and, more importantly, on the allowable error in time, which cannot be defined objectively and changes for different authors. Additional problems may arise from inaccuracies in the seismicity and magnitude data used by different authors (see Geller, 1996, for a thorough documentation). There have also been considerable differences in accounting for the inhomogeneous distribution of earthquakes in space and time and the statistical model describing it.

In the absence of definitive physical constraints (*i.e.* the rules of the game), it is difficult to apply methods of statistical inference in a rigorous and objective manner. Thus, different authors can formulate different approaches for testing different null hypotheses with contradictory conclusions. In such cases, however, the line between objective and subjective judgement is very thin and can easily be crossed, though unintentionally, if personal opinion or predisposition set in and the demand for scientific rigour and independent validation of the data is relaxed. Accordingly, models can be tuned to deliver the most suitable answer, sometimes regardless of intuition or physical validity. As Rhoades and Evison (1996) succinctly and perceptively pointed out «*objective tests on the performance of the [VAN] method, using independent data, cannot begin until the VAN hypothesis and the proposed null hypothesis have been fully formulated*». This is precisely the point we try to make herein, albeit for the general case of EEP phenomena.

6. Of local effects and stranger things

The vast majority of studies on electrical precursory phenomena considered the EEP to be large scale variation of an electric field, much greater than the span of the measuring system.

Other studies, however, reported effects of much shorter scale. For instance, Morat and Le Mouël (1992) reported signals higher than 0.05 V/m over dipole lengths of 1 m in partially saturated limestone rocks, lasting for hours to days and correlated with variations of the atmospheric pressure. Morat and Le Mouël (1994) also reported potentials of similar amplitudes and biogenic origin, due to sap circulation in trees. These authors ponder the question of whether such self-potentials may complicate the correlation of electric signals with tectonic events. In another well documented case, Miyakoshi (1986) described an anomalous electric field variation which he ascribed to a nearby (Δ = 3 km, H = 17 km) intermediate size earthquake (M = 5.6). Potential differences were monitored on two short parallel dipoles with one common electrode. The shorter dipole (~ 20 m long) terminated inside the fault zone, while the longer (~ 30 m long) traversed the fault. Clear time dependent changes were observed only in the shorter dipole for approximately two months, culminating just prior to the earthquake. These changes cannot be attributed to an electric field from a source at any appreciable distance, otherwise they should have been observed in both dipoles. Miyakoshi (1986) proposed a tectonic explanation of the signal with a model involving fluid flow and changes of the self-potential in the surrounding rock. Whether in the fault zone or at the electrode, Miyakoshi observed a purely local effect. Disturbing is also the fact that the mode and shape of the signal would hardly cause any suspicion of an impending earthquake and needless to say, it would have been rejected with the VAN empirical rules, even if it was of definite tectonic origin. It is therefore apparent that the reliable identification of remote or local tectonic effects requires observations on multiple sensors and additional corroborating measurements (*e.g.*, meteorological data), to identify non-tectonic phenomena (*e.g.*, as in Shirman and Shapira, 1997; Enomoto *et al.*, 1997; Takeuchi *et al.*, 1999, etc). Although this necessity is well understood by many research groups, true multi-parametric observations are seldom made.

Since very ancient times, earthquake phenomena have been enshrouded with a mythology that allowed ample space for tales of unusual electric and electromagnetic effects. These are encountered most frequently in China and Japan and include anomalous (spastic) animal behaviour, particularly of catfish and eels (*i.e.* creatures with electrosensory organs which they use to seek their prey, Ikeya *et al.*, 1996), as well as peculiar stories of bowing, *U*-shaped candle flames, iron nails dropping from magnets, jumping metallic objects and lighting of fluorescent lamps. The interesting news is that such phenomena have been reproduced by Ikeya and Matsumoto (1997) using a 250 kV Van de Graaff generator. This certainly gives more credibility to the legends and if proven to be the results of electrostatic fields or charged aerosols, such phenomena may also lead to constraints on the mechanisms of precursory electrification and charge propagation in the epicentral area (consider for instance the mechanisms in Sasaoka *et al.*, 1998; Scudiero *et al.*, 1998 and Freund *et al.*, 1994). Therefore, it should not be a surprise, if such effects eventually qualify as genuine EEP. Finally, we note that catfish and candles are not the only beings considered as alternative EEP sensors. Toriyama (1994) measured bioelectric potentials in trees and claimed to have observed anomalous behaviour for almost two weeks prior to the 12/7/1993 M 7.8 Hokaido earthquake, at a distance of 700 km from the epicentre. The physical basis, repeatability and prospects of this approach, however, are still open to question.

7. Quo vademus?

As stated in the introduction, earthquake processes are very complex and occur at time scales and places completely indifferent to the plans and requirements of our science, sparingly providing information and insights into their secrets. There were several examples of geophysicists waiting to study earthquakes at the wrong place, or the wrong time or both, Parkfield being the prime example. Such adversities have rendered any progress slow and painstaking and failures frequent and inevitable. They have also brought about frustration and scepticism. A number of renowned geophysicists posited that precursors do not exist and earthquakes are inherently unpredictable, using as their main argument the critical nature of seismogenetic processes. According to Geller *et al.* (1997), «... *the Earth is in a state of self-organised criticality, where any small event has some probability of cascading into a large event*», adding that «*whether any particular small earthquake grows into a large earthquake depends on a myriad of fine details of physical conditions throughout a large volume ... This highly sensitive nonlinear dependence of earthquake rupture on unknown initial conditions severely limits predictability*». These views were repeated by Geller *et al.* (1997), Kagan (1997), Main (1997) and others, starting a long debate on the predictability of earthquakes, which we shall not endeavour to discuss as it is beyond the scope and the space allocated for our review. However, to assert that Self-Organised Critical (SOC) systems are unpredictable presupposes a thorough understanding of SOC processes, which nobody can claim as yet. If for this reason only, the 'unpredictability' thesis is untenable and has recently been refuted by Hainzl *et al.* (2000) who utilised a slider-block model with transient-creep properties to obtain a SOC state with definite precursory phenomena (short term foreshock acceleration and intermediate term quiescence). Recently, there have been attempts to 'renormalise' the philosophy of earthquake prediction research acknowledging the difficulties and re-defining the objectives (*e.g.*, Sykes *et al.*, 1999), while the sceptic side appears to follow a corresponding, more moderate course (*e.g.*, Kagan, 1999). The initial optimism may have been curtailed, but prediction was not proven to be impossible and most researchers now acknowledge that it may be a very difficult, yet attainable objective.

EEP research followed a similar course. After a rush of optimism almost twenty years ago, there followed a period of puzzlement, with very few solid facts to be shown and a multitude of inconsistent or conflicting ideas attempting to explain diverse observations of poorly defined observables. As has (frequently) been indicated above, many of the formulistic models put forward as possible explanations of the EEP, are indefensible when tested against known facts of geology, tectonics and electromagnetism. Earthquake physics is much more complex than anticipated and in many cases, research was derailed by the aggressive advertisement of VAN and diverted from the fundamental concepts to field experiments lacking specific objectives. The inevitable failures spawned scepticism and harsh criticism, which included accusations of 'scientific pathology' that were not entirely groundless (Geller, 1996). By that time, it had become apparent that a great deal more is required before one can decide on the nature of some anomalous electric field variation and, to a point, the situation was like Faust's before the appearance of Mephistopheles: frustrating. The time had matured for a renormalisation in the philosophy of EEP research, which we think is already in progress. In the following, we will try to outline where current research is heading and which objectives need, in our view, to be pursued intensively.

In terms of field experiments and data acquisition, progress is steady. Observation technologies in place by the beginning of the last decade were already mature and could guarantee reliable electric field measurements. Of course, improvements are still possible, as for instance with new generation electrodes (*e.g.*, Petieau, 2000) and smart measurement schemes facilitating noise discrimination and suppression (*e.g.*, Shirman and Shapira, 1997; Takeuchi *et al.*, 1999). Our review has also shown that simultaneous electric and magnetic field measurements are indispensable for signal evaluation and source modelling, so that new experiments should be designed for multi-parametric data acquisition and analysis (*e.g.*, as in Troyan, 1999). It should also be noted that hitherto, mostly narrow band observations in the ULF-ELF or ELF-VLF ranges were conducted. It is apparent that such data may yield incomplete information, only partially constraining any qualitative or quantitative models of the earthquake preparation processes. Wide band observations should provide far better data and constraints, but progress to this end has not been made as yet. However, the most significant drawbacks of EEP research are not in the data *per se*, but in their interpretation. Therefore, as much as new and reliable observations are indispensable, the large volumes of digital data accumulated over the past two decades have not been fully deciphered and certainly require better scrutiny and re-evaluation with novel analysis and source modelling methods.

We think that EEP research should go back to the drawing board and emphasise more on fundamental principles, less on field experiments, building appropriate physical models for the generation and propagation of EEP and simulating their received characteristics. The comparison and possible agreement of theory with observations may provide a basis for the recognition of some classes of EEP and advance our understanding of earthquake physics and preparation processes. Such efforts have already begun and we believe that there are two major areas on which research may focus.

One such area of outstanding importance is the physics of electrification mechanisms. At this point in time, research has revealed the mechanisms of spontaneous electric charge production in rocks under stress. We also know that charge and current densities under controlled conditions are such that if scaled up to the size of seismogenic zones, they would yield observable EEP. However, only electrokinetic large-scale effects have been verified with field experiments, especially in volcanic areas. There are several unknowns about the other mechanisms, regarding their efficiency, interactions and scaling up in real earth conditions. Even partial answers to such questions will provide valuable information of what kind of signals should (or should not) be expected. These objectives require careful experimentation and theoretical development. Experiments on both small and large (metric) scale samples are needed, with particular emphasis on the latter, because they can be considered more representative of large rock volumes. The first examples of such experiments were reported by Baddari *et al.* (1999) and Gensane *et al.* (1999).

Intensive research should also be directed towards decoding the large scale processes that may induce rock electrification, *i.e.* the physics of stress/strain changes at the earthquake source. As any survey of the literature will readily demonstrate, many of the hitherto published EEP source models did not build on such intrinsic properties, but rather considered the effects of some 'massive' or 'sudden' stress variations without specific spatial and temporal characteristics. This is clearly not enough. It is probably more important to consider the modes of stress and strain changes, since these and only these determine the properties of the EEP signal. Research can expand on knowledge that was almost unavailable very few decades ago, and specifically on the fractal characteristics of fragmentation and faulting, as well as Self-Organised Criticality (SOC) and/or Critical Point behaviour, that appear to describe seismogenetic processes at all scales. We assert that any valid model of the EEP source must be consistent with these fundamental principles, or, at least not contradict them. Hitherto, only Cuomo *et al.* (1997, 1999) attempted to evaluate natural electric signals in terms of fractal/SOC properties, while applicable analyses with similar philosophy are reported by Hayakawa *et al.* (1999, 2000). The latter work is also important in that it provides the first evidence of electromagnetic precursors due to a SOC system. Attempts to incorporate fractal geometry in the models of the EEP source are very few and in their majority very recent (Sornette and Sornette, 1990; Molchanov, 1999; Vallianatos and Tzanis, 1999b), while models at least consistent with SOC properties were proposed by Molchanov and Hayakawa (1994, 1998), Molchanov *et al.* (1995), Patella *et al.*, (1997) and Tzanis *et al.* (2000a,b).

Advanced signal analysis techniques may contribute significantly in accomplishing the above objectives. A number of recent papers implemented some very advanced methods of signal recognition (*e.g.*, Ifantis *et al.*, 1999; Rovithakis and Vallianatos, 2000), but as much as they are welcome, these techniques are also impaired by their inability to discriminate signals on the basis of physical and analytical properties, relying on empirical (therefore subjective) rules. Until EEP physics is deciphered, such methods are not guaranteed to deliver valid EEP signals. Moreover, EEP processes may not always appear in the form of distinguishable transient signals, but may hide in the background in the form of slow changes in fundamental properties of signal structure (for instance of the source fractal dimension, *i.e.* the distribution of the electric field emitters). Whereas general purpose algorithms cannot be constructed as yet, *ad hoc* pattern recognition methods can be very useful in searching for specific precursory characteristics in the data. For instance, analysis methods such as in Cuomo *et al.* (1999), Hayakawa *et al.* (1999) and Alperovich and Zheludev (1999) can be programmed to identify quasi-real-time changes in the structure of electromagnetic signals, which in turn, may be attributable to SOC processes in the crust and the approach to the critical point. The resulting data sets will certainly prove to be invaluable in understanding source properties and the nature of pre-seismic effects.

Source modelling should eventually allow the determination of the expected waveforms of EEP signals, as understandably this is a primary means by which to authenticate them (for example, a seismologist can tell an earthquake from a quarry blast). The development of this important subject is still in its infancy, with a very few authors having proposed generic models of the source, but progress is nevertheless being made. In Section 4.1 we reviewed the work of Molchanov and Hayakawa (1994, 1998), Patella *et al.* (1997) and Tzanis *et al.* (2000a,b), while Surkov's (1999) approach should also be mentioned. Although these models apply to certain classes of signals and require further development and rigorous verification, they do demonstrate that observed signals can be described with generic theories of the source and provide some useful examples of the emerging EEP research philosophy. This is certainly much more than could be claimed a very few years ago.

It appears that after the near-impasse of the mid-90's a major re-thinking of EEP research has begun to take place, with reformulation of its queries and objectives (the 'renormalisation' process we have referred to). It has been made clear that experimental methods, however elaborate, cannot provide viable answers without hard physical constraints and the research is now focusing on such problems with evident progress. On the other hand, we could still not claim that EEP data are indisputable, if we were to apply the scientific methods of testing and verification to their full rigour. There are no definite answers to the very basic questions and research must be given time to progress, albeit with vigilance and adherence to the rules of the scientific game. We cannot assess when it will be possible to predict earthquakes and we also note that earthquake prediction is not yet a scientific discipline. It is science in the making and this should not be overlooked by both its critics and its defenders.

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