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A critical review of Electric Earthquake Precursors

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Abstract

The generation of transient electric potential prior to rupture has been demonstrated in a number of laboratory experiments involving both dry and wet rock specimens. Several different electrification effects are responsible for these observations, but how these may scale up co-operatively in large heterogeneous rock volumes, to produce observable macroscopic signals, is still incompletely understood. Accordingly, the nature and properties of possible Electric Earthquake Precursors (EEP) are still inadequately understood. For a long time observations have been fragmentary, narrow band and oligo-parametric (for instance, the magnetic field was not routinely measured). In general, the discrimination of purported EEP signals relied on 'experience' and *ad hoc* empirical rules that could be shown unable to guarantee the validity of the data. In consequence, experimental studies have produced a prolific variety of signal shape, complexity and duration but no explanation for the apparently indefinite diversity. A set of inconsistent or conflicting ideas attempted to explain such observations, including different concepts about the EEP source region (near the observer or at the earthquake focus) and propagation (frequently assumed to be guided by peculiar geoelectric structure). Statistics was also applied to establish the 'beyond chance' association between presumed EEP signals and earthquakes. In the absence of well constrained data, this approach ended up with intense debate and controversy but no useful results. The response of the geophysical community was scepticism and by the mid-90's, the very existence of EEP was debated. At that time, a major re-thinking of EEP research began to take place, with reformulation of its queries and objectives and refocusing on the exploration of fundamental concepts, less on field experiments. The first encouraging results began to appear in the last two years of the 20th century. Observation technologies are mature and can guarantee reliable electric field measurements, although improvements are still possible with new generation electrodes and smart measurement schemes facilitating noise suppression. It is increasingly apparent that simultaneous electric and magnetic measurements are indispensable and conducted in most new experiments. There is also an emerging trend towards multi-parametric, broadband observations that should provide far better data and constraints on the source processes. The physics of electrification mechanisms are beginning to clarify, as also is the potential of solid state effects: 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, there are still many unknowns, requiring careful experimentation and theoretical development. Research is also directed towards decoding the physics of stress/strain changes that cause electrification, exploiting properties such as are the fractal nature of faulting and Self-Organised Criticality (SOC). The first evidence of possible electromagnetic precursors due to a SOC system has been published recently. Modelling of the source processes from first principles is stepping up and certain classes of observed signals can now be predicted by theory, providing new and more rigorous means of data authentication; such models have also established the feasibility of long range EEP signals. Although progress is apparent, the knowledge is still grossly incomplete and EEP data are not indisputable, if tested with the full rigour of scientific verification methods. The new research philosophy requires time and vigilance before it begins to pay off, but it appears to have taken a more promising course.

Key words *earthquake prediction – earthquake precursors – Electric Earthquake Precursors (EEP) – Seismic Electric Signals (SES)*

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1. Introduction

Earthquakes are thought to be associated with a broad range of broadband EM phenomena, from precursory to co-seismic and from luminous effects to ULF variations and long term changes in the electric properties of crustal rocks. The mechanisms generating these phenomena are thought to be multiple, complex, complicatedly interacting and, accordingly, subject to intensive research with diverse methods of scientific inquiry. Inasmuch as a comprehensive update of this broad and rapidly expanding field is impractical, earlier reviews (Park *et al.*, 1993; Park, 1996; Johnston, 1997) only attempted to appraise the more important topics and promising research trends, according to their authors' reckoning. Even so, the interesting subjects are many and journal space is limited, so that some important, perhaps cardinal questions may not be addressed in an all encompassing review. In an attempt to be as meticulous and thorough as possible in the space provided, we limit our inquiry to the Electrical Earthquake Precursors (EEP), which are only a subset of broad range of earthquake-related EM phenomena. As such, we define all the electric effects that are generated in the crust as part of an earthquake preparation process and are measurable on, or under the surface of the Earth, irrespective of how they propagate to the receiver.

Another reason why the EEP call for additional attention, is because they have been subject to debate and controversy due to the VAN prediction method, which utilises ULF transient fields. The VAN affair brought into the limelight several problems concerning the application of scientific inquiry methods, when only poorly constrained data and theories are available. It also helped to set off a wave of dispute as to the feasibility and merits of earthquake prediction research *per se*, to the point that the very existence of precursors has been questioned (*e.g.*, Geller *et al.*, 1997). Unfortunately for everyone, earthquakes and especially large ones, occur in a manner completely indifferent to the requirements of human science and reveal their secrets with great parsimony. The process of understanding them has necessarily been slow, fragmentary and therefore prone to error. This is a fact that both the critics and defenders of earthquake prediction research and the VAN method in particular, should always bear in mind. In the latter case, both sides argued on the basis of incomplete and occasionally misleading information, with only a few sober voices advising the careful adherence to the spirit and rules of the scientific method. Thus, the debate over VAN is a paradigm of science developing under conditions of poorly controlled (though not uncontrollable) and fragmentary accumulation of knowledge.

Although to a much lesser degree, similar problems pester the entire spectrum of EEP research. A lot of work needs to be done, to convincingly demonstrate the causal relationship between observations and earthquakes and, more importantly, to develop viable models of the EEP source (*i.e.* predictive tools – the ultimate goal of any scientific endeavour after all). In consequence, we emphasise reviewing which aspects of hitherto data, models and claims have scientific merit, which expand on loose conjecture and where research is heading, while much space is reserved for ULF transients. The success of this undertaking will be judged by the reader.

2. EEP generation: laboratory experiments and electrification mechanisms

The generation of transient electric potential/current during the loading cycle prior to, and concurrently with rupture has been demonstrated in a number of laboratory experiments involving both dry and wet rock specimens.

Electrification by microfracturing, *i.e.* the appearance of spontaneous charge production and transient electric and electromagnetic emission (E-EME) associated with the opening of microcracks, has been discussed by several authors in connection to laboratory experiments. Some authors have also provided quantitative estimates of charge production and currents associated with microfracturing. For instance, Warwick *et al.* (1982), measured current spikes from individual microcracks of the order of 10^{-3} A, associated with crack opening times of the order of 10^{-6} s, thus providing a net charge density of 10^{-3} C/m^2. A similar value of 10^{-2} C/m^2 is reported by Ogawa *et al.* (1985), while Enomoto and Hashimoto (1990) measured a charge production of 10^{-9} C for cracks with surface of the order 10^{-6} m^2, thus yielding a charge density of 10^{-3} C/m^2. A younger generation of experiments (*e.g.*, Fiffolt *et al.*, 1993; Chen *et al.*, 1994; Enomoto *et al.*, 1994; Hadjicontis and Mavromatou, 1994, 1996; Yoshida *et al.*, 1994, 1997), observed simultaneous Acoustic and E-EM signals, confirming that electrification effects arise during microfracturing. On an even larger scale, Tomizawa *et al.* (1994) observed direct ELF/VLF emission from underground explosions, while Bella *et al.* (1994) observed simultaneous Acoustic and E-EME under real world conditions in caves.

Although the electrification of rock prior to and during rupture is clearly observed in laboratory experiments, there are two cardinal and inter-related problems hindering the compilation of viable, self-consistent theories of EEP generation and propagation. First, there is incomplete understanding of how laboratory results may scale up to the enormous, heterogeneous rock volumes involved in the preparation of large earthquakes. Second, the *efficiency* of the different electrification mechanisms is as yet unspecified and if more than one mechanism is operative, their (constructive or destructive) interaction is poorly understood, as also is their individual contribution to the total effect. Hitherto theoretical attempts to address such questions were usually generically associated with some particular mechanism producing different source geometries and propagation/decay laws (*e.g.*, Gokhberg *et al.*, 1985; Dobrovolsky *et al.*, 1989; Slifkin, 1993; Varotsos *et al.*, 1993; Bernard and Le Mouël, 1996; Vallianatos and Tzanis, 1999a). It is also well known that many published interpretations of EEP generation mechanisms calling for an electric source at the hypocentral area, encounter a difficulty in providing a correct order of magnitude for signals measured hundreds of kilometres away.

To begin with, we shall not address exotic EEP generation models that are either purely hypothetical (*e.g.*, Lazarus, 1993), or chimerical (*e.g.*, Rokityansky, 1999). Yet, other mechanisms rigorously promoted as explanations of EEP phenomena, have actually never been verified by laboratory experiments. For instance, Varotsos and Alexopoulos (1986) and the VAN group in numerous publications, have proposed a mechanism involving Piezostimulated Depolarisation Currents (PDC). This requires the polarisation of point defects of the form 'anion + cation vacancy', by some external electric field. The polarised defects can change their orientation through jumps of the neighbouring cations to the vacancy, this process having a relaxation time $\tau = \tau_0 \exp(g_m/K\Theta)$, where g_m is the Gibbs energy for the migration process, K is the Boltzmann constant and Θ is the temperature. A massive change in point defect orientation is expected to stimulate a macroscopic, short-lived current. The relaxation time decreases exponentially with temperature and there is a number of experiments accounting for thermally stimulated currents. However, in order for it to decrease with stress or pressure p in constant temperature, one requires that the migration volume $v_m = \partial g_m/\partial p < 0$, a property that has not been demonstrated for crustal materials (*e.g.*, Varotsos and Alexopoulos, 1986). This drastic assumption is still awaiting verification. Another drastic requirement is for an external electric field of duration considerably longer than τ in order to polarise the point defects, the origin of which is rather obscure, at least in the case of non-piezoelectric materials. Varotsos *et al.* (1999a) presented a refinement of the model to accommodate some laboratory data, but the whole concept remains as yet unverified. In an alternative approach, Teisseyre (1995, 1997) proposed that the motion of charged dislocations (line defects) provides the electric field by which to polarise the point defects and the rapid stress drop during crack opening allows for the generation of a depolarisation current that enhances or reduces the electric field of MCD dislocations. This is the *piezo-stimulated dilatancy* current, but there is still no indication that the mechanism is physically realisable.

Piezoelectricity is a real effect and has been considered a possible EEP generator since the very early times of earthquake prediction research (*e.g.*, Nitsan, 1977; Warwick *et al.*, 1982; Yoshida *et al.*, 1994, 1997). An objection to the feasibility of the piezoelectric mechanisms is the possible self-cancellation of a macroscopic effect due to the expected random orientation of quartz crystals, unless a large proportion of them is aligned (*e.g.*, Tuck *et al.*, 1977). Parkhomenko (1972) indicates that this can happen, albeit on the basis of laboratory scale samples. In general, experiments demonstrate the generation of macroscopic signals in quartz bearing rocks and, more importantly, associated with microfracturing (*e.g.*, Enomoto *et al.*, 1994; Yoshida *et al.*, 1997, in simulated faults). The latter results are important in showing that piezoelectric signals may come from source regions where the stress distribution takes the same value and geometry. Yoshida *et al.* (1997) fitted their experimental data with an electric dipole potential of the form

$$V(t) = \frac{-\tau}{4\pi\varepsilon_d}\frac{r_i}{r^3}WZ\int_0^L C_{ijk}(x)\cdot h_{jk}\left(t-\frac{x}{\mathrm{v}_r}\right)dx, \tag{2.1}$$

$$h_{jk}(t) = \begin{cases} 0, & t<0, t>T_r \\ -\Delta\sigma_{jk}/T_r, & 0\le t\le T_r \end{cases}$$

where r is the distance of the observer, not dependent on the position in a source region, L, W and Z are respectively the length, width and height of a propagating fracture, C_{ijk} is the piezoelectric modulus, T_r and v_r respectively are the rise time and velocity of fracture propagation, $\Delta\sigma$ is the stress drop effecting the piezoelectric polarisation reduction, τ is the relaxation time of charge density and ε_d the dielectric permittivity of the medium. The high stress rates during (micro)fracturing may partially counter the objection of Dmowska (1977), that observable piezoelectric phenomena should only be co-seismic, because only then high enough stress rates may occur. In corroboration of this concept, Sasaoka *et al.* (1998) observed transient dipole electric field in granite and concrete, during stress reduction prior to failure, which they attributed to migration of bound charges due to the corresponding reduction of piezoelectric polarisation. The piezoelectric effect due to statistical deviation was estimated to be approximately three orders of magnitude less than the longitudinal effect of pure quartz crystals. Hence, they suggested that the low piezoelectric fields observed by Tuck *et al.* (1977) resulted from cancellation of piezoelectric polarisation by free charge carriers.

It is equally, if not more important, that E-EME are observed in completely quartz-free rocks (*e.g.*, Fiffolt *et al.*, 1993; Enomoto *et al.*, 1994; Hadjicontis and Mavromatou, 1994, 1996; Freund and Borucki, 1999), while Vallianatos and Tzanis (1998, 1999a) showed that the stress sensitivity coefficient $F = E/\dot{\sigma}$, which determines the dependence of the transient electric field E on the applied stress rate, is comparable in both quartz-bearing and quartz-free rocks. Thus, additional mechanisms have been considered to account for the observations. Contact or separation electrification is favoured by Ogawa *et al.* (1985). The Motion of Charged Dislocations (MCD) has also been proposed by some authors, both for the case of elastic rock deformation (*e.g.*, Slifkin, 1993; Hadjicontis and Mavromatou, 1994, 1996), and for the case of non-elastic deformation, when dislocations move and pile up to form and propagate cracks (*e.g.*, Ernst *et al.*, 1993; Vallianatos and Tzanis, 1998, 1999a). Cress *et al.* (1987) also suggested that the ionisation of the void space within the crack and the acceleration of unbounded electrons may intensify charge production. Freund *et al.* (1994), demonstrated the existence of highly mobile positive O^- type charge carriers, generated in oxide/silicate minerals from electrically inactive peroxy defects deriving from OH^- dissolved in the mineral structure. Along the same vein, Freund and Borucki (1999) demonstrated the existence of positive hole type dormant charge carriers in quartz-free or low-quartz rocks, which they attribute to the same process. These can be activated by low velocity impacts generating electromagnetic emission. The authors conjecture that similar activation may take place by the acoustic waves or direct impulse generated during crack opening (microfracturing), thus electrifying an otherwise insulating rock medium. Gas electrification is yet another mechanism. Enomoto (1996) speculated that exoelectrons (unbounded electrons trapped by lattice defects and impurities) can be thermally stimulated and electrify gases trapped in cracks and pores. More recently, Scudiero *et al.* (1998) show by means of experiment that electrons, due to tribological action between two surfaces, can release free charge into a flowing gas, to be transported over lengths of a few centimetres thereby stimulating electric polarisation. In both cases, it is suggested that electrified gas flow during the propagation and fusion of cracks may result in a macroscopic electric field.

What makes the MCD mechanism attractive is the fact that it always occurs in association with brittle failure, since stress concentration and crack opening take place when, after some critical stress threshold, edge dislocations multiply, migrate and pile up against an obstacle. Dislocations may occur in different mechanical 'flavours' which would move in opposite directions under stress. Thus, although the dislocation density may be as high as $10^{14}/\mathrm{m}^2$ for heavily deformed materials and both flavours carry comparable charges, any net electric polarisation of one sign must be the result of a net excess of charged dislocations with a particular mechanical flavour. Such an excess may have been introduced into crustal rocks in order to accommodate previous cycles of non-elastic deformation (also see Slifkin, 1993 for an example). In the thermodynamic conditions of the schizosphere this process will result in an elongated electric dipole oriented in the slip plane and perpendicular to the moving dislocation lines. Vallianatos and Tzanis (1999b) showed that the MCD current density is

$$J_{\mathrm{MCD}} = \frac{\sqrt{2}\cdot(\Lambda^{+} - \Lambda^{-})}{\Lambda^{+} + \Lambda^{-}} \cdot \frac{q_l}{\boldsymbol{b}} \cdot \frac{\partial \varepsilon}{\partial t} = C \cdot \delta\Lambda \cdot q_l \cdot \dot{\varepsilon} \tag{2.2}$$

where Λ^{+} and Λ^{-} are the dislocation densities of opposite flavours, $\delta\Lambda$ the excess dislocation density, q_l is the charge per unit length on the dislocation (of the order 10^{-11} Cb/m), and $\varepsilon = ½ (\Lambda^{+} + \Lambda^{-}) \cdot \boldsymbol{b} \cdot \delta x$ is the plastic contribution to strain, when edge dislocations of Burgers vector $\boldsymbol{b}$ move through a distance δx. The observed transient electric variation is related to the non-stationary accumulation of deformation in the neighbourhood of the moving dislocations. Interestingly enough, the ratio $(\Lambda^{+} + \Lambda^{-})/(\Lambda^{+} - \Lambda^{-})$ is usually between 1 and 1.5 in alkali halides (Whitworth, 1975). Assuming the highest value for rocks, *i.e.* lower excess dislocation density and $\partial\varepsilon/\partial t \approx 10^{-4}\mathrm{s}^{-1}$, approx. equal to co-seismic deformation rates, we obtain $J_{\mathrm{MCD}} \approx 5 \times 10^{-6}$ $\mathrm{A/m^2} \approx 0.5$ $\mathrm{nA/cm^2}$ which is comparable to the values quoted from the experiments. It should also be expected that when ionic crystals and rocks undergo such drastic changes, more than one electrification mechanism is operative. It appears reasonable to suggest that moving dislocations acting as stress concentrators, may guide and focus additional effects. For instance, MCD may propel dormant charge carriers, while bond breaking and separation effects take place in their slip plane. Moreover, the piezoelectric polarisation reduction due to the stress drop associated with crack opening, releases bound charges (as in the experiments of Yoshida *et al.*, 1997 and Sasaoka *et al.*, 1998). Determining if and how these multiple mechanisms interact and their interaction dynamics, will be prized objectives of both theory and experiment. Theoretical work to this effect is still in its infancy and pursued by a small number of investigators (*e.g.*, Schloessin, 1994; Teisseyre, 1995, 1997; Teisseyre and Nagahama, 1999). It is interesting, however, to point out that due to their very nature (guided charge motion), any constructive superposition of multiple mechanisms along the lines discussed above, will amount to an electric dipole source.

Charge production and current generation during crack opening is a short-lived effect. For common petrogenetic mineral and rock resistivities (ρ) and dielectric permittivities, any charge and electromagnetic fluctuations with source dimension $l \approx 10^{-4} - 10^{-1}$ m (typical cracks) will disappear after a time $t_e \approx \varepsilon_d \cdot \rho \approx 10^{-5} - 10^{-7}$s (if no external sources are applied). This is comparable to the duration of crack opening ($10^{-4} - 10^{-7}$ s). Charge production inside the crack is quickly destroyed by redistribution of the displacement currents and the current appears only while the crack propagates. If any long-lasting EEP is to be observed, it will have to be generated by the superposition of the signals from all the simultaneously propagating cracks and will evolve in time just like crack propagation. Accordingly, the electric field, measured at a point on the surface of the Earth located at distance $\boldsymbol{r}$ from the source and at time t_j, may be qualitatively expressed as

$$\begin{aligned} E(\boldsymbol{r}, t_j) \approx c_s \sum_{i=1}^{n(t_j)} [\rho_i (J_{\mathrm{MCD}} + \\ + J_0)_i G(\boldsymbol{r}, \boldsymbol{r}_i)] \cdot \left[u(t_j) - u\left(t_j - \frac{l_i}{v_i}\right)\right] \end{aligned} \tag{2.3}$$

where $\dot{n}(t_j)$ is the number of active cracks at time t_j, c_s is a sensitivity coefficient at the location of the receiver $\boldsymbol{r}$ and $G(\boldsymbol{r}, \boldsymbol{r}_i)$ describes the propagation and attenuation of the dipole field generated by MCD and other effects due to a crack opening at point $\boldsymbol{r}_i$; $u(t_j)$ is the Heaviside step function, l_i the crack propagation length and v_i the opening velocity, so that the right hand factor in the sum allows the *i*th crack to contribute only while it is opening. Note that (2.3) has a structure intrinsically similar to (2.1). A determinative factor of this model is the magnitude of the function $\dot{n}(t_j)$, which must be large enough to form a macroscopic field. The dynamics of crack propagation processes, however, are incompletely understood and progress is slow (also see Section 4.1). Consider also that when seismogenesis is mainly determined by friction on the fault, brittle behaviour is limited and may be insufficient to build up an observable signal. Conversely, strong signals may be expected during large scale brittle deformation, which is more likely to occur in compressive or transpressive stress regimes. This hypothesis may need to be investigated in more detail. The dependence on resistivity is another cardinal factor. Consider that the value of the charge redistribution (discharge) constant t_e quoted above, is calculated for resistivities of the order 10^6-$10^4\ \Omega \cdot \text{m}$. If the dielectric permittivity remains the same and the resistivity in the neighbourhood of the crack decreases to, say, $100\ \Omega \cdot \text{m}$, charge redistribution will occur only after $t_e \approx 10^{-9}$ s. This is orders of magnitude faster than crack opening times and does not allow for a macroscopic field to build up, unless the number of cracks increases by a forbiddingly excessive factor (at least as many orders of magnitude, as t_e decreases). The result is consistent with the majority of laboratory experiments observing precursory electric signals in dry (*i.e.* resistive) rock samples and indicates that strong precursory fields due to solid state mechanisms are anticipated from resistive rock blocks. More work is needed in order to observe how wet rocks behave during microfracturing and only a few such experiments exist (Chen *et al.*, 1994; Yoshida *et al.*, 1998).

Electrokinetic effects (EKE), *i.e.* electrification due to the flow of water driven through permeable rock by crustal strain or gravity, have amply been demonstrated by laboratory experiments (*e.g.*, Morgan *et al.*, 1989, and references therein; Jouniaux and Pozzi, 1995a,b, 1997 and references therein). The current density $\boldsymbol{J}$ and fluid flow velocity $\boldsymbol{v}$ are related to the coupled equations

$$\begin{aligned} \boldsymbol{J} &= -\frac{1}{\rho_f \phi} \nabla V + \frac{\varepsilon_{df} \zeta}{\eta \phi^\circ} \nabla P, \\ \boldsymbol{v} &= \frac{\varepsilon_{df} \zeta}{\eta \phi^\circ} \nabla V - \frac{k}{\eta} \nabla P \end{aligned} \tag{2.4}$$

where V and P are the streaming potential and pressure respectively, ρ_f and ε_{df} are the fluid resistivity and dielectric constant respectively, ζ is the zeta potential, η is fluid viscosity, ϕ, ϕ° are formation factors with and without surface conduction and k is the permeability of the porous medium. Under quasi-static conditions the convection current (due to ∇P) is balanced by the conduction current (due to ∇V), so that

$$\Delta V = \left(\frac{\rho_f \varepsilon_{df} \zeta}{\eta} \frac{\phi}{\phi^\circ} \right) \Delta P. \tag{2.5}$$

The term in brackets is the Electrokinetic Coupling Coefficient C_s. In fact, conditions suitable for EKE are plausible, at least in the near-surface parts of seismogenic zones, and quite consistent with the wet models of the earthquake preparation process (for instance, the Dilatancy-Diffusion model of Scholz *et al.*, 1973). In consequence, the EKE is a frequently quoted mechanism of precursory electric fields (*e.g.*, Mizutani *et al.*, 1976; Dobrovolsky *et al.*, 1989; Bernard, 1992; Fenoglio *et al.*, 1995; Bernard and Le Mouël, 1996; other references therein). In a recent paper, Yoshida *et al.* (1998) suggested the EKE as the prime source of electric potential changes during microfracturing of saturated sandstone samples.

Electrokinetic fields are weak and might be undetectable at long distances, because of natural limitations to the magnitude of C_s contrasts and pressure differences necessary to drive strong currents. Thus, C_s differences of the order 100 mV/MPa may be reasonable, but they may also comprise an upper limit, especially at depths comparable to the nucleation depths of large earthquakes (several kilometers). Based on laboratory measurements, Morgan *et al.* (1989) remark that differences in C_s may be quite small, even for different rocks. Furthermore, conductive pore fluids inhibit the C_s, and especially its increase as a function of permeability (Morgan *et al.*, 1989; Jouniaux and Pozzi, 1995a). In granitic and metamorphic rocks, conductive ($< 3\ \Omega \cdot$m) pore fluids are very important fluid phases and have been observed in the Russian Kola and German KTB ultra-deep boreholes; if present, they may tend to compensate any changes in permeability by dilatancy or other means. Vertical pressure differentials may be as high as the difference between lithostatic and hydrostatic pressure (up to 100 MPa at 6 km depth and 250 MPa at 15 km), which is respectively 100 and 250 times higher than the average pressure change given by stress heterogeneities around active faults. At the same time, it is hard to see how it is possible to have such high lateral pressure differences, except on limited patches collocated with domains of increased loading (*e.g.*, asperities). Even such pressures, however, would yield a potential difference of the order of 10-20 V, which is demonstrably insufficient to generate fields observable at long distances from the source. Shallow sedimentary rocks could be expected to exhibit larger lateral C_s differences, due to the higher inhomogeneity of near surface rock formations and the expected lower pore fluid conductivity. These may also be reduced by surface conductivity effects and low resistivity geological formations (*e.g.*, rich in clay minerals).

The situation may be quite different near the fault zone. Recently, Yoshida *et al.* (1998) conducted a series of experiments on electrical potential changes prior to shear rupture in saturated sandstone and found that the amplitudes of electrokinetic precursory signals were as large as the co-seismic. Hence, they concluded that precursory signals were caused by accelerating evolution of dilatancy, resulting in (forced) water flow into the dilatant region. Similar observations were first made by Chen *et al.* (1994) on saturated granite, marble and limestone samples, albeit this experiment was not thoroughly documented. In a larger scale experiment, Gensane *et al.* (1999) observed that the most significant electrokinetic potential variations, corresponding to the most significant stress/strain variations, occurred in the vicinity of active crack tips or crack intersections and proposed a real-time monitoring technique that may predict rupture. Thus, it appears that EK signals may arise during (micro)fracturing of wet rock samples, provided that simultaneous fluid flow is enforced. Along this vein, Fenoglio *et al.* (1995) suggested that intermittent fracture propagation connecting high and low pressure domains may initiate rapid fluid flow and ULF signals. Patella *et al.* (1997) independently developed a theoretical model of such a mechanism, in an attempt to explain some observations of anomalous electric fields prior to earthquakes in Japan and China. Their Dilatancy-Diffusion Polarisation (DDP) model requires an initial stage of crack formation (dilatancy) to increase the porosity and generate a pressure gradient towards the cracked volume. This is followed by fluid diffusion into the open pores from neighbouring saturated rock volumes, thus producing bipolar electrical polarisation which fades as the pressure gradients drop while the empty pore space becomes saturated. The model predicts potential differences as high as 30 mV above the source, but rather low amplitudes at distances of a few tens of kilometers. Although we are still far from understanding all the phenomena involved, it is clear that such experiments and models open new windows in the research for EEP generating mechanisms.

Another EEP mechanism that may result from large scale microfracturing involves current excitation due to the motion of conductive earth material in the geomagnetic field, by crack-emitted acoustic waves. Surkov (1999) showed that under certain conditions, at distances far enough from opening cracks where the acoustic wave front is approximately spherical, the EM forerunners, *i.e.* the electromagnetic perturbations appearing just prior to the arrival of the acoustic wave, all have the same sign, independent of crack orientation. The superposition of all forerunner fields results in a macroscopic effect, which Surkov estimated that may be as high as 1-10 nT and 1-10 mV/km in 100 $\Omega \cdot$m media and at distances of the order of 20 km from a dilatant 10^3 km^3 source volume. At the same time, coda EM and the entire acoustic wave fields radiated by a system of randomly oriented cracks are oscillatory and may cancel out, so that a ULF precursor may be observed even in the absence of microseismic activity. We emphasise that this is not the seismoelectric effect used in geophysical exploration (*e.g.*, Beamish, 1999), although vibrational current excitation can also take effect in the presence of conductive fluids and may be enhanced by a contributing electrokinetic mechanism. Apparently, the time function of the EEP signal will follow the time function of the microfracturing process, but the geometry of the EEP field will be quasi-spherical, or, rather, the resultant of many distributed spheroidal sources. In contrast, the EEP geometry resulting from solid state electrification processes (assumed to result from quasi-aligned cracks) will be approximately dipolar. In principle, this might provide a means by which to distinguish between the two mechanisms.

As is apparent, the earthquake source may be host to a number of different electrification phenomena, whose spatial and temporal sequence is not at all clear and which may be synergistic or competitive in a complex manner that is inadequately understood. Accordingly, the nature and properties of possible Electrical Earthquake Precursors are still poorly understood, to the point that their very existence can be debated. These problems (and possible answers thereof) will be reviewed in the following Sections 3 to 5.

3. Observations and signal identification

The first observations for EEP signals were conducted in the ULF-ELF frequency band with grounded horizontal dipoles and non-polarising electrodes (usually $Cu/CuSO_4$ or $Pb/PbCl_2$), although many experiments, even in the late 90's, were still using metal rod electrodes. Later, vertical potential difference measurements were introduced and recently, the observational bandwidth was expanded to include VLF, using grounded electrodes or vertical antennae in boreholes, with or without reflectors. The field studies have produced a prolific variety of signal shape, complexity and duration. A brief survey of the international literature will show:

– VLF and pulse like signals appearing in swarms (*e.g.*, Fujinawa and Takahashi, 1994, 1998; Enomoto and Hashimoto, 1994; Enomoto *et al.*, 1997; Singh *et al.*, 1999).

– ELF-ULF single pulses of variable duration with shapes like spikes, delta functions or boxcars (*e.g.*, Varotsos and Lazaridou, 1991; Varotsos *et al.*, 1993, 1996a; Maron *et al.*, 1993; Kawase *et al.*, 1993). These were classified as 'single' or 'solitary' Seismic Electric Signals (SES) (fig. 1a).

– ULF transient, bay-like or asymmetric bell shaped variations with durations of a few minutes to a few hours (*e.g.*, Varotsos and Alexopoulos, 1984a,b; Maron *et al.*, 1993). These were also classified as single SES (fig. 1b).

– ULF transient multiple pulses of variable duration and shapes as above, appearing either discretely in time, or in a cascade succession (*e.g.*, Varotsos *et al.*, 1996a); such signals are 'SES Activities' (fig. 1c).

– Very long period (days or weeks) variations (*e.g.*, Sobolev, 1975; Sobolev *et al.*, 1986). This category includes the 'Gradual Variations of the Electric Field' (*e.g.*, Meyer and Pirjola, 1988; Varotsos *et al.*, 1993; Ifantis *et al.*, 1993).

– Periodic Variations of the Electric Field (*e.g.*, Thanassoulas and Tselentis, 1993, and references therein).

– Short and long term irregular shapes attributed to local and/or EK fields (*e.g.*, Mizutani *et al.*, 1976; Miyakoshi, 1986; Zhao *et al.*, 1997).

– Irregular activity at large (*e.g.*, Ralchovsky and Komarov, 1993).

The difficulty in understanding what produces the EEP and how it reaches the observer, raises a more important question: How can we tell what is an EEP from what is not? Let alone the difficulty in explaining the origin of the signal, the (seemingly limitless) diversity of forms and shapes reported as EEP is bewildering. For a long time, the identification of possible EEP signals relied on 'experience' and intuition, but not hard evidence. A frequently invoked argument for nominating a possible precursor was that some (unusual) signal appeared some time before an earthquake and/or

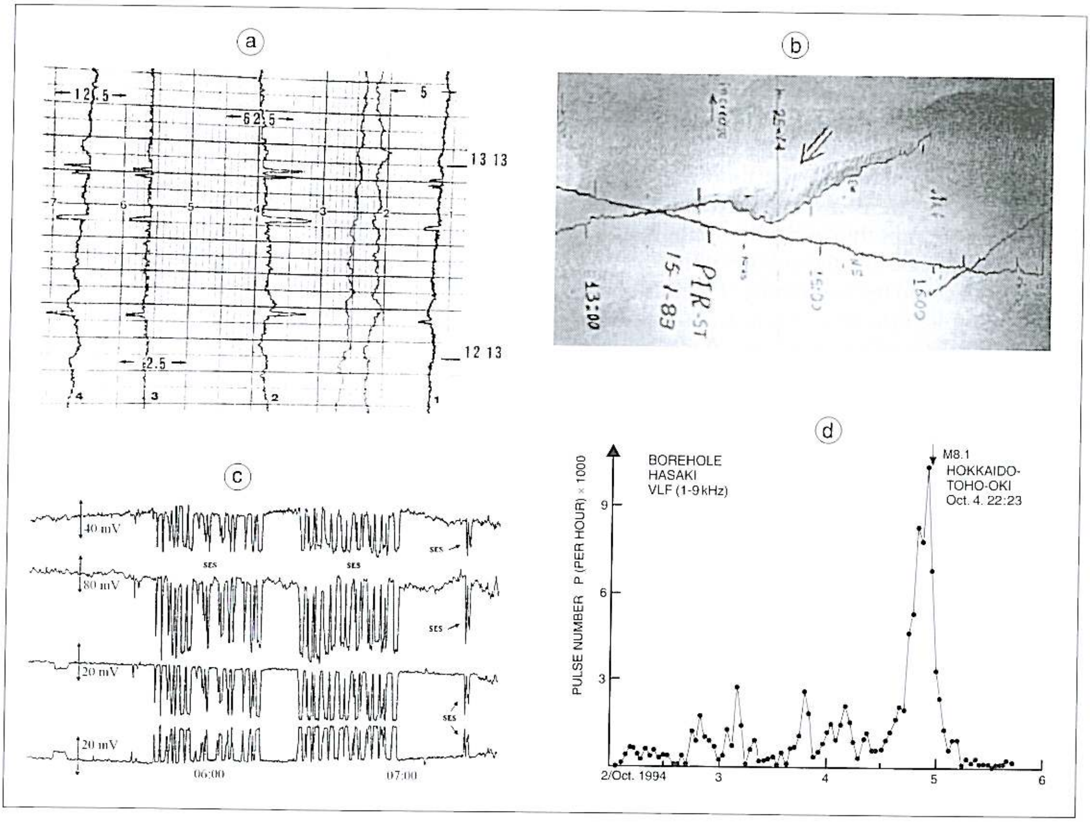

Fig. 1a-d. Different types of purported EEP signals. a) Short duration (1-2 min) single spikes, modified from fig. 8 of Varotsos and Lazaridou (1991). b) An asymmetric bell shaped signal of long duration (2 h), recorded on 15/1/1983 at Pirgos, Greece, prior to the 17/1/1983 *M* 7 Kefallinia earthquake (modified from fig. 7 of Varotsos and Alexopoulos, 1984a). c) 'SES activity', recorded on 30/4/1995 at Volos, Greece and supposed to precede the 15/6/1995 *M* 6 Aegion earthquake (modified from fig. 10 of Varotsos *et al.*, 1996b). d) Time dependence of hourly VLF (1-9 kHz) pulse count, prior to the 4/10/1994 *M* 8.1 Kuril islands earthquake (redrawn from fig. 3 of Fujinawa and Takahashi, 1998).

no other such (unusual) event was observed, there might be a relationship between signal and earthquake. Let us now attempt a brief review.

VLF and pulse-like signals are the latest addition to the EEP inventory. Fujinawa and Takahashi (1994) used vertical borehole antennae to observe subsurface VLF electric signals appearing as a series of swarms with durations of 1-2 h, alternating with quiescent intervals with the same time constants. Eleven such cases were observed in two years at more than one location simultaneously and according to the authors, only prior to earthquakes at distances shorter than 200 km from the receiving stations, with lead times of a few to several days. This, however, was the only means by which to relate signals and earthquakes, let alone the fact that many other earthquakes in the area were not preceded by similar VLF activity. Using similar procedures, Fujinawa and Takahashi (1998) observed a precipitous increase in the occurrence of VLF emissions, culminating at the time of the great Kuril Islands earthquake (4/10/1994, *M* 8.1, $\Delta = 900$ km) and disappearing soon afterwards (fig. 1d). A similar pattern was observed in other cases of distant earthquakes ($\Delta > 400$ km). The authors explain the observations at such long range with propagation of the VLF field in the Earth-Ionosphere waveguide and could distinguish between signals emitted directly from the epicentral area and signals originating in the ionosphere. Co-seismic effects were also observed. Only an elementary attempt to identify lightning signals (sferics) was made and the authors point out that their results could be useful only if sferics could be routinely identified and removed. Enomoto *et al.* (1997) also measured vertical electric potential differences and went into great pains to substantiate their observations, using elaborate procedures for noise identification and reduction (for instance, lightning signals were identified using a lighting positioning and tracking system). The very few signals to have passed the tests may have been related to earthquakes, with lead times of the order of days. Definite answers could not be provided however.

Let us now present a case which we believe deserves some attention because it exemplifies the degree of caution needed before a precursor is declared. Singh *et al.* (1999) observed subsurface VLF anomalies with a vertical borehole antenna at Agra, India, which they related to earthquakes in Afghanistan more than 1000 km away. The anomalous signals «*... are usually not observed in the absence of earthquake activities...*», but there is no conclusive evidence to this effect. The observations are explained as a result of guided propagation along an active fault «*lying in the North-West direction from Agra which includes regions of Pakistan, Iran, Afghanistan etc...*», but the plausibility of this assertion is not established. An important aspect of this paper, is the observation of similar anomalies coincident with the Pakistani nuclear test explosions of the 28/5/1998. It is not specified whether the same fault is thought to connect the Pakistani test site with Agra. Nuclear explosions are known to affect the regional properties of the Earth-Ionosphere waveguide. Yet, the authors do not discuss whether the similarities between the 'nuclear' and 'seismogenic' signals may suggest an alternative explanation of the latter. Certainly the Agra data set deserves much more scrutiny before any useful conclusions can be reached.

ULF transient electric signals have received the utmost attention, partly because of the experimental conveniences at this frequency band, but mainly because of the VAN prediction method, which has been the pacemaker in this branch or EEP research since the mid 80's. Having postulated that the SES signal is generated at the earthquake focus, the VAN research team adopted a systematic approach towards signal identification, by devising a set of *ad hoc* empirical rules to distinguish noise from signals arriving from distant sources. In short, SES are required to appear simultaneously on all of the short and long dipoles at the station or stations concerned and the local horizontal difference field ($\Delta V/L$) must be constant or comparable over the short dipoles, as well as over dipoles of unequal lengths. Finally, the polarity of potential differences (ΔV) between the short and long dipoles should be the same (since the signal is arriving unilaterally). Details can be found in Varotsos and Lazaridou (1991). Such constraints may help in identifying electrochemical noise and are compatible with the distant source assumption; if violated, the source of the signal should be located within the span of the long dipoles, or at distances comparable to their length.

The VAN criteria have been coded into an automatic signal discrimination system by Ifantis *et al.* (1999), but have never been rigorously tested for their limitations. As Nagao *et al.* (1996) state, «*the physical meaning of these rules is straightforward*» and as such they have been adopted by other researchers of electrical earthquake precursory phenomena (*e.g.*, Uyeshima *et al.*, 1998), while Park *et al.* (1996) assert that «*the ability to distinguish SES from other electric field variations using objective criteria appears to be established*». However, this statement could not be true, because there can be several types of distant, non-tectonic ULF electric signals that can easily satisfy the criteria. For instance, it has long been recognised that accelerating or decelerating DC electric railways generate stray currents recorded at distances of 30-50 km from their sources (*e.g.*, Jones and Kelly, 1966; Fournier and Rossignol, 1974; Fontes *et al.*, 1988), which comprise a dreaded source of noise in MT sounding. Similar effects may arise from the switching of grounded machines, or variable loads on an unbalanced power distribution grid, providing time-variable line sources and wide-band contamination; such electric and magnetic variations can be generated by a number of industrial activities (*e.g.*, Kishinovye, 1951). Finally, Tsutsumi *et al.* (1999) demonstrated that lighting sources as far as 150-400 km away may contaminate the geoelectric field, meaning that rare, exceptionally strong distant lightning discharges, may produce signals with SES-like characteristics. Only recently has the VAN group attempted the physical justification of the criteria, with modelling on the basis of *ad hoc* geoelectric structural models (*e.g.*, Sarlis *et al.*, 1999; also see Section 4.2) or homogeneous, simply-layered structures (*e.g.*, Varotsos *et al.*, 1999d). However, a critical appraisal of the $\Delta V/L$ and polarity criteria by Tzanis and Gruszow (1998) has shown that in the general case they may be misleading due to the strong dependence of the electric field on lateral inhomogeneities existing along the propagation path, and/or local lateral resistivity contrasts: noise may be identified as distant signal and *vice versa*. In consequence, when local sources are concerned, the criteria can only recognise known emitters. New or shifting ones can easily deceive them.

Other attempts to discriminate transient EEP signals from noise include empirical implementations of the magnetotelluric impedance, in order to deconvolve the induced part, from the total observed electric field (Chouliaras and Rasmussen, 1988; Hadjioannou *et al.*, 1993; Arvidsson and Kulhanek, 1993). More recently, Shirman and Shapira (1997) presented a notable attempt to understand the nature of electrochemical noise and worked out methods to suppress it, while Takeuchi *et al.* (1999) tried to discriminate non-tectonic and extraneous effects with simultaneous measurements of multiple geoelectric parameters, namely vertical potential differences, surface charge density and the vertical atmospheric electric field. Finally, Rovithakis and Vallianatos (2000) presented a potentially useful neural network approach to the automatic discrimination of transient events. It is also apparent that wavelet analysis methods initially developed for geomagnetic data (*e.g.*, Alperovich and Zheludev, 1999), can also be applied to geoelectric time series. None of the above methods exploit signal properties known to be generic EEP characteristics. They merely allow some exceptional waveforms of unspecified origin to be recovered from ambient noise.

In general, hitherto debates on the nature of the data used for certain predictions (for instance the case of the Kozani-Grevena event, Gruszow *et al.*, 1996; Pham *et al.*, 1998, 1999; Sarlis *et al.*, 1999; Varotsos *et al.*, 1999b,d), were based on arguments deriving from experience, conjecture and/or common sense, not knowledge of intrinsic EEP properties. Likewise, Honkura *et al.* (1996) rejected the seismogenic origin of boxcar shaped anomalous signals, with reasoning quite similar to that of Gruszow *et al.* (1996). So much as educated common sense may be an effective filter, it is apparent that without proper knowledge of true EEP properties, empirical rules and noise reduction methods may detect unusual rare events, but cannot determine their nature. The association of such 'unusual' signals with distant earthquakes is *arbitrary* and largely responsible for many of the problems and controversy discussed in Section 5 below.

Empirical studies have also produced a set of laws for the behaviour and propagation of the EEP, the most interesting of which have been reported by Varotsos and Alexopoulos (1984a). The first associates signal amplitude and earthquake magnitude with a scaling relationship of the form $\log E = \alpha M + C$, where α is a positive slope in the range 0.3-0.4 and C is different for different seismic regions. The authors attribute the almost universal slope to fundamental processes at the source, but cannot explain it. The second law relates the SES amplitude with epicentral distance (r) for different magnitudes; according to Varotsos and Alexopoulos (1984a), it varies approximately as $1/r$.

Although derived from very few earthquake sequences in Western Greece (and therefore lacking statistical robustness), the data presented by Varotsos and Alexopoulos (1984a) are sufficient to demonstrate the amplitude-magnitude scaling relationship. This may explain why the law has been taken for granted by several other authors without due consideration. Scrutiny will also show that most signals used in the construction of the law belong to the transient, bay-like class. An interpretation attempt was made by Sornette and Sornette (1990) on the basis of a self-organized critical system at the earthquake focus and long range correlation between source and observer, which triggers piezoelectric effects in the vicinity of the observer. Recently, Molchanov (1999) reproduced the relationship on the basis of the electrokinetic effect, making the crucial assumption that the electric signal is a product of foreshock activity. Finally, Vallianatos and Tzanis (1999b) showed that a log amplitude-magnitude scaling with a universal slope of 0.3-0.4 should be a direct consequence of the fractal distribution of electric field sources and suggested that that transient precursors may result from microfracturing and fragmentation processes in the earthquake preparation zone. There is no known attempt to explain the *1/r* amplitude dependence. We note that this apparent relationship may be an artefact due to the slower attenuation of far electric fields in a conducting medium (when the 'law' was constructed, there were no near field data to indicate the attenuation rate at short epicentral distances, also see Varotsos and Alexopoulos, 1884a, p. 93). Moreover, there has been no update ever since, neither by VAN nor by anybody else.

During the last few years, some researchers focused on the fundamental properties of observed ULF electric fields, in a systematic attempt to determine their nature. In a prime example of such work, Cuomo *et al.* (1997, 1999) investigated the time-dynamics of geoelectric time series with stationary (global) and evolutionary (time-local) autoregressive models. They concluded that long-term electric field data can better be described with stationary stochastic processes, while featuring inverse power spectral scaling laws indicative of self-organised systems. Such information can be essential in devising objective methods of discriminating transient events from background activity and ambient noise.

Instead of searching for individual signals, some researchers prefer to monitor for fast or slowly varying systematic changes in the background levels of ULF fields. For instance, Miyakoshi *et al.* (1994) monitored daily mean and standard deviation values of potential differences over short grounded dipoles. They reported extreme sensitivity to external influences (*e.g.*, rainfall), but also a small number of cases of elevated field amplitude levels unrelated to apparent external effects which they consider to be possible precursors. Still, the interpretation remains questionable because the changes appear at selected electrode pairs, away from tectonic structures that might cause local effects (as for instance in Miyakoshi, 1986). Zhao *et al.* (1997) monitored daily mean values with a conventional experimental setup and observed irregular pre-seismic changes beginning months prior to great earthquakes in China. Finally, in a somewhat different approach, Yépez *et al.* (1999) integrated power spectra over consecutive non-overlapping windows of 4.5 h duration. They noted that several earthquakes with $M_w > 6$ at distances $\Delta > 100$ km, produced noticeable changes beginning several months before the respective events and that observations at different stations shared the same qualitative characteristics. Their data, however, still require rigorous analysis to exclude the possibility of extraneous effects, before their conclusions are proven. The practice of monitoring the background level yields irregular changes increasing and possibly maximising towards the earthquake, but hitherto there has never been any clear indication of a correspondence between the onset or the maximum of the 'precursory activity' and the earthquake nucleation time. In this respect, such practices can only provide auxiliary observational evidence.

3.1. *On the question of associated magnetic fields*

The absence of a magnetic field was considered to be one of the most salient features of the SES. For instance, Varotsos and Alexopoulos (1984a) were confident that «*no significant variation is produced by the signal*». This statement is somewhat surprising because at that time, they only made occasional observations of the total magnetic field with low sensitivity proton precession magnetometers and more often they compared the analogue electric field records with analogue magnetic field charts, independently observed at the Penteli geomagnetic observatory in Athens. Subsequently, a number of papers discussed the elimination of the magnetotelluric field (which in this case is noise), using a linear relationship of the form $\boldsymbol{E}_{\text{reduced,AC}} = \boldsymbol{E}_{\text{obs,AC}} - \boldsymbol{ZH}$, where $\boldsymbol{Z} = \boldsymbol{E}_{\text{obs,AC}}\boldsymbol{H}^{*}/\boldsymbol{HH}^{*}$ is the magnetotelluric tensor impedance and AC denotes the frequency dependent part of the electric field (Chouliaras and Rasmussen, 1988; Hadjioannou *et al.*, 1993; Arvidsson and Kulhanek, 1993). This led Park (1996) to suggest that since the MT relationship $\boldsymbol{E} = \boldsymbol{ZH}$ does not alter the waveform of an anomalous $\boldsymbol{E}$, then there should be no $\boldsymbol{H}$ field associated with it. In conjunction with Park and Fitterman (1990), who did not observe a magnetic companion of far field electric signals from injected currents, *«the mechanism generating the SES does not result in observable magnetic fields regardless of location»*. We believe that such a conclusion is not entirely justified, because the analyses of all these authors were based on intermittent and limited data sets of the type collected during standard MT surveying, not long-term observations that would allow rigorous testing and robust inference. In addition, there has been no hint whatsoever (let alone proof) that the anomalous signals treated by the above authors were indeed some form of EEP. Conversely, the possibility of magnetic fields from electrokinetic currents had long been established. Moreover, to reject the possibility of a magnetic field would be equivalent to rejecting all sources with non-vertical current configurations, which is rather arbitrary. More recently (after the early 90's), VAN began to measure magnetic field with induction coils at selected locations (mainly IOA) and after the debate over the prediction of the 13/5/1995 Kozani-Grevena *M* 6.6 earthquake (Gruszow *et al.*, 1996; Pham *et al.*, 1998, 1999; Varotsos *et al.*, 1996b, 1999b), they moderated their opinion to *«... we have never considered the absence of magnetic signal as a firm criterion to select genuine SES»* (Sarlis *et al.*, 1999).

As late as 1997, Johnston (1997) wrote that *«while both electric and magnetic fields are expected to accompany dynamic physical processes in the Earth's crust, simultaneous measurements of both fields are not made»*. To some extent, this is true even today. Thus, little can be said about the possible magnetic companions of EEP, which is regrettable given that the magnetic field can be valuable in identifying the nature of a subsurface current source and in some cases, may provide more significant information than the electric field. Note that the properties of quasi-static magnetic fields in a conducting earth medium are well known from the Magnetometric Resistivity method (*e.g.*, Edwards and Nabighian, 1991 and references therein). To summarise, *external magnetic fields can only be generated by subsurface current configurations with a significant horizontal component*. Horizontal current sheets such as might flow in thin layers above a resistive basement and point sources may only generate horizontal external fields. Accordingly, electrokinetic phenomena generate non-zero external magnetic fields only in the case of a lateral inhomogeneity of the Electrokinetic Coupling Coefficient (Fitterman, 1979, 1981; Dobrovolsky *et al.*, 1989). The surface magnetic field from *any* type of current distribution is *independent* of the geoelectric structure in a homogeneous or layered half space (*e.g.*, Stefanesku, 1929), so that it cannot be influenced by factors attenuating the electric field (*e.g.*, the water table). Finally, in cases of inhomogeneous (or anisotropic) geoelectric structures, the distortion of the magnetic field may vary from a few to several tens percent, but certainly not by orders of magnitude as the electric field may, across high contrast interfaces. Numerical values of the magnetic field calculated on the basis of plausible source models, are much more robust and reliable (at least to several tens percent) and can be compared more confidently with the observations.

In spite of these advantages, hitherto there have been only two attempts to evaluate an anomalous electric signal by means of its companion magnetic field (Gruszow *et al.*, 1996; Tzanis *et al.*, 2000b), with the former sparking vigorous objection by VAN (Varotsos *et al.*, 1996b, 1999b). Little has also been done towards modelling magnetic fields from EEP source processes other than EK. In one such attempt, Vallianatos and Tzanis (1999b) showed that at long distances from spheroidal sources, the magnetic field should be mainly vertical and observable only if the seismogenic process generates a polarisation rate perpendicular to the plane defined by the vertical and the radius joining the source and the observer.

Finally, it should be emphasised that there is quite strong evidence for ULF magnetic fields of lithospheric origin. Well known are the observations and models by Fraser-Smith *et al.* (1990) and Fenoglio *et al.* (1995). In addition, Kopytenko *et al.* (1993, 1994a,b), Hayakawa *et al.* (1996) and Kawate *et al.* (1998) observed possible precursory ULF data whose distinguishing feature was the high polarisation ratio of the vertical over the horizontal magnetic field components ($Z/H \geq 1$), while the typical magnetospheric ULF emissions exhibit low Z/H ratios. This means that the presumed precursory ULF magnetic data were overall vertically polarised, which is in accord with the theoretical predictions of Molchanov and Hayakawa (1998) and Vallianatos and Tzanis (1999b). In an even more interesting development, Hayakawa *et al.* (1999, 2000), argued that the lithospheric ULF magnetic data recorded prior to the Guam earthquake (8/8/1993, $M_s = 8$) evolved towards the structure of flicker noise, which characterises Self-Organised Critical systems. In another case, Dea and Boerner (1999) observed possible lithospheric ULF and ELF magnetic activity at a distance of 160 km to the south of the 17/1/1994, M 6.7 Northridge, California (U.S.) earthquake, commencing two weeks prior to the event (more work is required in order to better constrain this data set). Conversely, Pilipenko *et al.* (1999) failed to detect any anomalies prior to the great Kobe earthquake (16/1/1995, $M_s = 7.2$), at a distance of 400 km from the epicentre. In conclusion, there is clear evidence that magnetic fields are indeed generated in the Earth, in which case there may exist companion, either inducing or induced electric fields. In principle, the lithospheric electric and magnetic fields could be distinguished from data of different origin (*e.g.*, see Pilipenko *et al.*, 1999), while Molchanov *et al.* (1995) have made progress towards defining the received characteristics and relation between seismogenic ULF electric and magnetic fields. Unfortunately, in most of the cases cited above, simultaneous electric and magnetic field measurements were not made. Kopytenko *et al.* (1993, 1994b) suggested that differential measurements of three-component magnetic fields may separate lithospheric from magnetospheric fields and discussed the application of a method to locate the ULF source. The development of this technique is further discussed by Troyan *et al.* (1999), in association with simultaneous electric field measurements.

To summarise, the thesis that ULF electric precursors do not have magnetic companions and *vice versa*, is no longer defensible, as it was made on the basis of incomplete information. However, it should be acknowledged that the magnetic field may not always be detectable. Thus, it is clear that the complete lithospheric ULF electromagnetic field must be recorded and evaluated in the hope of understanding the secrets of its generation mechanisms. In a final comment, we note that any possible precursory ELF-VLF signals propagating through the Earth-Ionosphere cavity must be associated with a magnetic field observable at the Earth's surface.

4. Empirical modelling and propagation studies

A natural course of action is to inquire about the plausibility of EEP by modelling the source and propagation characteristics, necessary to produce a signal amplitude of a few mV/km at intermediate-large distances. Such attempts have led to several different concepts of the EEP source and signal physics, which can be broadly classified in two schools. The first proposes that the EEP is generated locally (near the observer), by some long range interaction of local geo-dynamic conditions with the earthquake source. The second school maintains that the EEP is produced at the epicentral area of the impending earthquake and propagates to the receiver as a transient field. A review of the fundamental concepts of these quite different views is provided below.