



On the biophysical mechanism of sensing upcoming earthquakes by animals



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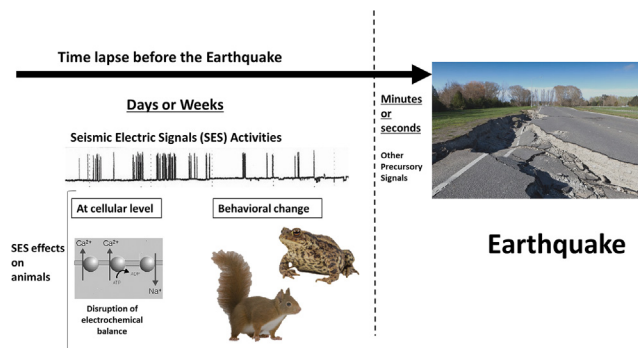
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HIGHLIGHTS

- Days or Weeks before major Earthquakes changes in animal behavior are detected.
- At the same time electric pulses called Seismic Electric Signals (SES) are recorded.
- These pulses can irregularly gate electro-sensitive ion channels on cell membranes.
- Disruption of electrochemical balance can be sensed by living organisms as stress.
- Unusual animal behavior is explained according to this mechanism.

GRAPHICAL ABSTRACT



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ABSTRACT

It is documented that a few days or weeks before major Earthquakes (EQs) there are changes in animal behavior within distances up to 500 km from the seismic epicenter. At the same time Seismic Electric Signals (SES), geomagnetic and ionospheric perturbations, are detected within similar distances. SES consist of single unipolar pulses, and/or groups of such pulses called "SES activities" with an average frequency between successive pulses on the order of ~ 0.01 Hz and electric field intensity on the order of $\sim 10^{-5}$ – 10^{-4} V/m (Frazer-Smith et al., 1990; Rikitake, 1998; Varotsos et al., 1993, 2011, 2019; Hayakawa et al., 2013; Grant et al., 2015). We show that the SES activities can be sensed by living organisms through the "Ion Forced-Oscillation Mechanism" for the action of Electromagnetic Fields (EMFs) on cells, according to which polarized EMFs can cause irregular gating of electro-sensitive ion channels on the cell membranes with consequent disruption of the cell electrochemical balance (Panagopoulos et al., 2000, 2002, 2015). This can be sensed by sensitive animals as discomfort in cases of weak and transient exposures, and may even lead to DNA damage and serious health implications in cases of intense exposure conditions (as in certain cases of man-made EMF exposures). Moreover, we show that the geomagnetic and ionospheric perturbations cannot be sensed through this mechanism. The same mechanism has explained meteoropathy, the sensing of upcoming thunderstorms by sensitive individuals, through the action of the EMFs of lightning discharges (Panagopoulos and Balmori, 2017). The present study shows that centuries-long anecdotal rumors of animals sensing intense upcoming EQs and displaying unusual behavior, lately documented by systematic studies, are now explained for the first time on the basis of the electromagnetic nature of all living organisms, and the electromagnetic signals emitted prior to EQs.

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1. Introduction

1.1. Changes in animal behavior prior to earthquakes

Reports regarding changes in animal behavior prior to major Earthquakes (EQs) have been known since antiquity, but neglected by Western organizations primarily because of the anecdotal nature of much of the evidence, and lack of a plausible mechanism explaining the phenomenon. In 373 BCE the Roman historian Aelian recorded descriptions of rats, dogs, snakes and weasels deserting in droves the Greek city Helike a few days before a catastrophic EQ which sunk the city into the sea (Soter, 1999). Since that time, unusual animal behaviors preceding major EQs have been reported in a wide variety of animals, including many species of mammals, birds, reptiles, fish, and insects. The reported precursory lead times vary from a few minutes to several months prior to the EQ (Tributsch, 1982; Rikitake, 1998; Bhargava et al., 2009; Hayakawa, 2013; Lakshmi et al., 2014; Woith et al., 2018).

It has been suggested that ground vibrations, humidity, temperature, atmospheric pressure changes, Electromagnetic Field (EMF) emissions, and/or gas/chemical emissions prior to EQs could be sensed by animals through a seismic escape behavioral system, and careful observations of animal populations could possibly be used for EQ prediction (Rikitake, 1998; Kirschvink, 2000; Cicerone et al., 2009; Bhargava et al., 2009; Hayakawa, 2013; Lakshmi et al., 2014). In August 1971 the State Seismological Bureau of China started collecting reports of unusual animal behavior for EQ prediction purposes. Four years later, based on such observations and geophysical measurements, they evacuated Haicheng city several hours before a powerful EQ of Magnitude (M) 7.3 on February 4, 1975. This EQ devastated the city and it is believed that the successful evacuation saved thousands of lives (Chinese Academy, 1977; Tributsch, 1982; Ikeya et al., 2000; Cicerone et al., 2009; Bhargava et al., 2009; Lakshmi et al., 2014).

In recent years, systematic studies have confirmed the changes in animal behavior prior to major EQs beyond any doubts (Rikitake, 1998; Hayakawa, 2013). Rikitake (1998) summarized many recorded cases of unusual animal behavior prior to large EQs and made statistical evaluations in terms of the distance (D) from the seismic epicenter and the time (T) before the EQ. He found that for strong EQs ($M \geq 6$), T ranges from minutes to (usually) ~ 100 days for any specific M , and D increases with M according to the equation: $M = 1.86 + 2.6 \log D$ or

$$\log D = 0.4M - 0.7 \quad (1)$$

Moreover, Rikitake concluded that from all possible triggers mentioned above for the abnormal animal behaviors, the most plausible seems to be EMF-emissions associated with the upcoming EQs, although additional influences such as ground vibrations and/or chemical emissions could not be ruled out (Rikitake, 1998; Hayakawa, 2013). Apart from Rikitake's first systematic study on the animal behavioral changes prior to EQs, other important case/statistical studies followed more recently:

A population of reproductively active common toads (*Bufo bufo*) monitored over a period of 29 days, before, during, and after an EQ ($M = 6.3$) at 74 km distance, showed a dramatic change in behavior 5 days before the EQ, abandoning spawning and not resuming until several days after the event. The recorded reduced toad activity coincided with pre-seismic Very Low Frequency (VLF: 3–30 kHz) EMF-emissions attributed to ionospheric perturbations (Grant and Halliday, 2010).

A more recent study (Grant et al., 2015) recorded changes in the behavior of mammals and birds obtained over a 30 day period by motion-triggered cameras located in a large national forest in Peru prior to a major EQ ($M = 7.0$) that occurred at a distance of 323 km from the forest. In addition, they collected VLF EMF measurements, along a propagation path passing over the epicentral region, attributed to ionospheric perturbations. The study found that animal activity declined significantly over a 3-week period prior to the EQ compared to periods of

low seismic activity while VLF perturbations started 2 weeks before the EQ with a large fluctuation 8 days prior to the EQ coinciding with a second sharp decrease in animal activity.

Another recent study recorded the daily milk yields of dairy cows for one year during which a total of 32 EQs occurred, 11 of them being of $M \geq 5$. They also collected VLF and Low Frequency (LF: 30–300 kHz) EMF data of ionospheric perturbations. The results revealed a statistically significant decrease in milk yields approximately 3 weeks before the occurrence of each EQ. In addition, while ionospheric VLF/LF perturbations occurred prior to all of the EQs, the milk yields decreased earlier than these VLF/LF EMF anomalies, suggesting that the animals responded to a stimulus different than VLF/LF EMF (Yamauchi et al., 2017).

Unusual reaction of many different animal species has been recorded in laboratory experiments after application of static electric field, or single monopolar electric pulses. In both cases the applied electric field intensity was significantly greater than that of the electric pulses preceding EQs (see Section 1.2) (Ikeya et al., 1996, 1998). Behavioral changes of animals accompanied by alterations in blood parameters were also recorded in laboratory experiments during electromagnetic emission generated by granite rock compression (Ikeya et al., 2000).

Another study showed changes in the circadian rhythms of mice, as well as dramatic increases in locomotor activity several times higher than the standard deviation, one day before an EQ ($M = 7.3$) in Japan, 50 km away from the seismic epicenter (Yokoi et al., 2003). Similarly, in another study in China, locomotor activity and circadian rhythm of laboratory mice dramatically decreased 3 days before an EQ ($M = 8$) (Li et al., 2009).

Regardless of EMF-emissions associated with EQs, it is well-known that animals are affected by EMFs in a wide range of frequencies (from 0 Hz up to the GHz range of modern mobile telecommunications) with Ultra Low Frequency (ULF) (0–3 Hz) and Extremely Low Frequency (ELF) (3–3000 Hz) EMFs being specifically bioactive (Presman, 1977; Panagopoulos and Margaritis, 2003; Panagopoulos et al., 2004, 2013a; Panagopoulos, 2016, 2019; Balmori, 2005, 2010; Nishimura et al., 2010).

1.2. Electromagnetic emissions prior to earthquakes

EMF-emissions prior to EQs have been recorded by many investigators and are considered to be a significant signature for short-term EQ prediction (Rikitake, 1998; Hattori, 2004; Hayakawa, 2013). Most important types of such emissions are:

1.2.1. VLF/LF ionospheric perturbation signals

Preseismic VLF/LF EMF-emissions (already reported in studies on animal behavioral changes) are considered to be due to ionospheric perturbations linked in recent years with EQs, indicating a seismo-ionospheric coupling (Maekawa et al., 2006; Rozhnoi et al., 2007). It has been suggested that electric charges produced by rock compression at the EQ focal area are released into the atmosphere causing perturbations in the Earth-ionosphere electric field (Grant et al., 2015). The electric field intensity of such emissions is found to be on the order of ~ 1 mV/m measured at ~ 200 kHz (Biagi et al., 2008). These EMF-emissions in several cases are reported to occur a few days later than the animal behavioral changes (Grant et al., 2015; Hayakawa, 2013; Yamauchi et al., 2017)

1.2.2. Seismic Electric Signals (SES)

Since the early 1980s Varotsos et al. have systematically detected Seismic Electric Signals (SES) before EQs within a range of 300–400 km from the seismic epicenter (Varotsos and Alexopoulos, 1984a, 1984b; Varotsos and Lazaridou, 1991; Varotsos et al., 1993, 2001, 2005a, 2005b, 2011, 2019). These are usually regarded in the literature as geoelectric field changes and are either single monopolar

electromagnetic pulses or groups of hundreds of such pulses called “SES activities” (Fig. 1). In both cases they are detected as voltage changes between two electrodes (metallic rods made of various metals such as Pb, Cu, etc., inserted at a depth of ~2 m in the ground) at several tens of km distance from each other (Varotsos et al., 1993, 2011). The SES (single or in groups) occur one time, usually a few weeks or months before an EQ, lasting from a few min up to a few days (Varotsos and Lazaridou, 1991; Varotsos et al., 2011). It is considered that once the SES have appeared, the seismic process has passed a “critical stage” after which the EQ is inevitable. The “critical stage” is also recognized by the temporal succession of pre-earthquakes in relation to their magnitude (Varotsos et al.,

2011). Apart from the SES occurrence, the “critical stage” seems to correlate with the initiation of changes in animal behavior (Grant et al., 2015; Yamauchi et al., 2017).

Major EQs have been found to be preceded by intense SES activities - with lead time generally ranging from a few (~7) hours to a few (~5.5) months before the EQ - accompanied by geomagnetic field variations mainly recorded on its vertical component (Varotsos et al., 2011, 2019). For isolated events (i.e. when a single SES and a single EQ allow a one-to-one correlation), the time-lag T between SES and EQ lies between 7 h and 11 days. For cases of prolonged electrical and/or seismic activity (i.e. when a number of SES detected within a time period is

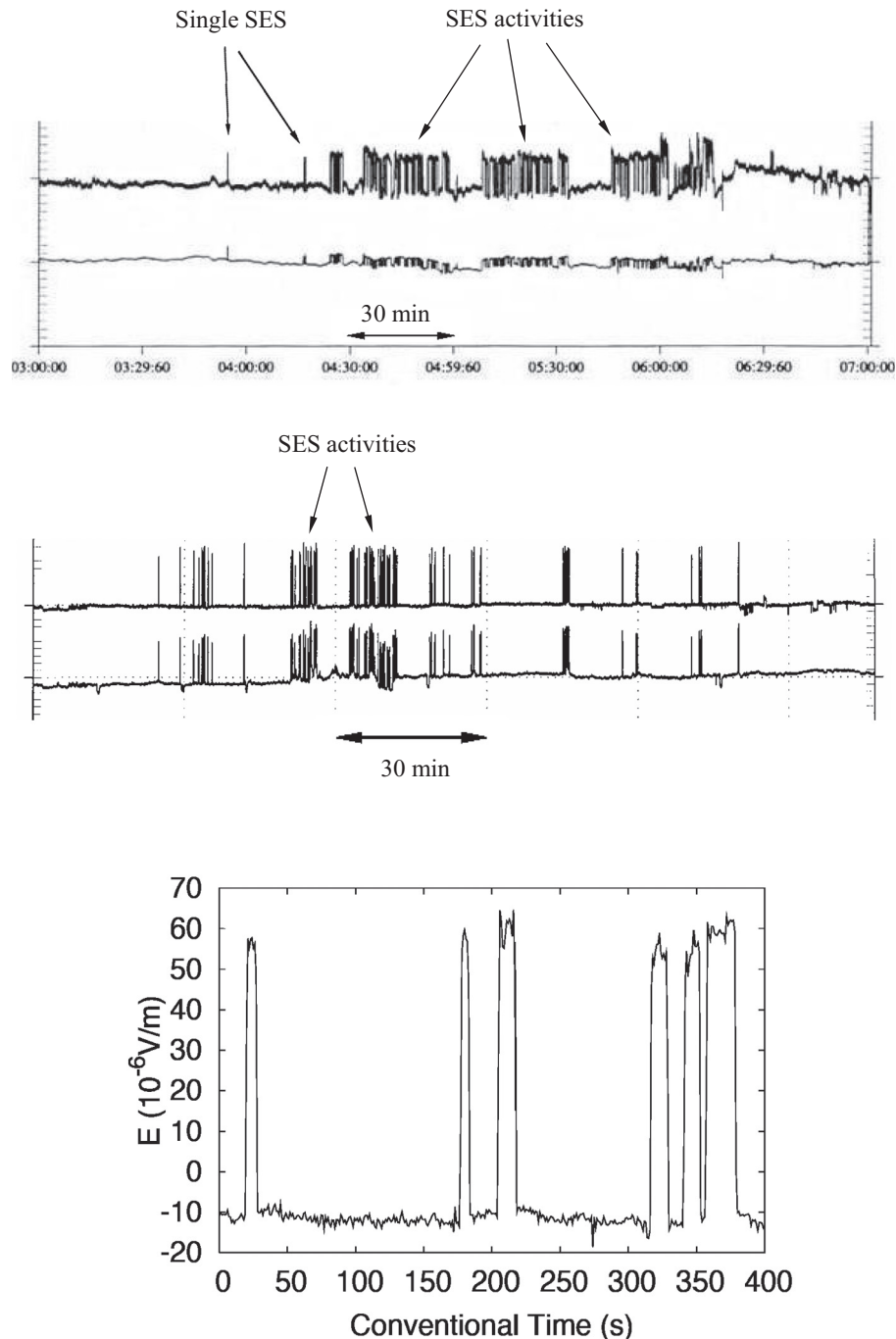


Fig. 1. a Simultaneous recording of SES activities by two different pairs of electrodes at different locations. In the vertical axis are the voltages between the two electrodes of each pair (arbitrary units). In the horizontal axis is the time (hr:min:sec) (from Varotsos et al., 2001) b: Simultaneous recording of SES activities by two different pairs of electrodes at different locations. In the vertical axis are the voltages between the two electrodes of each pair (arbitrary units). In the horizontal axis is the time (arbitrary units) (from Varotsos et al., 2005a) c: Small time-scale recording of SES activity. Electric field intensity is $\sim 70 \times 10^{-6}$ V/m, and pulse repetition frequency 0.007–1 Hz (from Abe et al., 2005).

followed by a number of EQs) it has been observed that, although the time-lag between the onsets of the electrical and seismic activity does not usually exceed 11 days, the time-lag between the largest SES and the strongest EQ may be much longer, usually around 22 days. No correlation between T and M has been observed (Varotsos and Lazaridou, 1991; Varotsos et al., 2011). [We note here a remarkable similarity of the reported time-lag between the strongest SES and the strongest EQ (~22 days) by Varotsos et al., with the 3-week period prior to the EQ when the changes in animal behavior were reported to initiate by Grant et al., 2015, and Yamauchi et al., 2017].

Frequently in the literature, SES are referred to as “DC” (direct current) geoelectric field emissions (Hayakawa, 2013). While the single SES pulses are indeed DC (unipolar) pulses, the “SES activities” are actually ULF EMF-emissions since they are groups of pulses with a repetition frequency in the ULF band. The average repetition frequency of the SES activities is on the order of 0.01 Hz (it ranges from ~0.001 to ~0.1 Hz), and the electric field intensity on the order of 10^{-5} – 10^{-4} V/m (at a few hundreds of km from the epicenter) (Fig. 1). The SES are recorded as polarized electric pulses emitted from the focal area of an EQ when the gradually increasing mechanical stress before the EQ occurrence reaches a critical stage during which electric dipoles formed in the Earth’s crust due to point defects and normally having random orientations, attain cooperative orientations [in other words, when the electric dipoles become polarized] (Varotsos and Alexopoulos, 1984a, 1984b; Varotsos et al., 1993, 2011, 2019; Abe et al., 2005). Other investigators have also recorded SES-like emissions prior to EQs confirming the reports by Varotsos et al. (Orihara et al., 2002; Huang and Lin, 2010). There are significant developments on successful EQ-prediction within a time-window of a few days, based on SES observation and a method developed by Varotsos et al. called “natural time analysis” (Uyeda and Kamogawa, 2008; Varotsos et al., 2011).

Varotsos and Alexopoulos (1984b) have suggested the following empirical equation between SES max intensity E , the distance D between focal area and SES recording location, and M (a , b are constants determined empirically from the observed data):

$$\log(ED) = aM + b \quad (2)$$

We note a profound similarity of Eq. (2) with Eq. (1) empirically suggested by Rikitake (1998) for the occurrence of the animal behavioral changes.

It has been reported that there is selectivity in the areas where the SES can be detected. This means that the SES can be detected only at certain sites, while most of randomly chosen sites are insensitive, and a sensitive site is sensitive only to SES from some specific focal area (s) (Orihara et al., 2002; Varotsos, 2005; Huang and Lin, 2010). It was found that this selectivity depends upon the conductivity of the path between the seismic focal area and the recording site (Huang and Lin, 2010) which is absolutely expected for electromagnetic signals transmitted through a medium (in this case the Earth’s crust) which is not homogeneous/isotropic.

Apart from the SES (with lead times ranging from several hours to a few months as already reported), just a few minutes before the EQ electric and magnetic pulses 10–100 times stronger than SES are emitted from the seismic focal area (Varotsos et al., 1993, 2011). Moreover, minutes or seconds before the EQ mechanical elastic waves referred to as P and S waves are emitted (Cicerone et al., 2009; Lakshmi et al., 2014). Unfortunately these precursory emissions (both the mechanical and the electromagnetic) are not very useful for prediction as they occur very short time before the EQ.

1.2.3. ULF geomagnetic field changes

ULF geomagnetic field changes were recorded before the 1989 Loma Prieta EQ ($M = 6.9$) in California USA, 7 km from the epicenter. The changes/anomalies started about a month before the EQ suggesting a specific precursor activity. A first anomaly started ~4 weeks before the

EQ with frequency close to 0.1 Hz and a second anomaly started ~2 weeks later with frequency close to 0.01 Hz. Finally two more anomalies occurred during the last day before the EQ. The largest magnetic field intensity changes were on the order of 20–60 nT. Simultaneous recordings in the ELF and VLF bands (10 Hz–32 kHz) did not reveal any specific precursor activity (Frazer-Smith et al., 1990).

Kopytenko et al. (1993) reported ULF geomagnetic field changes on the order of 0.2 nT at 0.1–1 Hz, a few hours before a $M = 6.9$ EQ in Spitak (Armenia) 1988, at distances 120–200 km from the epicenter.

Hayakawa et al. (1996) reported geomagnetic field changes with main frequency 0.02–0.05 Hz and maximum intensity ~ 0.1 nT, before an $M = 7.1$ EQ at Guam island (Japan) 1993, 65 km from the epicenter. The changes started about a month before and had a peak about 2 weeks before the EQ.

The smaller magnetic field intensities recorded by Kopytenko et al. (1993) and Hayakawa et al. (1996) than those by Frazer-Smith et al. (1990) are obviously due to the longer distances. Since most of the animal observations account for distances of a few hundreds of km from seismic epicenters, a value of 0.1 nT for these emissions will be considered as representative in our study.

Hayakawa (2013) compared the temporal occurrence between animal behavioral changes as summarized by Rikitake, and the seismogenic EMF-emissions at different frequency bands. He concluded that ULF geomagnetic changes should be the main trigger of abnormal animal behavior, underscoring however that the biophysical mechanism is unknown.

The occurrence of the preseismic EMF-emissions described above - especially the SES and the geomagnetic field changes - seem to temporally correlate with the animal behavioral changes. In the present study we examine whether these pre-seismic EMF-emissions can theoretically be sensed by living organisms according to the Ion Forced-Oscillation mechanism for the action of polarized EMFs on living cells (Panagopoulos et al., 2000, 2002, 2015).

2. The sensing of upcoming earthquakes by living organisms according to the “Ion Forced-Oscillation” mechanism

2.1. The mechanism

According to a published biophysical mechanism (Panagopoulos et al., 2000, 2002, 2015), polarized EMFs can alter the function of any living cell by irregular gating of electro-sensitive ion channels on the cell membranes and consequent disruption of the cell’s electrochemical balance, at very low field intensities especially in the ULF and ELF bands. The mechanism is based on molecular/physical data and predicts that the bioactivity of the externally applied EMF is proportional to its intensity, inversely proportional to its frequency, and doubles for pulsed EMFs. The mechanism was verified for its plausibility by numerical test while other suggested mechanisms did not pass the same test (Halgamuge and Abeyrathne, 2011). The basic idea of the mechanism is that the forced-oscillation of ions in the vicinity of the voltage-sensors of voltage-gated ion channels caused by externally applied polarized EMFs can exert forces on these sensors equal to or greater than the electrostatic forces - exerted by changes in the transmembrane electric field - known to physiologically gate these channels. Irregular gating of these channels can disrupt any cell’s electrochemical balance and function (Alberts et al., 1994), leading to a variety of biological/health effects ranging from a transient mild stress to the most detrimental effects, such as DNA damage, cell death, or cancer development through induction of oxidative stress (Barzilai and Yamamoto, 2004; Pall, 2013).

A review of the whole EMF-bioeffects literature reveals that the most bioactive EMFs are the lower frequency ones, especially the ULF/ELF fields. In many cases of radio-frequency (RF) signals modulated by ELF signals, it is found that the modulation (ELF) and not the carrier (RF) is responsible for the biological effects. Moreover it has been repeatedly shown that RF EMFs modulated by ELF pulses are more bioactive than

continuous fields (without pulse-modulation) of the same rest characteristics (Bawin et al., 1975, 1978; Bawin and Adey, 1976; Frei et al., 1988; Bolshakov and Alekseev, 1992; Goodman et al., 1995; Penafiel et al., 1997; Huber et al., 2002; Höytö et al., 2008; Franzellitti et al., 2010; Campisi et al., 2010; Panagopoulos et al., 2013a; Panagopoulos, 2019). These facts are in agreement with the Ion Forced-Oscillation mechanism.

All critical biomolecules are either electrically charged or polar (Alberts et al., 1994; Stryer, 1996). The sum electric field from an infinite number of individual electric pulses of random polarizations (as e.g. with natural light), tends to zero

$$\lim_{n \rightarrow \infty} \sum_{i=1}^n \vec{E}_i = \vec{E}_1 + \vec{E}_2 + \vec{E}_3 + \dots + \vec{E}_n = 0 \quad (3)$$

and thus, unpolarised EMFs at any intensity cannot induce any parallel/coherent oscillation on these molecules (Panagopoulos et al., 2015). On the contrary, polarized EMFs induce a parallel and coherent forced-oscillation on every charged/polar molecule within biological tissue. This is fundamental for understanding the induction of biological effects through the described mechanism. This oscillation will be most evident on the free (mobile) ions (the smallest charged free particles in biological tissue) which carry a net electric charge and exist in large concentrations in all types of cells and extracellular tissues determining practically all cellular/biological functions (Alberts et al., 1994). Although all molecules move randomly in every direction with much higher velocities/displacements due to thermal motion, this has no biological effect other than increasing tissue temperature. But a parallel and coherent oscillation of even millions of times smaller energy than average thermal molecular energy can initiate biological effects (Panagopoulos et al., 2002, 2013b). Most cation channels (Ca^{+2} , K^+ , Na^+ , etc.) on the membranes of all animal cells, are voltage-gated, or “electro-sensitive” (Alberts et al., 1994; Stryer, 1996). They interconvert between their open and closed state, when the electrostatic force on the electric charges of their voltage sensors due to transmembrane voltage changes, transcends some critical value. The voltage sensors of these channels are four symmetrically arranged, transmembrane, positively charged helical domains, each one named S4. Changes in the transmembrane voltage on the order of ~30 mV are normally required to gate electro-sensitive channels (Noda et al., 1986; Liman et al., 1991). Several ions may interact simultaneously each moment with an S4 domain from a distance on the order of 1 nm, as - except for the single ion that may be passing through the channel pore at any instant while the channel is opened - a few more ions are bound close to the pore of the channel at specific ion-binding sites (e.g. three in potassium channels) (Miller, 2000).

Consider e.g. four potassium ions at distances on the order of 1 nm from the channel-sensors (S4), and an externally applied oscillating EMF. The average electric (and magnetic) force on each ion due to any unpolarized EMF/EMR is zero (Eq. (3)). On the contrary, the force due to a polarized field with an electrical component E , is $F = Ezq_e$, (zq_e the ion's electric charge).

It has been shown that for a sinusoidal alternating electric field $E = E_o \sin \omega t$, the motion equation of a free ion is (Panagopoulos et al., 2000, 2002, 2015):

$$m_i \frac{d^2 r}{dt^2} + \beta \frac{dr}{dt} + m_i \omega_o^2 r = E_o z q_e \sin \omega t \quad (4)$$

where m_i is the ion's mass, r is the ion's displacement due to the forced-oscillation, z is the ion's valence ($z = 1$ for potassium ions), $q_e = 1.6 \times 10^{-19} \text{C}$ the elementary charge, β the damping coefficient for the ion's displacement (calculated to have a value within a channel $\beta \approx 6.4 \times 10^{-12} \text{ kg/s}$), $\omega_o = 2\pi\nu_o$ (ν_o the ion's oscillation self-frequency taken equal to the recorded spontaneous intracellular ionic

oscillation frequencies on the order of 0.1 Hz), $\omega = 2\pi\nu$ (ν the frequency of the applied field), and E_o the amplitude of the applied field.

The right part of Eq. (4) is the force on the ion due to the externally applied E -field. The second term of the left part ($\beta \frac{dr}{dt}$) is the damping force on the ion, the third term of the left part ($m_i \omega_o^2 r$) is a restoration force on the ion exerted by the medium, and the first term of the left part ($m_i \frac{d^2 r}{dt^2}$) is the resultant force on the ion (Panagopoulos et al., 2000, 2002). [We note that while any oscillating ion close to the S4 sensors exerts gating forces on them, receives zero opposite force from them since the S4 charges are paired with opposite charges from adjacent parts of the channel (Stryer, 1996)].

The general solution of Eq. (4), is (Panagopoulos et al., 2000):

$$r = \frac{E_o z q_e}{\beta \omega} \cos \omega t + \frac{E_o z q_e}{\beta \omega} \quad (5)$$

The constant term $\frac{E_o z q_e}{\beta \omega}$ in the solution, represents a constant displacement, but has no effect on the oscillating term $\frac{E_o z q_e}{\beta \omega} \cos \omega t$. This constant displacement doubles the amplitude $\frac{E_o z q_e}{\beta \omega}$ of the forced-oscillation at the moment when the field is applied or interrupted, or during its first and last periods, and the ion's displacement would be twice the amplitude of the forced-oscillation. For pulsed fields (such as those associated with SES activities, or the fields of modern digital telecommunications) this takes place constantly with every repeated pulse. Thus, pulsed fields are - theoretically - twice as much bioactive as continuous/non-interrupted fields of the same other parameters, in agreement with many experimental data (Frei et al., 1988; Bolshakov and Alekseev, 1992; Huber et al., 2002; Höytö et al., 2008; Campisi et al., 2010; Franzellitti et al., 2010).

The amplitude of the forced-oscillation (ignoring the constant term in Eq. (5)) is:

$$A = \frac{E_o z q_e}{\beta \omega} \quad (6)$$

The force acting on the effective charge q of an S4 domain, via an oscillating single-valence free ion, is: $F = \frac{1}{4\pi\epsilon\epsilon_o} \cdot \frac{q \cdot q_e}{r^2}$, (r is the distance of the free ion from the effective charge of S4). Each oscillating ion displaced by dr , induces an additional force on each S4 sensor, due to its displacement:

$$dF = -\frac{q \cdot q_e}{2\pi\epsilon\epsilon_o r^3} dr \quad (7)$$

While in the case of an oscillation induced by a non-polarized applied field $\sum d\vec{r} = 0$, and $\sum d\vec{F} = 0$, in the case of a polarized applied field (such as those of SES and possibly the geomagnetic field changes), the sum force on the channel sensor from all four ions, is:

$$4dF = -2 \frac{q \cdot q_e}{\pi\epsilon\epsilon_o r^3} dr \quad (8)$$

The effective charge of each S4 domain is found to be: $q = 1.7 q_e$ (Liman et al., 1991). The minimum force on this charge required normally to gate the channel - equal to the force generated by a change of 30 mV in the membrane potential - is calculated to be (Panagopoulos et al., 2000):

$$dF = 8.16 \times 10^{-13} \text{ N.}$$

The displacement of one single-valence ion within the channel, necessary to exert this minimum force is then calculated from Eq. (7) to be:

$$dr = 4 \times 10^{-12} \text{ m}$$

For 4 cations oscillating on parallel planes and in phase due to an external polarized field, the minimum displacement is (according to Eq. (8)) reduced to:

$$dr = 10^{-12} \text{ m}$$

Therefore, we come to a crucial finding: Any external polarized oscillating EMF able to force free ions to oscillate with amplitude

$$\frac{E_0 z q_e}{\beta \omega} \geq 10^{-12} \text{ m} \quad (9)$$

is able to irregularly gate electro-sensitive ion channels on cell membranes. For $z = 1$ (e.g. potassium ions), and substituting the values for q_e , β on the last condition, we get:

$$E_0 \geq 0.25\nu \times 10^{-3} \quad (\nu \text{ in Hz, } E_0 \text{ in V/m}) \quad (10)$$

For double-valence cations ($z = 2$) (e.g. Ca^{+2}) the condition becomes,

$$E_0 \geq \nu \times 10^{-4} \quad (\nu \text{ in Hz, } E_0 \text{ in V/m}) \quad (11)$$

For pulsed fields (such as those of SES activities) the right part of Condition 11 is divided by 2, and becomes:

$$E_0 \geq 0.5\nu \times 10^{-4} \quad (\nu \text{ in Hz, } E_0 \text{ in V/m}) \quad (12)$$

It is clear that the amplitude of the ions' forced-oscillation given by Eq. (6) is the crucial parameter to quantitatively estimate the ability of an externally applied polarized EMF to induce biological/health effects. We shall call this amplitude, "Bioactivity of the EMF", or "EMF-Bioactivity". Thus:

$$\text{EMF-Bioactivity} = \frac{E_0 z q_e}{\beta \omega} = k \cdot \frac{E_0}{\nu} \quad (13)$$

where $k = \frac{z q_e}{2\pi\beta}$ is a constant quantity for any specific ion type in the vicinity of a voltage-gated ion channel in a cell membrane, E_0 the intensity amplitude and ν the frequency of the applied electric field.

Eq. (13) shows that the bioactivity of an oscillating EMF is proportional to the field's maximum intensity (amplitude) (E_0) and inversely proportional to the field's frequency (ν). Thus, lower frequency fields are more bioactive than higher frequency ones with the same other parameters. This refers to all types of polarized harmonically oscillating EMFs. Non-harmonically oscillating EMFs can also be approximately described in terms of their bioactivity by Eq. (13).

For pulsed EMFs with harmonically oscillating carriers, the bioactivity doubles:

$$\text{Pulsed EMF-Bioactivity} = 2k \cdot \frac{E_0}{\nu} \quad (14)$$

The same mechanism can explain the biological action of polarized oscillating magnetic fields as well, if we replace the electric force $F_E = Ezq_e$, by the force:

$$F_B = Buzq_e \quad (15)$$

exerted on an ion with charge zq_e , moving with velocity u , vertically to the direction of a magnetic field of intensity B . In the simplest case of an alternating magnetic field $B = B_0 \sin \omega t$, with intensity amplitude B_0 and according to the same reasoning as above, we get corresponding bioactivity conditions for an oscillating magnetic field.

For one single-valence ion moving through an open channel vertically to the direction of the applied magnetic field with $u = 0.25 \text{ m/s}$ (the velocity calculated for ions moving through an open channel) (Panagopoulos et al., 2000) and for the case of a continuous oscillating magnetic field, the corresponding bioactivity condition is:

$$\frac{B_0 u q_e}{\beta \omega} \geq 4 \times 10^{-12} \text{ m} \quad (\omega \text{ in rad/s, } u \text{ in m/s, } B_0 \text{ in T}), \quad (16)$$

from which, we get:

$$B_0 \geq 4 \times 10^{-3} \nu \quad (\nu \text{ in Hz, } B_0 \text{ in T}) \quad (17)$$

or

$$B_0 \geq 4 \times 10^6 \nu \quad (\nu \text{ in Hz, } B_0 \text{ in nT}) \quad (18)$$

For double-valence ions and pulsing magnetic field the right parts are divided by 4, and the bioactivity condition becomes:

$$B_0 \geq 10^6 \nu \quad (\nu \text{ in Hz, } B_0 \text{ in nT}) \quad (19)$$

[We note that apart from the ion's drift velocity through the channel ($u = 0.25 \text{ m/s}$) that we accept as initial velocity, the ion will acquire an additional velocity dr/dt due to the forced-oscillation. The corresponding magnetic force due to this additional velocity $Bzq_e(dr/dt)$ is negligible ($>10^8$ times smaller) compared to the damping force $\beta(dr/dt)$ and thus it is not taken into account in Eq. (4)].

2.2. Testing the bioactivity of EQ precursory EMF-emissions according to the Ion Forced-Oscillation mechanism

2.2.1. VLF/LF ionospheric perturbation signals

For 10 kHz (VLF) EMFs, Condition 12 gives: $E_0 \geq 0.5 \text{ V/m}$, and for 200 kHz (LF) EMFs, $E_0 \geq 10 \text{ V/m}$. These are the minimum required intensity values in order for the VLF/LF EMF-emissions (assuming they are pulsed and totally polarized even though this is rather unlikely) to be able to produce bioeffects. As we can see they are $\sim 10^3$ – 10^4 times stronger than the measured intensity values at this band (up to $\sim 1 \text{ mV/m}$) (Biagi et al., 2008). Thus according to the presented biophysical mechanism, preseismic VLF/LF electromagnetic signals are not expected to be responsible for the animal behavioral changes.

2.2.2. SES activities

As already described, SES activities are polarized and pulsed EMFs in the ULF band (0.001–0.1 Hz) recorded with intensities on the order of $\sim 10^{-5}$ – 10^{-4} V/m at distances 300–400 km from EQ epicenters (Varotsos et al., 1993, 2001, 2005a, 2005b, 2011, 2019). For SES activities with an average pulse repetition frequency $\nu = 0.01 \text{ Hz}$, Condition 12 becomes:

$$E_0 \geq 0.5 \times 10^{-6} \text{ V/m} \quad (20)$$

Conservatively accepting a higher average pulse repetition frequency of 0.1 Hz, Condition 12 gives:

$$E_0 \geq 0.5 \times 10^{-5} \text{ V/m} \quad (21)$$

The intensity of recorded SES activities at distances 300–400 km away from the location of seismic epicenters is on the order of 10^{-5} – 10^{-4} V/m, and thus the bioactivity [Condition 12](#) is well satisfied both for the most representative (0.01 Hz) and the higher (0.1 Hz) average pulse repetition frequencies. Thus, for both average SES activity frequencies 0.01 Hz, and 0.1 Hz, the recorded SES intensities $\sim 10^{-5}$ – 10^{-4} V/m are above the minimum values required to produce bioeffects given by [Conditions 20, 21](#).

It follows that SES activities ULF EMFs recorded usually a few weeks prior to large EQs are able to induce irregular gating of electro-sensitive ion channels on animal cell membranes and thus be sensed by sensitive animals (e.g. in the form of stress).

2.2.3. ULF geomagnetic field changes

For $\nu = 0.01$ Hz a frequency close to the recorded ULF geomagnetic changes, [Condition 19](#) gives:

$$B_0 \geq 10^4 \text{ nT} \quad (22)$$

The maximum ULF geomagnetic field changes recorded prior to EQs are ~ 0.1 nT at a few hundreds of km away from focal area ([Kopytenko et al., 1993](#); [Hayakawa et al., 1996](#); [Cicerone et al., 2009](#)), and thus are $\sim 10^5$ times smaller than the above minimum required bioactive magnetic field intensity. Thus, the recorded changes of the geomagnetic field, even at its lower frequency and even if we consider these field anomalies totally polarized and pulsing, are unlikely to constitute the triggers for the recorded animal behavioral changes.

2.3. Results

It follows that according to the Ion Forced-Oscillation mechanism, the VLF/LF ionospheric emissions or the ULF geomagnetic field changes detected before EQs are not likely to be the triggers that induce the recorded animal behavioral changes. On the contrary, the SES activities can very well be. This is a crucial finding of the present study.

3. Discussion

We showed here that the SES activities ULF EMFs emitted before EQs ([Varotsos and Alexopoulos, 1984a, 1984b](#); [Varotsos and Lazaridou, 1991](#); [Varotsos et al., 1993, 2001, 2005a, 2005b, 2011, 2019](#); [Abe et al., 2005](#)) can be sensed by animals according to the Ion Forced-Oscillation mechanism for the action of polarized EMFs on cells ([Panagopoulos et al., 2000, 2002, 2015](#)). Moreover we showed that the other precursory EMF signals (the ionospheric VLF/LF and the geomagnetic ULF emissions) cannot be sensed according to the same mechanism.

Although some researchers have objected to the existence of the SES as well as of the ULF geomagnetic field changes claiming that the recordings might be artifacts due to sources other than the seismic preparation area or due to malfunction of the recording systems ([Lighthill, 1996](#); [Kirschvink, 2000](#); [Thomas et al., 2009](#)), our present study is in good agreement with both the physical parameters of the SES activities, and the animal behavioral changes that seem to temporally correlate with these emissions.

Probably all types of EMF pre-seismic signals are interrelated between them, since our whole planet is of electromagnetic nature with its geoelectric, geomagnetic, and atmospheric EMFs interconnected, and associated with natural phenomena and with all forms of life ([Presman, 1977](#); [Dubrov, 1978](#); [Panagopoulos, 2013](#); [Panagopoulos and Balmori, 2017](#); [Panagopoulos and Chrousos, 2019](#)). It has been reported that SES are accompanied by geomagnetic field variations mainly recorded on its vertical component ([Varotsos et al., 2011, 2019](#)). The reason why the VLF/LF emissions usually seem to take place a little later than the animal behavioral changes (and the other two types of EMF-emissions) ([Hayakawa, 2013](#); [Grant et al., 2015](#))

may be the time needed for the electric charges produced at the seismic focal area to be released in the atmosphere and produce ionospheric perturbations.

Although the animal behavioral changes prior to major EQs reported since antiquity were treated with skepticism by scientific authorities in the Western world ([Woith et al., 2018](#)), now for the first time they are fully explained by our present study.

The SES activities ULF EMFs recorded prior to EQs have not been specifically considered until now as the possible trigger for the recorded animal behavioral changes. On the contrary, the ULF geomagnetic or the VLF/LF EMF-emissions were mostly considered as such ([Hayakawa, 2013](#); [Grant et al., 2015](#)).

[Hayakawa \(2013\)](#) suggested that the ULF geomagnetic field changes should be the main trigger, arguing that the second (stronger) anomaly reported by [Frazer-Smith et al. \(1990\)](#) in the geomagnetic field ~ 2 weeks before the EQ temporally correlates with the animal behavioral changes as summarized by [Rikitake \(1998\)](#). But according to [Frazer-Smith et al. \(1990\)](#) the first ULF anomaly was recorded ~ 4 weeks before the EQ and the data correlate with the occurrence of the SES activities as well. According to [Rikitake \(1998\)](#) the majority of recorded animal changes start 10–25 days before large EQs which also correlates with both the geomagnetic changes and the occurrence of the SES activities. However, the mechanism predicts that minimum intensities on the order of $\sim 10^4$ nT are necessary for the geomagnetic emissions to be bioactive for a frequency at 0.01 Hz, while the recorded magnetic field intensities at distances of a few hundreds of km from EQ-epicenter are on the order of ~ 0.1 nT ($\sim 10^5$ times smaller) ([Kopytenko et al., 1993](#); [Hayakawa et al., 1996](#); [Cicerone et al., 2009](#)). Finally, any magnetically induced corresponding electric field within living tissue would be insignificant due to the very small temporal variation of the ULF magnetic fields, since a magnetically induced electric field would be proportional to the rate of magnetic field variation.

Similarly for the case of the ionospheric VLF/LF perturbations, the mechanism predicts that $\sim 10^3$ – 10^4 times stronger intensity values would be required for them to be able to induce biological changes.

In this study, like in the case of atmospheric discharges of upcoming thunderstorms ([Panagopoulos and Balmori, 2017](#)), we showed that according to the Ion Forced-Oscillation mechanism it is rather unlikely that the electromagnetic emissions responsible for the effects on animals and sensitive individuals are those in the VLF/LF band, and seems that the responsible emissions are the lower frequency ones in the ULF/ELF band, and more specifically the SES activities EMFs in the case of EQs.

Thus, the same mechanism explains both the sensing of upcoming EQs by animals, and the sensing of upcoming thunderstorms by sensitive individuals (meteoropathy) when the thunderstorm is thousands of km away and there are no meteorological signs denoting its advent. In both cases the key-trigger seems to be the ULF/ELF EMF-emissions associated with each phenomenon. Interestingly, it has been observed that some of the behaviors displayed by animals before EQs resemble their behaviors prior to thunderstorms ([Tributsch, 1982](#); [Bhargava et al., 2009](#)). These observations further confirm the validity of the presented mechanism.

Apart from the SES and the other precursory EMF-emissions, electric and magnetic pulses 10–100 times stronger than SES emitted from the focal area minutes or seconds before EQs ([Varotsos et al., 1993, 2011](#)) can certainly be sensed by animals according to the same mechanism as well. These emissions may explain reports of changes in animal behavior a short time before EQs ([Tributsch, 1982](#); [Rikitake, 1998](#); [Cicerone et al., 2009](#)). But as already argued in the Introduction, these precursors are of limited usefulness for EQ prediction because of the short time of occurrence before the EQ.

In the present study we provided a plausible mechanism which explains the reported sensing of upcoming EQs by animals. We did not distinguish between externally applied EMFs and internally induced ones within living tissue, especially in the case of ULF/ELF EMFs, as these

fields penetrate living tissue with small attenuation (magnetic fields penetrate with zero attenuation), and moreover the eyes, the brain, the skin cells, or the nerve fiber terminals ending up on the outer epidermis, are directly exposed to the field intensities measured externally on the surface of the organism. Moreover, it has been shown that tissue preparations (such as bovine fibroblasts or chicken tendons) respond to externally applied pulsed or sinusoidal ELF electric fields (by changes in DNA or protein synthesis rates, proliferation rates, alignment with respect to the field direction, etc.) at very low thresholds $\sim 10^{-3}$ V/m (Goodman et al., 1995; McLeod et al., 1987; Cleary et al., 1988; Lee et al., 1993). These thresholds are very close to those predicted for ELF EMFs by the mechanism described.

We note that a mechanism in science must be based on simple and reasonable postulates, and must necessarily be expressed quantitatively (by equations and numbers). Moreover, the values of the different parameters in the equations must be based on physical/molecular data. Qualitative descriptions alone or incomplete quantitative descriptions based on incomplete or unsolvable equations do not constitute a "mechanism". The above mechanism (Panagopoulos et al., 2000, 2002, 2015) is the only one that fulfills the above criteria in the case of EMF-induced bioeffects. Previous important attempts to formulate mechanisms for the action of EMFs on cells (Liboff, 1985; Lednev, 1991; Balcavage et al., 1996) were not successful, mainly because: 1) They had not taken into account damping and restoration forces. The difficulty was not related with considering such forces as this is standard in oscillation mechanics, but with calculating their parameters such as β and ω_0 , or the ion's maximum oscillation velocity within the biological medium. Without calculating these parameters, the motion Eq. [4] could not be solved. [For details on these calculations see Panagopoulos et al., 2000]. 2) They did not consider coordinating forces from several ions on the channel sensors due to polarization and coherence, which prevail against the greater but unpolarized forces due to the random thermal motion (Panagopoulos et al., 2002, 2015).

The suggestion that animals may sense upcoming EQs through the existence of biogenic magnetite in their brain which could be reoriented by geomagnetic field changes (Kirschvink and Gould, 1981; Kirschvink, 1989, 2000) may have a realistic base but a quantitative description of how reorientation of such particles (assuming they exist) could result in cellular changes has not been provided.

As mentioned in the Introduction, the reasons why reported changes in animal behavior prior to major EQs were neglected by Western authorities were: 1) The lack of systematic studies showing statistical significance of such changes, and 2) The lack of a plausible mechanism explaining the phenomenon. Now the animal behavioral changes are documented by systematic studies (Ikeya et al., 1996, 1998, 2000; Rikitake, 1998; Grant and Halliday, 2010; Hayakawa, 2013; Grant et al., 2015; Yamauchi et al., 2017), and the present study has explained the phenomenon according to a plausible mechanism.

It is remarkable that despite the fact that preseismic EMF-signals are observed for >35 years and the significant developments made by Varotsos et al. (Uyeda and Kamogawa, 2008; Varotsos et al., 2011), short-term EQ-prediction (time, location, magnitude) with a practical accuracy still remains a challenge. This shows the complexity of the problem but also the lack of adequate recording of the EQ precursory phenomena.

We hope that the responsible authorities and scientific organizations will pay the necessary attention and provide the appropriate means to organize better monitoring of both the preseismic EMF-emissions (especially the SES) and the animal behavioral changes.

Considering the reported selectivity of SES detection, and that the SES activities may be the main trigger for the reported animal behavioral changes, the same selectivity should also be observed in the animal behavioral studies. However, it seems this has not been examined. The best way this can be elucidated is the combined monitoring of both EMF precursory signals (especially SES) and the animal behavioral changes at the same places. Therefore we suggest the establishment of

small/mobile biological laboratories with a necessary population of laboratory animals e.g. frogs, mice, etc., that could be monitored in combination with the SES (and other EMF) emissions. This would contribute greatly a) in improving our knowledge on both EMF precursory signals and animal anticipatory behavioral changes, and b) in improving EQ prediction which remains an unresolved issue of extreme importance.

Declaration of competing interest

The authors declare they have no actual or potential competing financial interests.

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