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Tricritical crossover in earthquake preparation by analyzing preseismic electromagnetic emissions

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ABSTRACT

Fracture-induced electromagnetic emissions (EME) have been observed from the laboratory to the geophysical scale permitting the monitoring of damage evolution. It has been shown that the first appearing MHz EME presents second-order phase transition characteristics and has been attributed to the fracture process of the heterogeneous medium surrounding the family of strong entities (asperities) distributed along the fault sustaining the system. The finally, abruptly, emerged strong avalanche-like kHz EME do not present any footprint of a second-order transition in equilibrium, while they have been attributed to the fracture of the family of the, relatively homogeneous, asperities themselves. In the present work we show that between these two stages of the fracture process, an intermediate stage exists. This is reflected to the tricritical behavior which is revealed for the kHz EME just before the emergence of the strong avalanche-like kHz emission. The identification of this tricritical behavior is performed using the method of critical fluctuations (MCF). The results obtained for the kHz time-series are compatible with the results obtained for an introduced model map which describes the tricritical crossover. A Hurst exponent analysis shows that this crossover indicates the limit of an antipersistence dynamics. It is finally shown, by the MCF, that first-order phase transition characterizes the final rupture of the asperities.

1. Introduction

Material scientists are highly interested in the possible precursors of macroscopic failures. During mechanical loading of materials there are fracture-induced emissions that permit a real-time monitoring of damage development. In particular, opening cracks are accompanied by the production of electromagnetic emissions (EME) and acoustic emissions (AE) in a wide frequency spectrum ranging from the kHz to the MHz bands; these emissions can be considered as precursors of general fracture (Chishko, 1989, 1992; Fukui et al., 2005; Hadjicontis et al., 2007, 2011; Kumar and Misra, 2007; Stavrakas et al., 2007; Chauhan and Misra, 2008; Baddari et al., 1999, 2011; Baddari and Frolov, 2010; Lacidogna et al., 2011; Carpinteri et al., 2012). Several models have been put forth to explain the origin of electromagnetic (EM) emission (Hayakawa and Fujinawa, 1994; Gokhberg et al., 1982, 1995; Bahat et al., 2005; Contoyiannis et al., 2005, and references therein; Hadjicontis et al., 2007). We consider in particular the "movement of charged crack surfaces". In this model (Contoyiannis et al., 2005, and references therein), when a crack opens the rupture of interatomic (ionic) bonds leads to intense charge separation. Direct evidence of a surface charge of opposite polarity on fresh fracture surfaces has been provided. Simultaneous measurements of the electron, ion, and photon emission (fractoemission) accompanying fracture support the hypothesis that charge separation accompanies the formation of fracture surfaces. On the faces of a newly created crack the electric charges constitute an electric dipole or a multipole of higher order, and due to crack wall motion, EM radiation is emitted. Crack motion in fracture dynamics has recently been shown to be governed by a dynamical instability, which causes oscillations in the crack velocity and structure on the fracture surface. Evidence indicates that the instability mechanism is local branching; i.e., a multicrack state is formed by repetitive, frustrated microfracturing events. Laboratory experiments show

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intense EM fractoemission during this unstable crack growth. In this unstable stage we regard the emission from the correlated population of fractoemitters as a precursor of the final global instability. Note that, other models have also been proposed for the emission of a variety of signals detected prior to fracture (e.g., Vallianatos and Tzanis, 1999; Bahat et al., 2002, and references therein; Tzanis and Vallianatos, 2002; Vallianatos et al., 2004; Uritsky et al., 2004).

The Earth's heterogeneous crust under specific conditions experiences sudden release of energy following large-scale mechanical failure. These phenomena of potential catastrophic nature are known as earthquakes (EQs). MHz–kHz EM pre-failure emissions have been reported not only at the laboratory but also at the geological scale (Eftaxias et al., 2006, 2007, 2011; Uyeda et al., 2009; Cicerone et al., 2009). The hypothesis that the fracture-induced MHz–kHz EM fields should also permit the monitoring of the gradual damage of stressed materials in the Earth's crust, as actually happens during the corresponding mechanical loading laboratory experiments, is reasonable. Having as a springboard the research that had already systematically begun as early as the 1970s for the observation and the evaluation of electromagnetic anomalies emerged prior to significant earthquakes (Warwick et al., 1982; Gokhberg et al., 1995, and references therein; Hayakawa, 1999; Hayakawa and Fujinawa, 1994; Hayakawa and Molchanov, 2002), Prof. Nomicos from 1992 until 1995 developed the necessary instrumentation and installed a pilot network comprising 4 remote telemetric stations along the Island of Crete (south Greece) for the recording of EME in the MHz and kHz bands (Nomikos et al., 1997; Vallianatos and Nomikos, 1998). By 1998 Prof. Nomicos expanded his network to 12 stations throughout Greece (cf. map in the link: http://users.teiath.gr/gregkoul/emv/currentexperiments.html). Since 1994, our research team, in cooperation with Prof. Nomicos, was mainly focused on the modeling of the earthquake generation process by means of objectively identified, through multidisciplinary time-series analysis tools, MHz–kHz EME, leading to a continuing progress in the specific research over the last 20 years (e.g., Eftaxias and Potirakis, 2013, and references therein). Towards this aim, an exemplary remote telemetric station has been installed in 1994 at Zakynthos (Zante) Island in the Ionian Sea (western Greece), using instrumentation developed by Prof. Nomicos. Zakynthos Island is located at a region of high tectonic activity, right on the Hellenic Arc (Kopanas, 1997). The telemetric station has been installed on a carefully selected mountainous site at the south-west of the island (37.76° N–20.76° E) providing at the same time very low background noise and high earth conductivity. The magnetotelluric and magnetic prospection, showed that the deep geoelectrical structure beneath the station is of 1D symmetry and very conductive ($\rho \approx 10\,\Omega$m), while the upper is of 2D symmetry with characteristic principal axis strike direction N 35°±5° W (Antonopoulos, 1996; Makris et al., 1999; Eftaxias et al., 2001). The station has been operated during two periods: (i) a trial/calibration period from December 1994 to December 1995; and (ii) the regular acquisition period from September 1998 to date (Kopanas, 1997). The main aim of this station is the detection of MHz–kHz EM anomalies. Thus, the measurement system comprises (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 $\lambda/2$ electric dipole antennas detecting the electric field variations at 41, 54 (later at 46) and 135 MHz respectively. 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 in the mountainous area of Zakynthos. We have been studying the possible seismogenic origin of the MHz–kHz anomalies observed prior to significant shallow EQs that occurred on land, by trying to answer the following three fundamental questions, of which the second is the key question (Eftaxias, 2012):

(i) "How can we recognize an EM observation as an EQ-related one?"
(ii) "How can we link an individual EM precursor with a distinctive stage of the EQ preparation process?"
(iii) "How can we identify precursory symptoms in the EM observations that indicate that the occurrence of the EQ is unavoidable?"

Another target of our research was to study the possible seismogenic origin of the MHz–kHz anomalies by investigating their consistency with other precursors that are imposed by data from other disciplines, namely, seismology (e.g., Papadimitriou et al., 2008; Potirakis et al., 2013, 2014), Thermal Infrared (TIR) anomalies (e.g., Karamanos et al., 2006), Synthetic Aperture Radars Interferometry (e.g., Potirakis et al., 2012), and lithosphere–atmosphere–ionosphere-coupling (e.g., Eftaxias et al., 2013). For these purposes, the measurement system of Zakynthos Island moreover comprises: (i) Two Short Thin Wire Antennas (STWA) of 100 m length each, lying on the Earth's surface in the EW and NS directions, respectively; the aim of this installation is the detection of ultra-low-frequency (<1 Hz) EM precursors rooted in a pre-seismic lithosphere–atmosphere–ionosphere (LAI) coupling; (ii) a magnetic sensor detecting magnetic variations at 1–100 kHz; (iii) electric sensors detecting electric variations at higher frequencies (142, 178, 230, 320, 390, 415 MHz). Our attention is to proceed to a pilot installation of sensors in higher frequency bands, up to the GHz region, which will investigate for EME that may be radiated during the last stage of the earthquake preparation process; namely, the stage of the preparation of the dynamical slip which results to the fast, even super-shear, mode (Eftaxias and Potirakis, 2013). The emission of such a radiation by the gouge formation, which behaves as bearings and it is found to be ubiquitous in brittle faults at all scales, cannot be excluded (Eftaxias and Potirakis, 2013). Although there have not been any EME reported at higher frequency bands (e.g., at GHz band) so far by the published laboratory experiments, it could be interesting to further investigate experimentally this possibility in the field in the case of very shallow significant earthquakes that occur on land.

In our opinion, 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, as it happens in the laboratory scale, in a short time period, could be characterized as possibly EQ related one (Kopanas, 1997; Eftaxias and Potirakis, 2013). We clarify that the observed EM potential precursors are associated with shallow EQs that occurred on land or near coastline with magnitude ~6 or larger (e.g., Kapiris et al., 2002, 2003; Eftaxias et al., 2004; Karamanos et al., 2006; Eftaxias and Potirakis, 2013). It is known that for an EQ with magnitude ~6 the fracture process extends to a radius of ~120 km (Bowman et al., 1998). We suggest that, for such EQs, the physical mechanism that permits an adequately high amount of fracture-induced EM emissions to be directly launched to the atmosphere is that of a Fractal Geo-Antenna. A network of fracture traces having a fractal distribution in space is formed as the seismic event approaches. The creation of the aforementioned network of traces/new surfaces forms a fractal network of EM emitters, namely, a Fractal Geo-Antenna which radiate in a cooperative way at the last stages of EQ preparation providing thus traceable MHz–kHz EME (Eftaxias et al., 2004; Eftaxias and Potirakis, 2013). At this point we would like to note that different mechanisms have been proposed and experimental results presented supporting the idea of propagation of electromagnetic signals of MHz–kHz range through the multi-layered Earth structure without strong attenuation. These, some of them motivated by surface-underground mine communications, are mainly based on the idea of propagation through