CURRENT CHALLENGES IN THE RESEARCH OF THE FRACTURE-INDUCED PRE-SEISMIC ELECTROMAGNETIC EMISSIONS IN THE MHZ AND KHZ BANDS

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Abstract. A remote observation stations’ network has been developed in Greece for the recording of the pre-seismic electromagnetic (EM) variations at the MHz and kHz bands. The hypothesis that the fracture-induced electromagnetic emissions (EME), which emerge from a few days up to a few hours before the main seismic shock occurrence, permit a real time monitoring of the damage process during the last stages of earthquake (EQ) preparation, as it happens at the laboratory scale, has been formulated based on the analysis of EME recordings in terms of a wide variety of time-series methods. This hypothesis is critically examined through a shift in thinking towards the basic science findings of fracture and faulting processes. The resolution of different puzzling features observed in the recorded pre-seismic EME and the negative views that have been expressed concerning their credibility has been attempted. A three-stage model for EQ generation by means of pre-seismic fracture-induced EME is finally proposed.

1. Introduction

Earthquake (EQ) is a large scale fracture phenomenon happening in the Earth’s heterogeneous crust, which occurrence is perceived in the form of a sudden violent shaking of the Earth’s surface. However, the processes involved in the preparation of an EQ are complex while it is not easy to be directly monitored. Therefore, the view that “understanding how earthquakes occur is one of the most challenging questions in fault and earthquake mechanics” (Shimamoto and Togo, 2012) is not an overstatement. In the direction of understanding the underlying complex nonlinear processes involved in the preparation of an EQ two research fields have attracted the interest of the scientists; one of them, on which a large effort has been devoted, is the study of fracture phenomena on the laboratory scale (e.g., Lockner et al., 1991; Ben-David et al., 2010; Hadjicontis et al., 2011; Carpinteri et al., 2012; Chang et al., 2012), while the other is the study of different phenomena which are observed in the field prior to the occurrence of significant EQs.

It has been found that opening cracks are accompanied with electromagnetic emission (EME) ranging in a wide frequency spectrum, from the kHz band to the MHz band, while these signals are detectable both at the laboratory scale prior to global failure in fracture experiments (e.g., Hadjicontis et al., 2011; Carpinteri et al., 2012), and at the geophysical scale prior to significant EQs (e.g., Warwick et al., 1982; Hayakawa and Fujinawa, 1994; Qian et al., 1994; Gokhberg et al., 1995; .Kapiris et al., 2004; Contoyiannis et al., 2005, 2014; Uyeda et al., 2009; Cicerone et al., 2009; Potirakis et al., 2012, 2013, 2015; Eftaxias et al., 2013; Eftaxias and Potirakis, 2013). It is practically impossible to install an experimental network to measure stress and strain at the location where an EQ is generated (focus area) using the same instrumentation as in laboratory experiments. It is therefore impossible to investigate the corresponding states of stress and strain and their time variation in order to understand the laws that govern the last stages of EQ generation, or to monitor (much less to control) the principal characteristics of a fracture process. In principle, this disadvantage does not accompany the tool of the fracture-induced EME in the case of significant shallow EQs that occur on land, keeping in mind that laboratory experiments are man controlled while field observations are measurements of events over which researchers have no control. On the contrary, the EME method is expected to reveal more information when it is used at the geophysical scale. Indeed, a major difference between the laboratory and natural processes is the order-of-magnitude differences in scale (in space and time), allowing the possibility of experimental observation at the geophysical scale for a range of physical processes which are not observable at the laboratory scale (Main and Naylor, 2012). At the laboratory scale the fault growth process normally occurs violently in a fraction of a second (Lockner et al., 1991). Thus, the idea that field observations at the geophysical scale by means of EME will probably reveal features of the last stages of failure process which are not clearly observable at the laboratory scale, allowing the monitoring in real-time and step-by-step of the gradual damage of stressed materials during EQ preparation process, cannot, in principle, be excluded.

Two important features of the EME are observed both at the laboratory and the field: (i) the MHz radiation consistently precedes the kHz one, indicating that these two emissions correspond to different characteristic stages of the fracture / EQ preparation, while (ii) after the emission of the kHz EME an EM silence systematically emerges before the time of the global failure / EQ occurrence (e.g., Kumar and Misra, 2007; Qian et al., 1994; Baddari et al., 2011, Hayakawa and Fujinawa, 1994; Gokhberg et al., 1995; Matsumoto et al., 1998; Hayakawa, 1999; Eftaxias et al., 2013; Eftaxias and Potirakis, 2013; and references therein). Based on these features, and the results obtained through the analysis of the field observed MHz-kHz EME by multidisciplinary time-series analysis tools, we have introduced a three-stage model of EQ preparation process by means of fracture-induced EME (Eftaxias and Potirakis, 2013, and references therein; Contoyiannis et al., 2014, and references therein) as described in Section 3.

2. Telemetric Stations Network

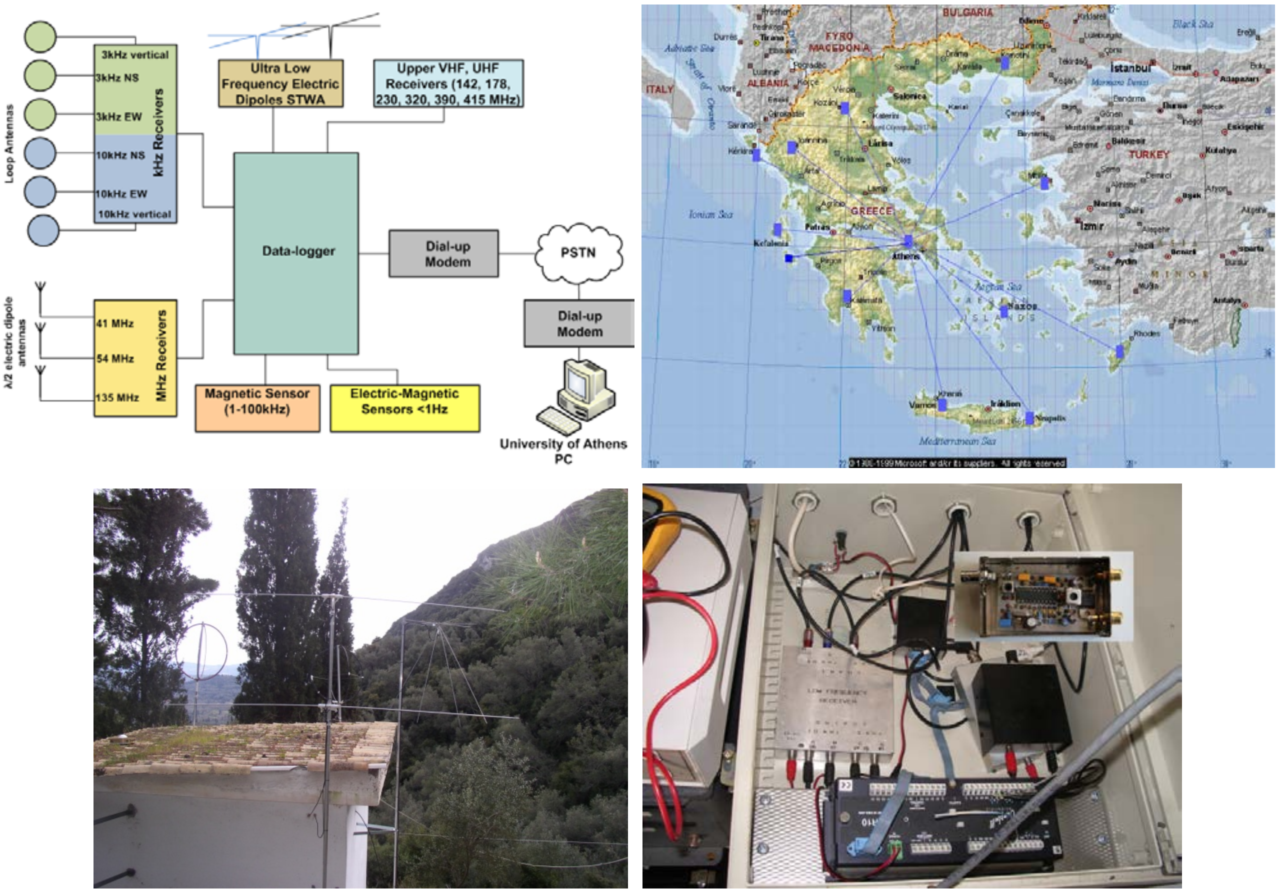

Fig. 1. (Top-Left): Block diagram of the exemplary telemetric measurement station installed at Zakynthos (Zante) Island. (Top-Right): The currently active telemetric stations network of Greece. (Bottom-Left): Typical example of antennas installation at the remote telemetric station of Kerkyra (Corfu) island (39.7127° N, 19.7962°E) for the measurement of geo-electromagnetic field variations. The two $\lambda/2$ dipole antennas can be seen in the foreground, while a pair of loop antennas is also mounted on the hovel hosting the receivers. (Bottom-Right): A typical installation of the receivers along with one of the employed data loggers from the remote telemetric station at Rhodes island (36.2135° N, 28.1212° E). The insert photo depicts the PCB of the MHz receivers unit.

A field measurement network using the same instrumentation as in laboratory experiments for the recording of fracture-induced kHz and MHz magnetic and electric fields, respectively, has been developed in collaboration with Prof. Nomicos. Since 1994, a telemetric remote station has been installed in a carefully selected mountainous site of Zakynthos (Zante) island at the south-west of the island (37.76^o N–20.76^o E) providing low EM background noise. The complete measurement system comprises of (i) six loop antennas detecting the three components (EW, NS, and vertical) of the variations of the magnetic field at 3 kHz and 10 kHz respectively; (ii) three vertical electric dipole antennas detecting the electric field variations at 41, 54 and 135 MHz respectively; (iii) other magnetic and electromagnetic sensors. All the time-series are sampled once per second, i.e., with a sampling frequency of 1 Hz. The block diagram of the measurement configuration is shown in Fig. 1(top-left). Note that the main focus is on the recorded MHz and kHz EME. The measured frequencies (3 kHz, 10 kHz, 41 MHz, 54 MHz and 135 MHz) were selected in order to minimize the effects of the man-made noise. A reduced configuration is installed at 11 more stations spread all over Greece, Fig. 1(top-right). The recorded data are acquired and regularly forwarded to the central telemetric station in Athens through PSTN. We note that the installed experimental setup helps us not only to specify whether or not a single MHz or kHz EM anomaly is possibly EQ-related in itself, but also whether a sequence of MHz and kHz EM disturbances which emerge one after the other in a short time period, could be characterized as possibly EQ-related one (Eftaxias, 2009; Eftaxias et al., 2001, 2002; Karamanos et al., 2005; Contoyiannis et al., 2005, 2014; Contoyiannis and Eftaxias, 2008; Potirakis et al., 2012, 2013, 2015).

3. Research Objectives - Challenges

Our main research motivation is based on the view that understanding of EM precursors in terms of basic science can lead to more sufficient knowledge of the last stages of the EQ preparation process and strict definitions of EM precursors. In this direction, we try to contribute to the establishment of strict criteria for the definition of an emerged EM anomaly as a possibly EQ-related one, by focusing on the answer of the questions:

(i) How can we recognize a MHz or kHz EME as a pre-seismic one?

(ii) How can we link the MHz and kHz EM precursors and the following EM silence with distinctive last stages of the earthquake preparation?

(iii) How can we identify precursory symptoms in EM observations which signify that the occurrence of the prepared EQ is unavoidable?

(iv) How can we explain the considered as paradoxes features?

(v) How can we link the observed EM precursors with other complex extreme events?

(vi) How can we link the observed EM precursors with other precursors?

As already mentioned in Section 1 (Introduction), (i) the MHz radiation consistently precedes the kHz one, indicating that these two emissions correspond to different characteristic stages of the fracture / EQ preparation, while (ii) after the emission of the kHz EME an EM silence systematically emerges before the time of the global failure / EQ occurrence. Based on these features, and the results obtained through the analysis of the field observed MHz-kHz EME by multidisciplinary time-series analysis tools, we have introduced the following three-stage model of EQ preparation process by means of fracture-induced EME (Eftaxias and Potirakis, 2013, and references therein; Contoyiannis et al., 2014, and references therein):

(1) The initially emerging MHz EM field is attributed to the cracking in the highly disordered material that surrounds the backbone of strong entities (asperities) distributed around the stressed fault sustaining the system (Fig. 2). It has been shown in terms of the Method of Critical Fluctuations (MCF) that this emission shows antipersistency and would be described in analogy to a thermal second order phase transition in equilibrium (Contoyiannis et al., 2005, and references therein), while an analysis by means truncated Lévy statistics, nonextensive Tsallis statistical mechanics, and criticality suggests that a truncated Lévy-walk-type mechanism can organize the heterogeneous system to criticality (Contoyiannis and Eftaxias, 2008). Importantly, based on the recently introduced method of Natural Time, it has been shown that the seismic activity that occurs in the region around the epicenter of the oncoming significant shock a few days up to approximately one week before the main shock occurrence, and the observed MHz EM precursor which emerges during the same period, both behave as critical phenomena (Potirakis et al., 2013, 2015).

(2) Our understanding of different rupture modes is still very much in its infancy; however, laboratory experiments of rock fracture and frictional sliding have shown that the relative slip of two fault surfaces takes place in two phases: a slow stick-slip like fracture-sliding precedes dynamical fast global slip (Ben-David et al., 2010; Chang et al., 2012). It has been suggested that the abrupt emergence of strong avalanche-like kHz EM field is due to the fracture of the family of the asperities themselves (Fig. 2), namely to the slow

stick-slip like stage of rupture mode. This emission shows: high information content and organization, preferred direction in the underlying fracto-EM mechanism, and persistency, namely it includes the key features of an extreme event (Eftaxias et al., 2013; Eftaxias and Potirakis, 2013; and references therein). The observed kHz EME precursor is characterized by the absence of any footprint of a second order transition in equilibrium or truncated- Lévy-walk-type mechanism, on the contrary shows footprints of a first order phase transition (Contoyiannis et al., 2014). The kHz EM time series includes well established universal structural patterns of fracture-faulting process, namely: (i) the activation of a single fault by means of kHz EM activity behaves as a reduced / magnified image of the regional / laboratory seismicity; (ii) its time profile is in consistency with the universal fractional Brownian motion spatial profile of natural rock surfaces; (iii) the roughness of its time profile coincides with the universal spatial roughness of fracture surfaces. Finally, the kHz EM emission is consistent with the fault modeling of the occurred earthquake which has been resulted by studies from different disciplines, e.g., satellite radar interferometry and seismology (Eftaxias et al., 2013; Eftaxias and Potirakis, 2013; and references therein).

(3) The systematically observed EM silence in all frequency bands is sourced in the stage of preparation of dynamical slip which results to the fast, even super-shear, mode that surpasses the shear wave speed. Recent laboratory experiments also reveal this feature (Eftaxias et al., 2013; Eftaxias and Potirakis, 2013; and references therein).

(*4) Recently, we have shown in terms of the MCF that between the first two stages of the fracture process, an intermediate stage exists which reflects the tricritical behavior (Contoyiannis et al., 2014). This stage appears in the kHz EME just before the emergence of the strong avalanche-like kHz emission. The results obtained for the kHz time-series are compatible with the results obtained for an introduced model map which describes the tricritical crossover. The tricritical crossover indicates the boundary of an antipersistence dynamics, namely the existence of a negative feedback mechanism that kicks the system away from extreme behavior.

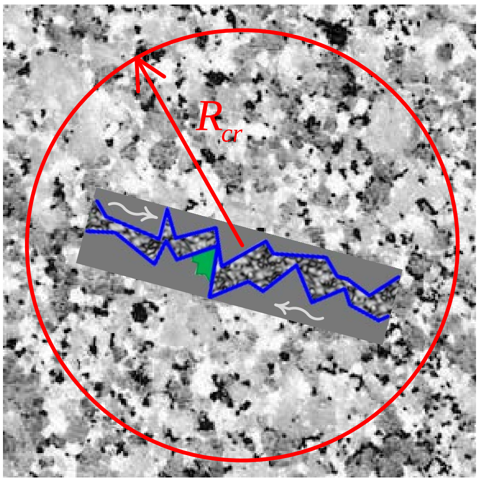

Fig. 2. A significant EQ is what happens when two surfaces of a major fault (blue lines) slip against one another under the stresses rooted in the motion of tectonic plates. A fault is embedded in a heterogeneous environment. The EQ preparation process at the first stage concerns the fracture of a disorder medium surrounding over a critical circle the major fault emitting the MHz EME which can be described by means of a phase transition of second order. The symmetry breaking signalizes the transition from the phase of non-directional, almost symmetrical, cracking distribution to a directional localized cracking zone along the direction of the fault. The EQ is inevitable if and only if the asperities break (green highlighted area), emitting the kHz EME during the second stage, and then an EME silence follows.

We clarify that an EME recording has to satisfy specific criteria (Fig. 3) before it can be considered a valid precursory signal; note that a valid MHz precursor indicates the preparation of a significant EQ, however the EQ is inevitable if and only if a valid kHz precursor is identified after a valid MHz precursor and then an EME silence follows. The above suggested three-stage model of EQ preparation process by means of fracture-induced EME, is a hypothesis that remains to be further verified; however, it should be noted that, up to now, it seems to be in agreement with both experimental (laboratory and geophysical) data, as well as theoretic and simulation studies of fracture phenomena, while no rebuttal has been published yet.

We note that the study of EME possibly related with an oncoming significant seismic event is associated with the existence of "paradox features" that accompany their observation; namely: Why an EM silence observed at the time of the EQ occurrence? Why the emerged EM signals are not accompanied by large precursory strain changes, much larger from co-seismic ones? Why EM emissions are not observed during the aftershock period? How the traceability of EM potential precursors is achieved on the grounds that they should normally be absorbed by the Earth's crust. An attempt to the answer to these questions has been recently presented (Eftaxias et al., 2013; Eftaxias and Potirakis, 2013; and references therein).

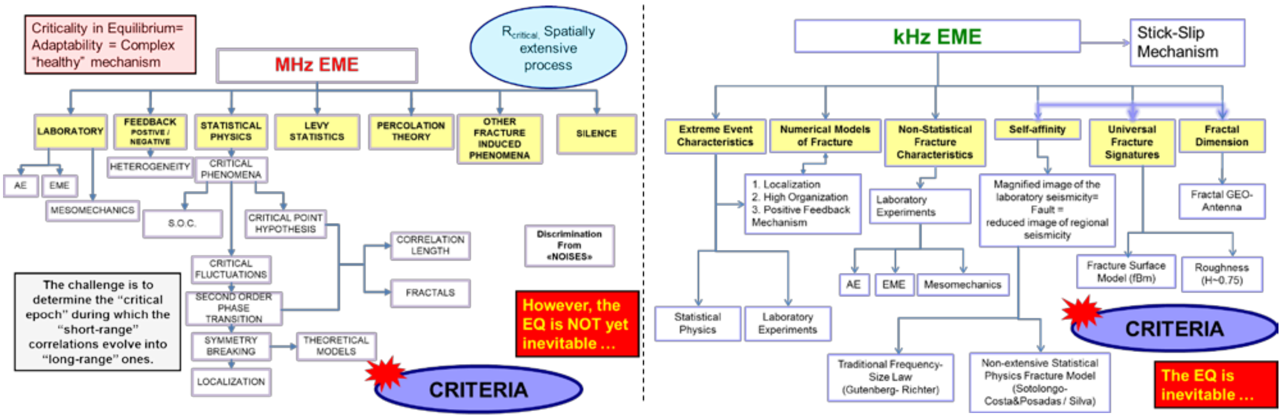

Fig. 3. The identification of a valid EME recording is performed by means of multidisciplinary time-series analysis. An EME recording has to satisfy specific criteria (MHz: left; kHz: right) before it can be considered a valid precursory signal. A valid MHz precursor indicates the preparation of a significant EQ, however the EQ is inevitable if and only if a valid kHz precursor is identified after the emergence of a valid MHz precursor and then an EME silence follows.

4. Conclusion

Fracture-induced EME in a wide range of frequency bands are sensitive to the micro-structural chances. Thus, their study constitutes a nondestructive method for the monitoring of the evolution of damage process at the laboratory scale. It has been suggested that fracture induced MHz-kHz EME, which emerge from a few days up to a few hours before the main seismic shock occurrence permit a real time monitoring of the damage process during the last stages of earthquake preparation, as it happens at the laboratory scale. Importantly, it is noted that when studying the fracture process by means of laboratory experiments, the fault growth process normally occurs violently in a fraction of a second. However, a major difference between the laboratory and natural processes is the order-of-magnitude differences in scale (in space and time), allowing the possibility of experimental observation at the geophysical scale for a range of physical processes which are not observable at the laboratory scale. Therefore, the study of fracture-induced EME is expected to reveal more information, especially for the last stages of the fracture process, when it is conducted at the geophysical scale. In this frame, we have installed a network of remote telemetric stations for the recording of fracture-induced EME and based on the results obtained through the analysis of the field observed MHz-kHz EME by multidisciplinary time-series analysis tools, we have introduced a three-stage model of EQ preparation process by means of fracture-induced EME. Since this is a short overview article, one should refer to our previously published articles in order to get more details on specific recorded MHz-kHz EME signals, their analysis, and the different aspects of the developed model.

5. References

Baddari, K., Frolov, A., Tourtchine, V., and Rahmoune, F. (2011), An integrated study of the dynamics of electromagnetic and acoustic regimes during failure of complex macrosystems using rock blocks, *Rock Mech. Rock Eng.*, 44, 269–280.

Ben-David, O., Cohen, G., and Fineberg, J. (2010), The dynamic of the onset of frictional slip, *Science*, 330, 211-214.

Carpinteri, A., Lacidogna, G., Manuello, A., Niccolini, G., Schiavi, A., and Agosto, A. (2012), Mechanical and electromagnetic emissions related to stress-induced cracks, *SEM Exp. Techniq.*, 36, 53-64.

Chang, J., Lockner, D., and Reches, Z. (2012), Rapid acceleration leads to rapid weakening in earthquake-like laboratory experiments, *Science*, 338, 101-105.

Cicerone, R. D., Ebel, J. E., Britton, J. (2009) A systematic compilation of earthquake precursors, *Tectonophysics*, 476, 371-396.

Contoyiannis, Y. F., Kapiris, P. G., and Eftaxias, K. A. (2005), A Monitoring of a pre-seismic phase from its electromagnetic precursors, *Phys. Rev. E*, 71(6), 66123/1–14, doi: 10.1103/PhysRevE.71.066123.

Contoyiannis, Y., Eftaxias, K. (2008), Tsallis and Levy statistics in the preparation of an earthquake, *Nonlin. Processes Geophys.*, 15, 379-388.

Contoyiannis, Y., Potirakis, S.M., Eftaxias, K., Contoyianni, L. (2014), Tricritical crossover in earthquake preparation by analyzing preseismic electromagnetic emissions, *J. Geodynamics*, doi: 10.1016/j.jog.2014.09.015.

Eftaxias, K. (2009), Footprints of nonextensive Tsallis statistics, selfaffinity and universality in the preparation of the L'Aquila earthquake hidden in a pre-seismic EM emission. *Physica A*, 389, 133-140.

Eftaxias, K., Kapiris, P., Polygiannakis, J., Bogris, N., Kopanas, J., Antonopoulos, G., Peratzakis, A., Hadjicontis, V. (2001), Signature of pending earthquake from electromagnetic anomalies. *Geophys. Res. Let.*, 28, 3321-3324.

Eftaxias, K., Kapiris, P., Dologlou, E., Kopanas, J., Bogris, N., Antonopoulos, G., Peratzakis, A., Hadjicontis (2002), EM anomalies before the Kozani earthquake: A study of their behavior through laboratory experiments, *Geophys. Res. Lett.*, 29(8), 1228(1-4), doi:10.1029/2001GL013786.

Eftaxias, K., and Potirakis, S. M. (2013), Current challenges for pre-earthquake electromagnetic emissions: shedding light from micro-scale plastic flow, granular packings, phase transitions and self-affinity notion of fracture process, *Nonlin. Processes Geophys.*, 20, 771-792, doi:10.5194/npg-20-771-2013.

Eftaxias, K., Potirakis, S. M., and Chelidze, T. (2013), On the puzzling feature of the silence of precursory electromagnetic emissions, *Nat. Hazards Earth Syst. Sci.*, 13, 2381-2397, doi: 10.5194/nhess-13-2381-2013.

Gokhberg, M. K., Morgounov, V. A., Pokhotelov, O. A. (1995), *Earthquake Prediction: Seismo-Electromagnetic Phenomena*, Singapore, Gordon and Breach Publishers.

Hadjicontis, V., Mavromatou, C., Mastrogiannis, D., Antsygina, T. N., and Chishko, K. A. (2011), Relationship between electromagnetic and acoustic emissions during plastic deformation of gamma-irradiated LiF monocrystals, *J. Appl. Phys.*, 110, 024907.

Hayakawa, M., and Fujinawa, Y. (1994), *Electromagnetic Phenomena Related to Earthquake Prediction*, Tokyo, Japan, Terrapub.

Hayakawa, M. (1999), *Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes*, Terrapub, Tokyo.

Kapiris, P., Eftaxias, K., and Chelidze, T. (2004), Electromagnetic signature of prefracture criticality in heterogeneous media, *Phys. Rev. Lett.*, 92(6), 065702/1-4, doi: 10.1103/PhysRevLett.92.065702.

Karamanos, K., Dakopoulos, D., Aloupis, K., Peratzakis, A., Athanasopoulou, L., Nikolopoulos, S., Kapiris, P., Eftaxias, K. (2006), Pre-seismic electromagnetic signals in terms of complexity. *Phys. Rev. E.*, 74, 016104.

Kumar, R., Misra, A. (2007), Some basic aspects of electromagnetic radiation emission during plastic deformation and crack propagation in Cu-Zn alloys, *Materials Sci. Eng. A*, 454, 203-210.

Lockner, D., Byerlee, J., Kuksenko, V., Ponomarev, A., and Sidorin, A. (1991), Quasi-static fault growth and shear fracture energy in granite, *Nature*, 350, 39-42.

Main, I., and Naylor, M. (2012), Extreme events and predictability of catastrophic failure in composite materials and in the earth, *Eur. Phys. J. Special Topics*, 205, 183-197, doi:10.1140/epjst/e2012-01570-x.

Matsumoto, H., Ikeya, M., and Yamanaka, C. (1998), Analysis of barberpole color and speckle noises recorded 6 and half hours before the Kobe earthquake, *Jpn. J. App. Phys.*, 37, 1409–1411.

Potirakis, S. M., Minadakis, G., Eftaxias, K. (2012), Relation between seismicity and pre-earthquake electromagnetic emissions in terms of energy, information and entropy content, *Nat. Hazards Earth Syst. Sci.*, 12, 1179-1183, doi:10.5194/nhess-12-1179-2012.

Potirakis, S.M., Karadimitrakis, A., Eftaxias, K. (2013), Natural time analysis of critical phenomena: the case of pre-fracture electromagnetic emissions, *Chaos* 23 (2), 023117, doi: 10.1063/1.4807908.

Potirakis, S. M., Contoyiannis, Y., Eftaxias, K., Koulouras, G., and Nomicos, C. (2015), Recent field observations indicating an Earth system in critical condition before the occurrence of a significant earthquake, *IEEE Geosc. Remote Sens. Lett.*, 12(3), 631-635, doi: 10.1109/LGRS.2014.2354374.

Qian, S., Yian, J., Cao, H., Shi, S., Lu, Z., Li, J., Ren, K. (1994), Results of the observations on seismo-electromagnetic waves at two earthquake areas in China, in: *Electromagnetic Phenomena related to Earthquake prediction*, Hayakawa, M., and Fujinawa, Y., (Eds), Tokyo, Japan, Terrapub, 205-211.

Shimamoto, T., Togo, T. (2012), Earthquakes in the Lab, *Science*, 338 (6103), 54-55, doi: 10.1126/science.1227085.

Uyeda, S., Nagao, T., Kamogawa, M. (2009), Short-term earthquake prediction: Current status of seismo-electromagnetics, *Tectonophysics*, 470(3-4), 205-213.

Warwick, J. W., Stoker, C., and Meyer, T. R. (1982), Radio emission associated with rock fracture: Possible application to the great Chilean earthquake of May 22 1960, *J. Geophys. Res.*, 87(B4), 2851-2859.