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Electromagnetic Fault for Earthquake Lightning

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A density of bound charges, q, which cancel piezoelectric polarization, appears at a fault zone upon the disappearance of piezoelectricity due to the release of seismic stress, σ. q is described as $dq/dt = -\alpha d\sigma/dt - q/\varepsilon\rho$, where α, ε and ρ are the piezoelectric coefficient, the dielectric constant and the resistivity of the earth, respectively. A model of a fault with length $2a$ and displacement time τ gives $q = [\alpha\sigma_0\varepsilon\rho\tau(\beta/a)/(\tau - \varepsilon\rho)](e^{-t/\tau} - e^{-t/\varepsilon\rho})$ using the velocity of s-waves, β and the stress along the fault plane, σ_0. The intensity of earthquake lightning (EQL) and its spatial distribution are calculated based on the excitation of molecules by electrons accelerated under an electric field using the assumed q, taking atmospheric polarization into account.

KEYWORDS: model, earthquake, lightning, EQL, fault, piezoelectric, charge, stress, polarization, displacement, mean free path

1. Introduction

Earthquake lightning (EQL) was observed at the time of the Hanshin Earthquake that destroyed Kobe in 1995. This phenomenon has been discussed since the early work by Terada in 1931[1] and was photographed during the Matnshiro Earthquake.[2] EQL has been discussed as a precursor to a major earthquake since electromagnetic waves arrive much faster than seismic p- and s-waves which have the velocity of 8 and 4 km/s, respectively. The Hanshin Earthquake occurred just a few seconds after lightning was witnessed by graduate students and some professors of Osaka University about 20 km away from the epicenter indicating the phenomenon occurred during the fault movement.

The proposed mechanisms of EQL are electroatmospheric effects due to the dipole field by the zeta potential of water[1,3] piezoelectricity,[4,5] auroral solar activity,[6] sonoluminescence,[7] and triboluminescence due to landslides.[1] Rock fracture luminescence has also been suggested.[8] Fault dating by electron spin resonance (ESR) is based on the mechanical annealing of radiation-induced defects based on such fractures.[9] However, EQL above mountains covered with trees[1] cannot be explained by solid-state luminescence.

Spontaneous polarization of dipolar defects by a piezoelectric field is considered for seismic electric signals (SESs).[10] The dipolar field due to charged dislocations is noted as an alternative.[11] Electric dipoles induced by piezoelectricity or any other mechanism would be immediately compensated by charges in a conductive earth. In this respect, the prevailing concept of piezoelectric polarization which produces an electric field due to the seismic stress at a fault zone is incorrect. How large charge densities are sustained in a fault zone has been the subject of major controversy concerning electroatmospheric effects. Frictional heating as a mechanism to increase the resistivity of the earth is the only proposal to put forth so far.[12]

A large-scale geophysical phenomenon must be investigated using calculations that are semiquantitative, and have high orders of the magnitude variation and are based on a hypothetical model. A mathematical model of a fault has been used to explain seismic waves.[13–15] Hence, an electromagnetic model of a fault combined with the mathematical model may help to explain EQL and electromagnetic phenomena.

We propose an electromagnetic model of a fault having a huge electrostatic dipolar zone to explain EQL in terms of electroatmospheric phenomenon. The appearance of bound charges, which compensate piezoelectric polarization, occurs due to the disappearance of the polarization due to the release of seismic stress. Free electrons accelerated by the field excite molecules in air above a fault zone.

2. Mathematical Model for Electrostatic Fault

A mathematical model of a fault having a fault plane with area A, length $2a$, final displacement D and rigidity ofthe rock μ, gives the earthquake moment, M_0 as $M_0 = \mu DA$, and the moment magnitude, M_W as $M_W = (\log M_0 - 9.1)/1.5$.[13] The time-dependent displacement, $D(t)$, is given using the initial displacement velocity, D', and the displacement time, $\tau = D/D'$, as

$$D(t) = D[1 - \exp(-D't/D)] = D[1 - \exp(-t/\tau)], \quad (1)$$

$$\tau = D/D' = (\Delta\sigma/\sigma_0)(a/\beta), \quad (2)$$

using $D = 2\Delta\sigma a/\mu$ and $D' = 2\sigma_0\beta/\mu$, where σ_0, $\Delta\sigma$ and β are the stress before faulting ($\sim 10^8$ N/m^2), the stress decrease due to the displacement and the velocity of secondary waves (3.5–4 km/s), respectively.[13–15]

Although the piezoelectric coefficient in a quartz-bearing rock associated with the orientation anisotropy of microcrystalline quartz grains is under investigation, bound charges will cancel the stress-induced piezoelectric polarization field around the fault zone. Neither electric field nor free charge is present at the fault zone. However, when stress is released by faulting or by local fracturing of rocks, the piezoelectric polarization field disappears leaving bound charges with the density of q for the stressed area of width, Y extending from 1 km to 10 km along the fault line.[13] The charges, $Q = 2aYq$ may be formed on the ground ($z = 0$) and $-Q$ at the depth, d of $A/2a$ for a granitic bedrock mass: the stress-induced phase change of quartz grains is another mechanism ofthe preferred piezoelectric axis orientation in granite.

A fault is a capacitor with capacitance, C with the dielectric constant ε of the earth ($\varepsilon^* = 8$), which discharges through the resistance, R, since the earth is a conductor with resistivity ρ. Both C and R are roughly described as $C = (\pi\varepsilon)/\log(2d/Y)$ and $R = (\rho/\pi)\log(2d/Y)$ for $Y \ll d$ for two line charges with an infinite length and radius $Y/2$.

$dQ/dt = -I = -V/R$ and $V = Q/C$ give $dQ/dt = -Q/\rho\varepsilon$ leading to $Q = Q_0\exp(-t/\varepsilon\rho)$ with a decay time generally ranging from $\varepsilon\rho = 10^{-8}$ to 10^{-4} s for typical values of $\rho = 10^2$ Ω·m (sediment) to 10^6 Ω·m (igneous and metamorphic rocks).[13] The increase of ρ to 10^9 Ω·cm with evaporation of water at the fault,[12] due to thermal diffusion of the frictional heat, leads to the time of $\varepsilon\rho$ within 0.1 s.

The charge density may be described using seismic stress σ as

$$dq/dt = -\alpha(d\sigma/dt) - q/\varepsilon\rho, \tag{3}$$

where α is the piezoelectric constant ($\alpha = 10^{-12}$ C/N for quartz). Using $\sigma(t) = \mu[D - D(t)]/2a = \mu(D/2a)\exp(-t/\tau) = \Delta\sigma\exp(-t/\tau) = \sigma_0\tau(\beta/a)\exp(-t/\tau)$, eq. (3) under the condition of $q = 0$ at $t = 0$ gives

$$q(t) = \alpha\sigma_0(\beta/a)[\tau\varepsilon\rho/(\tau - \varepsilon\rho)](e^{-t/\tau} - e^{-t/\varepsilon\rho}). \tag{4}$$

Charges may persist for τ as $q(t) = \alpha\sigma_0\varepsilon\rho(\beta/a)e^{-t/\tau} = 10^{-4}(\varepsilon\rho/\tau)e^{-t/\tau}$ C/m^2 for $\tau \gg \varepsilon\rho = 0.1$ s and $\sigma_0 = 10^8$ N/m^2.

Prior to a major shock, local fractures or small fractional fault movements occur. The stress decrease, $\Delta\sigma/\sigma_0$ is small resulting in a short τ. A short fault with a small a may be considered, which gives short τ and a large peak value of q. This may cause phenomena such as seismic animal anomalous behaviors (SAABs) due to an intense pulsed electric field, $F = q/\varepsilon$ before an earthquake.[16]

The potential $V(x, y, z)$ at an arbitrary point (x, y, z) and the induced electric field $F = [(dV/dx)^2 + (dV/dy)^2 + (dV/dz)^2]^{1/2}$ were calculated using $q' = 2\varepsilon_0 q/(\varepsilon + \varepsilon_0)$, assuming both charges exist in the dielectric earth. If q at $z = 0$ is on the ground surface, the electric field is $(1 + \varepsilon/\varepsilon_0)/2 = 5$ times more intense than the present estimation; this contributes to intense EQL, as explained in the following section.

3. Earthquake Lightning (EQL)

The free electron density, $n(z)$, at the altitude z of ionosphere ($z > 50$ km) at night and that produced by cosmic rays, $n = 10^5/\text{m}^3$, for $z < 50$ km were used to consider the atmospheric polarization field, $(e/\varepsilon_0)\ n(z)l(z)$ due to the movement of electrons over the distance $l(z)$. The effective field taking into consideration the polarization, $F(z) - (e/\varepsilon_0)n(z)l(z)$ was integrated with the distance from zero to $l(z)$ to give the acquired electron energy, $E(z) = el(z)[F(z) - (e/\varepsilon_0)n(z)l(z)/2]$.

Electrons with mass m are accelerated and excite or ionize atmospheric N_2 and O_2 molecules for $E(z) > 10$ eV with the probability of $\exp[-l(z)/\lambda(z)]$. The mean free path, $\lambda(z)$, depends on the pressure $P(z)$ in mmHg and the temperature $T(z)$ as

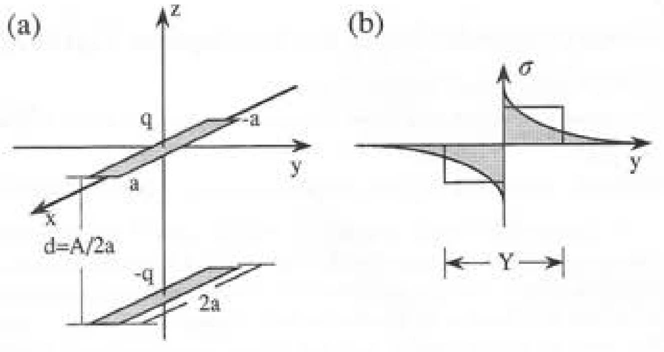

Fig. 1. (a) An electromagnetic model of a fault. The bound charge density, q [C/m^2], appears due to disappearance of piezoelectric polarization upon the release of seismic stress, σ_0 [N/m^2], in the fault zone. The area from $x = a = 5$ km to $x = -a$ on the x-axis and $-q$ at the depth of $A/2a = 20$ km, in the case of the Nojima Fault, both with width $Y = 1$ km are highly charged in this model. (b) Stress along the fault zone and approximation to $Y = 1$ km in a model calculation. Charges generated by the stress release are estimated as $q(t) = 10^{-5}e^{-t/\tau}$ C/m^2 for the displacement time $\tau = 1$ s (see the text).

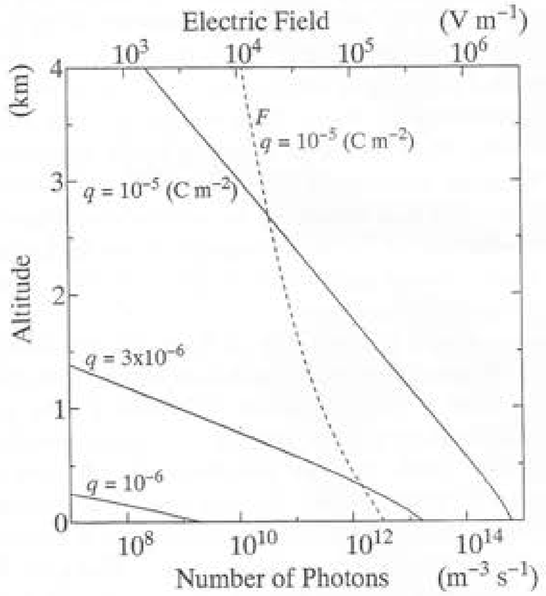

Fig. 2. The altitude (z) dependence of the intensity of electric field, $F(0, 0, z)$, (broken line curve) induced by $q = 10^{-5}$ C/m^2 and the number of photons per m^3 per second, $N_{ph}(z)$, emitted by energy transfer of more than 10 eV by accelerated electrons for the charge densities of $q = 10^{-6}$, 3×10^{-6} and 10^{-5} C/m^2. The intensity of earthquake lightning (EQL) observed close to the ground increases markedly by orders of magnitude for the increase of q (and F) by a factor of 3, suggesting that EQL occurs in the case of high magnitude earthquakes.

$$\lambda(z) = (\lambda_{eo}/P(z))(T(z)/273), \tag{5}$$

where λ_{eo} is the normalized mean free path depending on the energy of electrons ranging from $\lambda_{eo} = 37$ mm to 89 mm for N_2 and from 22 mm to 37 mm for O_2 at the pressure of 1 mmHg and $T = 273$ K.[17] The calculated $\lambda(z)$ is (4.2–5.1)×10^{-5} m for $z = 0$–2 km using $\lambda_{eo} = 30$ mm.

The number of emitted photons, N_{ph} per m^3 per sec-

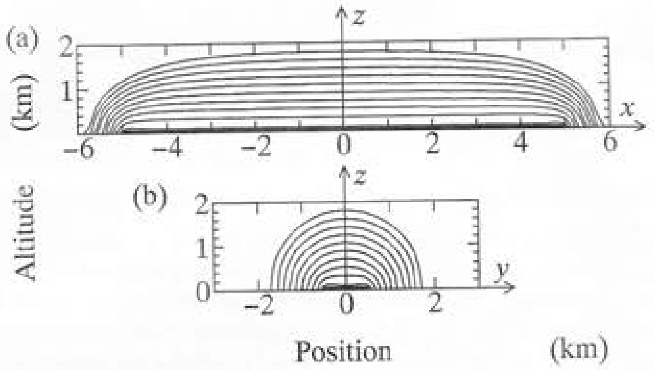

Fig. 3. The equi-intensity curves of EQL in (a) x-z plane and (b) y-z plane. The intensity for $q = 10^{-5}$ C/m^2 successively decreases from the curve closest to the ground: $N_{ph} = 5 \times 10^{14}$ photons/m^3 to 1/2, 1/4, 1/8,$\cdots (1/2)^n$ of N_{ph}.

ond, is given by $n(z)\exp[-l(z)/\lambda(z)]/t_e(z)$, as calculated in Fig. 2, where the time required to travel $l(z)$ is approximated as $t_e(z) = [2ml(z)/eF(z)]^{1/2}$ on the order of 10^{-9} s for small $l(z)$. EQL occurs close to the ground, while the polarization in the upper ionosphere cancels the electric field, leading to further enhancement of the effective field close to the ground. $F(z)$ with intensity of one order of magnitude intense can be considered if q is on the ground, which results in EQL intensity of 5 orders of magnitude at $z = 0$. EQL is a phenomenon before electric breakdown of air.

The spatial distribution of EQL calculated from $F(x, y, z)$ is shown for x-z and y-z planes m Figs. 3(a) and 3(b), respectively. The intensity of EQL with $N_{ph} = 5\times10^{14}$ /m^3 close to the fault zone decreases to 1/2, 1/4, 1/8 and $(1/2)^n$, as indicated by equiintensity curves. The EQL shape is similar to that photographed during the Matushiro Earthquake[2)] and also that witnessed a few second before the shock of the Hanshin Earthquake.[18)]

The estimated light intensity entering to 1 cm^2 of an observer looking along the fault line is 10^{10} photons per solid angle of 1 degree and 10^9 photonsis perpendicular to it. Roughly 5×10^7 photons will enter the eye of an observer 50 km away from the fault zone. These are light of sufficient intensity to be visible. Three faults are considered to have moved successively as estimated from seismic waves. Two successive occurrences of EQL during the Hanshin Earthquake might have arisen due to the movements of two faults. One fault under the sea might be electrically shielded by the conductive seawater.

4. Summary

An electromagnetic model of a fault having electrostatic charges at the two edges of a fault plane can explain EQL and some electromagnetic anomalies (EMAs) in terms of polarization of the upper ionosphere. The difficulty in the model of an electrostatic fault having a short decay time of $\varepsilon\rho$ has been overcome by considering the fault movement during which charges are generated. Further studies to estimate the piezoelectric coefficient of rocks are needed since the present model is based on assumptions to them. However, the model illustrates hitherto unexplained EQL before a major shock of an earthquake.

Electromagnetic waves including light from EQL and possible EMAs due to polarization of ionosphere propagate faster than seismic waves and might be used as input in a new early warning system and perhaps even for earthquake prediction though prediction of the exact time and place is in principle not possible for catastrophic fracture phenomena.

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