投　稿

Ferroelectric Alignment of Piezo-compensating Quasi-Dipolar Charges and Formation of Tornado-like Earthquake Cloud

By Motoji IKEYA, Hideki SASAOKA, Kazuhiko TERAMOTO and Cheng-gua HUANG

Department of Earth and Space Science, Graduate School of Science, Osaka University, 1-1 Machikaneyama, Toyonaka, Osaka 560 0027, Japan

Free charge densities $\pm q$ are generated on the surface of quartz grains in quartz-bearing rocks by the change of stress, σ as described by $\mathrm{d}q/\mathrm{d}t = -\alpha \mathrm{d}\sigma/\mathrm{d}t - q/\varepsilon\rho$, where α, ε and ρ are piezoelectric coefficient, dielectric constant and resistivity of the rock, respectively. A quartz grain with a length $2a'$ and a fracture time τ, gives pulsed charge densities $\pm q = [\alpha\Delta\sigma\varepsilon\rho/(\tau - \varepsilon\rho)](e^{-t/\tau} - e^{-t/\varepsilon\rho})$, where $\Delta\sigma$ is the stress release and $\tau' = a'/\beta$ using the velocity of S-waves, β. The dipole moment, $p = (2a')^3$ produces electromagnetic (EM) waves. A fault zone with area of fault plane, A, half-length a and volume ratio η of quartz in the bedrock granite have the number of quartz grains given as $n = 2aA\eta/(2a')^3 = (M_o/\Delta\sigma)\eta/(2a')^3$, where $M_o = 2aA\Delta\sigma$ is the earthquake moment giving the moment magnitude $M_W = (\log M_o - 9.1)/1.5$ in seismology. An ensemble of dipoles p_i in a random orientation and with no interaction among dipoles, i.e., $\Sigma p_i p_j = 0$ form a large dipole $P = \Sigma p_i$ with the magnitude $|P| = |\Sigma p_i^2|^{1/2} = n^{1/2}|p| = [(M_o/\Delta\sigma)\eta (2a')^3]^{1/2} q$. This paraelectric state leads to a scaling law, $\log V = 0.375 M_W + c$, where V is preseismic intensity of seismic electric signal (SES) and c, a constant. Ferroelectric orientation of quasidipoles in form of $P = \Sigma p_i = np = 2aA\eta p = (M_o/\Delta\sigma)\eta (2a')^3 q$ is expected before the decay of charges in $\varepsilon\rho$ since an enormously high Curie temperature $T_c = 10^6$ K for ferroelectric phase transition is obtained using the Ising's model in ferromagnetism for the Coulomb interaction energy of 10^6 eV. The ferroelectric transition of quasi-dipolar charges generate an intense electric field which ionize the super-cooled atmosphere: earthquake fogs and clouds may theoretically be formed. A high electric field between a high voltage sphere of the Van de Graaff electrostatic generator and a tip of a grounded needle dipped on the supercooled dry ice fog generated a jet stream type cloud like a tornado experimentally observed at the fault zone before the Kobe earthquake. The absorption of seismic EM waves by natural magnetic resonance both NMR and EPR under the earth magnetic field of $B = 0.03$ mT was assessed in addition to the loss by skin depth $\delta = c\,\varepsilon\,\rho$ rather than $\delta = (\omega\mu/\rho)^{1/2}$ at a high frequency.

Keywords: earthquake, precursor, cloud, ferroelectric, lightning, paraelectric, piezoelectric, polarization, seismic, stress, SES

論文要旨： 地震前兆現象の多くは電磁現象に過ぎない。本論文では、断層地帯の花崗岩の石英粒子の表面に出来ていた圧電補償電荷が解放され、その電荷対が擬似的電気双極子として強誘電体的な相転移を起こして配向するためであるとして、キュリー温度を計算して１００万度前後であることを示した。高い電荷密度で強電場が発生する。神戸地震で市民によって写真撮影されされた竜巻型の地震雲をバンデグラフを用いて実験室

で再現した。このような一種の放電によって、大気中のNO_xの発生が起こっていることを、兵庫県の大気汚染データからも見出しており、大気汚染データから地震起源のNO_xから警報をだすことも出来るかも知れない。また、地球磁場下で地震電磁波の天然の核磁気共鳴（NMR）や電子常磁性共鳴（EPR）が起こりうることを議論した。
この研究は、自然の縞模様を研究する文部省科研費の重点領域「全地球史解読」（代表者、熊沢峰夫）の援助を受けた。

1. Introduction

Earthquake precursor phenomena such as seismic anomalous animal behavior (SAAB), electromagnetic anomalies (EMA) and earthquake lightning (EQL) were observed before the Kobe earthquake that destroyed Kobe in 1995. Scientists are skeptical of the retrospective statements on precursor phenomena and tend to regard them as superstitions or superscience which can not be explained with the present level of sciences. On the other hand, a serious attempt to explain them have been made as published in a book (Ikeya, 1998). A hypothesis of an intense pulsed charge appearance at a fault zone have explained most of these phenomena.

The EQL which was photographed at the Matsushiro earthquake and discussed by Terada (1932) was explained as an electroatmospheric phenomenon (Ikeya and Takaki, 1996). Folk stories on SAAB abundant in China and Japan were ascribed to electro-physiological responses to seismic electromagnetic (EM) pulses or to field avoidance behavior of animals. Experiments on electric field effects explained some of these behavior (Ikeya *et al*. 1996a, b, 1997a, Huang and Ikeya, 1997). A mysterious shape of bent candle flame as a precursor of earthquakes in Japanese proverb as well as dropped nails from a magnet in the Ansei Chronicle (Ikeya and Matsumoto, 1997) were reproduced by a Van de Graaff electrostatic generator. Retrospectively collected precursor statements before the Kobe earthquake (Wadatsumi, 1995) can be explained as EM phenomena observed by citizens.

Physical mechanism of charge appearance has not yet been established. A mechanism of piezoelectricity (Finkelstein and Powell, 1970; Kumazawa 1962) was discarded since piezoelectric polarization of quartz grains in quartz-bearing rocks would immediately be compensated by free charges in a conductive earth in a time constant of $\varepsilon\rho$, with dielectric constant ε and resistivity ρ. How large charge densities are sustained in a fault zone has been the subject of major controversy. A spontaneous ferroelectric polarization of dipolar lattice defects under stress or during fractures was asserted for seismic electric signal (SES) known as VAN method (Varatos and Alexopoulos, 1984). Such transition is not possible since the dipolar defects such as complexes between aliovalent cation impurity and a cation vacancy or between ions and interstitial anion have no preferred orientation under stress; no energy difference is expected for the direction of electric dipoles under stress. A dipolar field due to charged dislocations is noted as an alternative.

Generation of seismic EM waves (Hayakawa and Fujinawa, 1994) fall in an interdisciplinary field between solid state physics and geophysics. We proposed an EM model of a fault having electrostatic dipolar zone transiently formed by free charges which compensated piezoelectric polarization of quartz grains in granitic rocks (Ikeya *et al.*, 1997). Both paraelectric and ferroelectric orientation of these quasidipoles free charges are discussed considering the Coulomb interaction energy among dipolar charges and the Ising's model in ferromagnetism.

2. Charges Freed from Piezoelectric Polarization by Stress Release

2.1 *Charges Produced on Both Side of a Quartz Grains*

An electromagnetic model of a fault indicated that free charges $\pm q$ are produced around a quartz grain by the stress change as described using seismic stress σ as

$$\mathrm{d}\,q/\mathrm{d}\,t = -\alpha(\mathrm{d}\sigma/\mathrm{d}t) - q/\varepsilon\rho\ , \tag{1}$$

where α is the charge generation constant, ε, the dielectric constant, and ρ, resistivity of quartz bearing rocks. In our tentative model, α is a piezoelectric constant ($\alpha = 2\times10^{-12}$ C/N for quartz) for a mechanism of piezo-compensating free charges. The first term on the right side of eq. (1) is the generation of charges, the second term is the decay through conductive earth. The free charges, $+q$ and $-q$ recombine with a time constant, $\varepsilon\rho = 70 - 0.7$ μs for $\varepsilon^* = \varepsilon/\varepsilon_o = 8$ and $\rho = 10^6 - 10^4$ Ω-m for granite; the decay through the quartz grain with a high resistivity of $\rho_{quartz} = 10^{15}$ Ω-m is almost negligible since the charges move through conductive feldspar.

If stress is released exponentially $\sigma(t) = \Delta\sigma \exp(-t/\tau)$, eq.(1) under the condition of $q = 0$ at $t = 0$ gives a pulsed charge $\pm q$ as

$$q(t) = \alpha\Delta\sigma[\varepsilon\rho/(\tau - \varepsilon\rho)](e^{-t/\tau} - e^{-t/\varepsilon\rho}). \qquad (2)$$

The pulse shape with the risetime of $\varepsilon\rho$ and the decay time of τ for $\tau > \varepsilon\rho$ (or vise versa for $\tau < \varepsilon\rho$). The maximum peak intensity, is $\alpha\sigma_o$ for $\varepsilon\rho >> \tau$ from the factor $\alpha\sigma_o[\varepsilon\rho/(\tau - \varepsilon\rho)]$. Charges may persist for τ as $q(t) = 2\times10^{-5} (\varepsilon\rho/\tau)e^{-t/\tau}$ C/m^2 for $\tau >> \varepsilon\rho$ and $\Delta\sigma = \sigma_o = 10^7$ N/m^2 assuming 10 % stress drop.

Fig.1 show the charge density for two cases of $\tau >> \varepsilon\rho$ and $\tau < \varepsilon\rho$. If quartz grains are close to each other, the Coulomb interaction among the quasi-dipolar charges is considerably large as to interact with each other: the ferroelectric alignment occurs as described later.

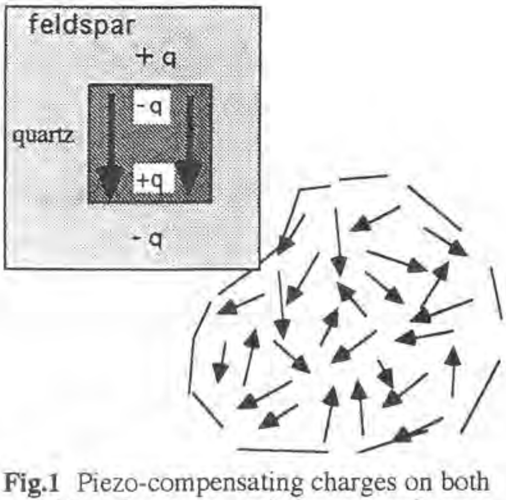

Fig.1 Piezo-compensating charges on both sides of a qaurtz grain by stress changes

2.2 *An Ensemble of Dipolar Charges with No Mutual Interactions: Paraelectric State*

2.2.1 A theory of resultant dipole moment

The microscopic dipole moment, p of a quartz grain with half length a' is $p = (2a')^3 q(t)$. The number of the dipoles, n in a volume of a fault zone considering that seismic stress spread to $\pm a$ on both side of a fault with length a and area A is $n = 2aA\eta/(2a')^3$ considering the volume fraction η '; accurately, η is a volume fraction of quartz grains whose EM waves are detected simultaneously at the observer point at the distance R as schematically shown in Fig. 2.

The earthquake moment in a mathematical model of a fault is given as $M_o = \mu DA = \mu(D/2a)(2aA) = 2aA\Delta\sigma$ using the displacement D and rigidity μ. The moment magnitude, M_W is defined as $M_W = (\log M_o - 9.1)/1.5$ in seismology and so n is given as

$$n = 2aA\eta/(2a')^3 = (\eta M_o/\Delta\sigma)/(2a')^3 \qquad (3)$$

An ensemble of dipoles p_i in a random orientation form a larger dipole $P = \Sigma p_i$. If there is no interaction among dipoles, i.e., $\Sigma p_i p_j = 0$,

$$|P|^2 = (\Sigma p_i)^2 = (\Sigma p_i^2 + 2\Sigma p_i p_j) = \Sigma p_i^2 = np^2 \qquad (4)$$

the magnitude $|P|$ is given as $|P| = n^{1/2}|p|$.

A lamp consisting of n excited atoms with a dipole moment p in optics is equivalent to a lamp with a large dipole moment of P : the energy of EM waves emitted from the source is n times of a small dipole. Hence, using $p = (2a')^3 q(t)$ and n , the total dipole moment is given as

$$P = n^{1/2} p = [\,\eta M_o (2a')^3/\Delta\sigma\,]^{1/2}\, q(t). \qquad (5)$$

Thus, the transient electric dipole moment at an epicenter is correlated with the earthquake moment, M_o and so the moment magnitude of an earthquake. One may consider a large amount of charges appear at both end of the fault edge separated by $2a$ with the charges $\pm Q = \pm P/2a = \pm [\eta M_o (2a')^3/\Delta\sigma]^{1/2} q(t)/2a$. This is the microscopic basis of our EM model of fault behavior.

2.2.2 Piezoelectric coefficient of gramite

Consider a rock specimen having quartz grains with half length a' , the total dipole moment was $P = n^{1/2}p = [2aA\eta(2a')^3/\Delta\sigma)]^{1/2}\ q(t)$ using $n = 2aA\eta/(2a')^3$. An effective piezoelectric coefficient, α_{eff} for a fault zone is given as

$$S(x,t) = (1/4\mathrm{p}\,R)^2(\mu_o/c)\,\eta M_o M_o'\ [\alpha\,\mathrm{e}^{-t/\varepsilon\rho}/\varepsilon^2\rho^2]^2\ \sin^2\theta\ .$$

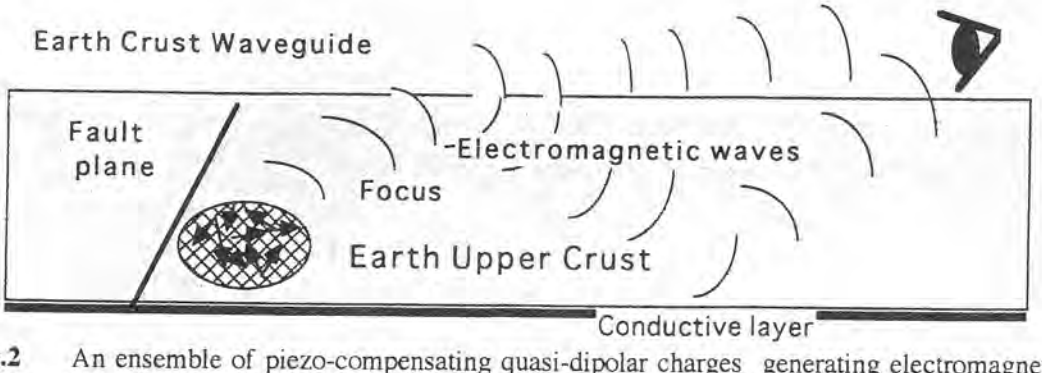

Fig.2 An ensemble of piezo-compensating quasi-dipolar charges generating electromagnetic (EM) waves . Preseismic EM waves were radiated from paraelectric states of the ensemble $P = \Sigma\, p_i = 0$, but the time averaged value is $|P| = n^{1/2}|p|$ for dipolar moment p_i , while ferroelectric transition, $P = \Sigma\, p_i = np$, occur for a large interaction energy among dipoles hacing a large dipolar moment p_i due to the large q in piezoelectricity .

$$\alpha_{\mathrm{eff}} = [\eta(2a')^3/2aA]^{1/2}\ \alpha_{\mathrm{quartz}} \qquad (6)$$

for paraelectric dipolar charges. This depends on the volume of the rock and about three orders of the magnitude smaller for a typical rock specimen in laboratory experiments considering 10 - 50 % volume fraction of quartz grains of $a' = 10^{-3}$ m and for $A = (2a)^2$ and $a = 0.1$ m (Sasaoka, 1997, Volarovich and Sobolev, 1965). The piezoelectric coefficient of granite rock was obtained experimentally as in Fig. 3.

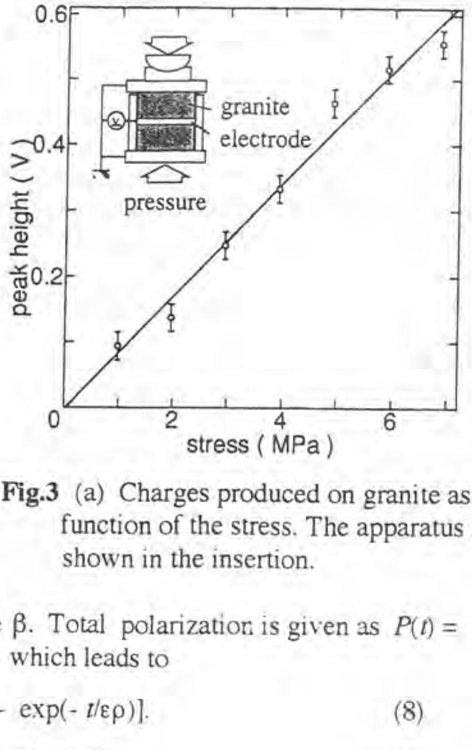

Fig.3 (a) Charges produced on granite as a function of the stress. The apparatus is shown in the insertion.

2.2.3 Generation of EM waves

The power of EM waves are related with P^2/τ, where τ is the displacement time or rupture time of a fault and given in a mathematical model of a fault as

$$\tau = (\Delta\sigma/\sigma_o)(a/\beta)\ . \qquad (7)$$

using the fracture stress σ_o and the velocity of S-wave β. Total polarization is given as $P(t) = \Sigma p_i\ (t, t_i) = n^{1/2}\ q(t)\,(2a')^3 = [2aA\eta(2a')^3]^{1/2} q(t)$, which leads to

$$P(t) = \alpha(\eta M_o(2a')^3\Delta\sigma)^{1/2}\ [\varepsilon\rho/(\tau - \varepsilon\rho)][\exp(-t/\tau) - \exp(-t/\varepsilon\rho)]. \qquad (8)$$

$$= \alpha(\eta M_\sigma M_o')^{1/2}\ [\varepsilon\rho/(\tau' - \varepsilon\rho)][\exp(-t/\tau') - \exp(-t/\varepsilon\rho)]. \qquad (8')$$

where $M_o' = (2a')^3\Delta\sigma$ is the earthquake moment of a single quartz grain.

The time-dependent electric dipole moment generates (EM) waves having a Poynting vector

$$S(x, t) = (1/4\pi R)^2(\mu_o/c)[d^2 P/dt^2]^2 \sin^2\theta$$
$$= (1/4\pi R)^2(\mu_o/c)\, \eta M_o M_o' \, [\alpha\varepsilon\rho/(\tau - \varepsilon\rho)]^2 \, [e^{-t/\tau}/\tau^2 - e^{-t/\varepsilon\rho}/\varepsilon^2\rho^2]^2 \sin^2\theta \ . \quad (9)$$

The spatial averaging gives $\sin^2\theta = 2/3$.

(i) Coseismic EM generation: for $\tau >> \varepsilon\rho$,

$$S(x, t) = (1/6\pi R)^2(\mu_o/c)\, \eta M_o M_o' \, [\alpha\varepsilon\rho/\tau]^2 \, [e^{-1/\tau}/\tau^2]^2$$
$$= [\alpha\varepsilon\rho]^2 M_o (1/\tau)^6 \exp(-t/\tau) \quad (10)$$

Considering $\tau = (\Delta\sigma/\sigma_o)(a/\beta)$ and $M_o = (2a)^3 \Delta\sigma$ and $M_o = (2a)^2 h \Delta\sigma$ for a large fault of $A = 2ah$ and a small fault of $A = (2a)^2$, where h is typically 10^4 m, $S(x, t) \propto M_o^{1}$ and $S(x, t) \propto M_o^{2}$. These leads to the seismic electric field intensity $F \propto S(x, t)^{1/2} \propto M_o^{-1/2}$ and to $F \propto M_o^{1}$ coseismically.

(ii) Preseismic EM generation: In preseimic case where the stress release is small, i.e., the fracture time τ is comparable to $\varepsilon\rho$ or $\tau << \varepsilon\rho$, eq.(9) becomes

$$S(x, t) = (1/4\pi R)^2(\mu_o/c)\, \eta M_o M_o' \, [\alpha e^{-t/\varepsilon\rho}/\varepsilon^2\rho^2]^2 \quad (11)$$

Hence, the electric field intensity is $F \propto S(x, t)^{1/2} \propto M_o^{1/2}$ leading to a scaling law of $\log F = 0.75 M_W + c$ for both a small and large earthquake. This paraelectric state leads to preseismic EM waves with a theoretical relation of $\log V = 0.375 M_W + c$, where V, M_W and c are the intensity of seismic electric signal (SES), moment magnitude and a constant.

3. Ferroelectric Transition of Quasidipolar Piezo-compensaring Charges

3.1 *Interaction Energy Among Quasidipoles and Ferroelectric Curie Temperature*

The interaction energy $\pm E$ among nearest neighbor quasi-dipoles with the average separation d can be written as

$$E = \{q^2(2a')^4/4\pi\varepsilon\}\{2/d - 1/(d - 2a') - 1/(d + 2a')\} \quad (12)$$

for dipoles aligned in the same direction or opposite to each other. The Ising model in ferromagnetism suggest that the Curie temperature of ferroelectric transition, T_c is given for the interaction energy E as

$$\tanh E/kT_c = 11/(z - 1) \ , \quad (13)$$

where z is the number of the nearest neighbor dipoles. Ferroelectric transitions of these dipolar charges occur when the quasi-dipoles have a large interaction energy. If Coulomb energy is calculated for the piezocompensating charges, the energy is of the order of $10^2 \sim 10^3$ eV because the charges $\pm q(2a')^2$ on both edges of a quartz grain is large of the order of 10^{-12} C or $10^7 e$ for $2a' = 10^{-3}$ m and $\Delta\sigma = 10^6$ Pa. An enormously low Curie temperature of 10^6 K is obtained using eq. (14) : The dip[olar charges will make ferroelectric alignment as described later.

A similar ferroelectric transition was once alleged over the physical reason of possible dipolar defect alignments to explain the observed seismic electric signal (SES) in Greek VAN method (Varatos and Alexopoulos 1986). The interaction energy is small even for the separation of a few atomic distances for dipolar lattice defects, where the charges $\pm q$ is more or less $\pm e$ *or* $\pm 2e$. The Curie temperature of 10^{-5} K was obtained from eq. (13), which indicates that no ferroelectric alignment of dipoles occurs.

3.2 *An Intense Charge Appearance at the Epicenter*

A temporary formation of ferroelectric alignment of quasi-dipolar charges in the ensemble of small dipoles give a total electric dipole moment of

$$P = \Sigma p_i = np = 2aA\eta q = (M_o/\Delta\sigma)\eta q \qquad (14)$$

The energy is proportional to

$$P^2 = (\Sigma p_i)^2 = (\Sigma p_i^2 + 2\Sigma p_i p_j) = n p^2 + n(n-1) p^2 = (np)^2 . \qquad (15)$$

A large coherent dipole like a laser might be formed, which leads to atmospheric lightning at large earthquakes and an intense charge required to explain such a phenomenon.

An intense electric charges causes mysteriously bent candle flames before Buddhist's or shrine altar and drop iron nails from magnet as told in Japanese proverbs and folk stories (Ikeya and Matsumoto, 1997). It also disable radio by giving an intense electric field to the bias voltage and causes noise by discharges. An intense charge may be responsible for mysterious stories on earthquake precursors retrospectively reported in a book (Wadatsumi, 1995).

4 Natural NMR and EPR and Attenuation due to Conductivity

4.1 *Attenuation of EM Waves in Conductive Media*

A wave vector of EM waves, k, in a conductive earth is a complex, i.e., $k = k' + ik''$ from Maxwell equations, where k'' is expressed, using the permeability μ, as

$$k'' = \omega(\mu'\varepsilon/2)^{1/2}[(1 + (1/\omega\varepsilon\rho)^2)^{1/2} - 1]^{1/2} . \qquad (16)$$

(i) $\omega\varepsilon\rho << 1$: A low resistivity and low frequency approximation

Most textbooks in geophysics deal with the propagation of EM waves with an abbreviated equation of skin depth δ obtained for $\omega\varepsilon\rho << 1$ for a conductive media having a small ρ as

$$k'' = (\omega\mu'/\rho)^{1/2} = 1/\delta \qquad (17)$$

Hence, using the frequency, f for $\omega = 2\pi f$, the skin depth $\delta = (\omega\mu'/\rho)^{-1/2}$ of EM waves is small at a high frequency. The intensity decays as $\exp(-k''R) = \exp(-R/\delta)$ for EM waves with Only EM waves at ULF close to DC can propagate. This common sense is only applicable for a conductive media like a metal ($\rho = 10^{-8}\ \Omega$m) and the practical frequency f up to GHz or THz .

(ii) $\omega\varepsilon\rho >> 1$: A high resistivity and high frequency approximation

In our case of granite with $\rho = 10^6\ \Omega$m - $10^4\ \Omega$m, eq. (17) should be used and so another skin depth equation at a high frequency limit $\omega\varepsilon\rho >> 1$ is

$$k'' = (\mu'\varepsilon)^{1/2}/\varepsilon\rho = 1/c\,\varepsilon\,\rho = 1/\delta \qquad (18)$$

k'' and so $\delta = c\,\varepsilon\,\rho$ become a constant, 210 m - 21 km for $\rho = 10^4\ \Omega$m - $10^6\ \Omega$m at a high frequency limit of $\omega\varepsilon\rho >> 1$ corresponding to the frequency higher than 1 kHz - 100 kHz. Hence, seismic EM waves at VLF and ULF come up from under the ground, especially if the source is a large volume of a fault zone where seismic stress is changed; Seismic EM waves might come not only from the underground focus but from the area close to the ground surface. This may be the reason why high frequency EM waves which gives barber pole color noise in TV images were observed ahead of earthquakes (Ikeya *et al.*, 1997).

4.2 *Natural Magnetic Resonance, NMR and EPR of Seismic EM Waves*

Absorption of EM waves by nuclear magnetic resonance (NMR) of mostly protons (^{1}H) and oxygen 17 (^{17}O) in water and electron paramagnetic resonance (EPR) of Fe^{3+} and Mn^{2+} under earth magnetic field must be considered in addition to the evanescent propagation in the earth crust waveguide (Ikeya et al., 1997).

The NMR frequency for the field of B is given as $f = (\gamma/2\pi)B$. The proton resonance frequency for 1 T is given for example as 42.57 MHz for the proton. The frequency for the earth magnetic field of $B = 31,196$ nT around Tokyo area is calculated as 1.328 kHz., while ^{29}Si and 17O having nuclear spins of $I = 1/2$ and $I = 5/2$ with the abundance of 4.7 % and 0.037 % give 265 Hz and 180 Hz, respectively. The NMR linewidth of liquid (water) is 1 -100 Hz, while that in solid is 1-100 kHz. Hence, only nucleus in liquid may be observed in the frequency spectrum of seismic EM waves. The absorption by ^{29}Si would be broadened considerably. The power spectrum of seismic EM waves observed around 1 -100 Hz and 2 - 10 kHz is consistent with this estimate.

Zero field splitting is greater than the Zeeman energy for Fe^{3+} in EPR. The hyperfine splitting energy of Mn^{2+} is also greater than the Zeeman energy. Hence, diagonalization of the spin Hamiltonian matrix must be done to obtain the accurates spectra. Radiation-induced radical species around $g = 2.0$ give absorption around 1 MHz. Only a broad line will be obtained around 1 MHz region. Thus, seismic EM waves are filtered strongly by both NMR and EPR.

5. Formation of Earthquake Clouds

A series of our works on earthquake precursors aims at elucidating phenomena scientifically assuming that such phenomena have been observed. Circumstantial evidences from retrospective statements by citizens indicate an intense charges at the epicenter area, though the mechanism of charge appearance has not yet clearly established. In other words, most of mysterious phenomena reported retrospectively as earthquake precursors can be explained if one assumes the appearance of intense charges and EMwaves before the Kobe Earthquake. This was demonstrated for a bent candle flame as an earthquake precursor in Japanese proverb and dropped nails in the Ansei Chronicle written in 150 years ago.

Reports and inquiries on the observation of earthquake clouds are sent by citizen retrospectively to the Meteorological Bureau and to the Institute of Earthquake. Meteorologists tell that there is no scientific reason that earthquake clouds are formed hundreds or sometimes a thousand km away from the epicenter. Proposed mechanism for earthquake cloud formation was ejection of exoelectrons or charged particles from a fault (Enomoto *et al.*, 1990). Electromagnetic waves were observed by several investigators (Oike and Yamada,) at LF and VLF ranges and are summarized in the conference proceedings (Hayakawa and Fujinawa, 1994). Our previous work indicated that seismic EM waves could propagate through the earth-crust waveguide over long distances and might form standing waves leading to ripple-wave clouds due to the ionization in the super-cooled atmosphere.

The effect of external electric field on the formation of clouds in supercooled atmosphere was studied using Van de Graaff electrostatic generator. The field gradient around a small needle electrode produced a spatial distribution of cloud similar to a vertical rod and to a small tornado photographed a day and also a week before the Kobe earthquake as shown in Fig.1.

Controversial earthquake clouds retrospectively told by ordinary people as a precursor to earthquakes and neglected by most scientists might be formed by seismic pulsed electric fields caused by charges appeared at the epicenter ahead of earthquake. The electric field of EM waves from an ensemble of dipolar charges at a fault zone might produces earthquake clouds and fogs. Note that we do not allege earthquake prediction since the charge generation occur ahead of fractures and the precursor time is still not certain. However, earthquake clouds might be a warning signal that the seismic stress changes is occurring underground.

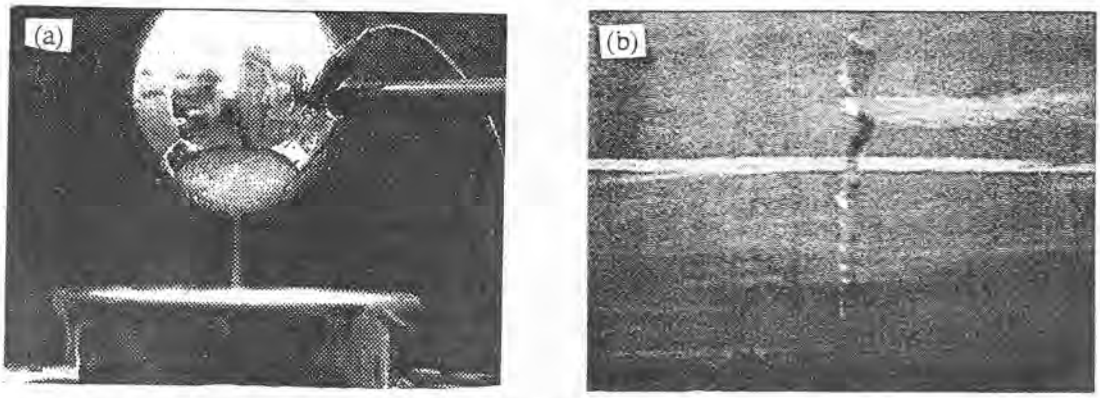

Fig.4 (a) A cloud like a tornado produced by super-cooled area in an experiment using an intense electric field generated by a Van de Graaff electrostatic generator. (b) Tornado-like cloud photographed by a citizen (after Wadatsumi, 1995).

5. Summary

An EM model of a fault in which freed bound charges that compensated the piezoelectric polarization of quartz grains in rocks recombine with emission of EM waves or form a large dipole by interaction with other charges following ferroelectric formation. If Coulomb energy is used as the interaction energy, the Ising model give the Curie temperature $T_c = 10^6$, while dipolar lattice defects has $T_c = 10^{-6}$ K. Ferroelectric transitions occur only for piezocompensating free dipolar charges, but not for dipolar defects as suggested in eleucidating VAN method.. Natural magnetic resonance, NMR and EPR under earth magnetic field has been assessed.

A part of this study was supported by the Decoding the Earth Evolution Program, Intensified Study Area Program of Ministry of Culture and Education (No.259, 1995-1997). The authors thank Prof. M. Kumazawa and Dr. M. Takano for their support and discussion on piezoelectricity.

References

Finkelstein, D. and Powell, J. : Earthquake lights. Nature 228, 759 (1970).

Hayakawa, M. and Fujinawa , Y. ed., *Electromagnetic Phenomena Related to Earthquake Prediction,* Terra Scientific, Tokyo, 1994, p. 677.

Huang, Q. and Ikeya, M. : Electric field effects on animals: Mechanism of seismic anomalous animal behavior (SAAB). *Earthquake Research in China* **11** (1997) 109-118.

Ikeya, M. and Takaki, S. (1986): Seismic electric signals (SES) and animal anomalies. *J. speleol. Soc. Japan* **20**, 38-47.

Ikeya, M. and Takaki S. : Electromagnetic model of a fault for earthquake lightnings (EQLs). *Jpn. J. Appl. Phys*. **35**, L355-L357 (1996).

Ikeya, M. Takaki, S. and Takashimizu, D. (1996a) Electric shocks for seismic animal anomalous behaviors (SAABs). *J. Phys. Soc. Japan* **65**, 710-712.

Ikeya, M., Huruta, H., Anzai, H. and Kajiwara, N. (1996b): Electric field effects on rats and sparrows for seismic animal anomalies (SAAs). *Jpn J. Appl. Phys*. **65**, 4587-4594.

Ikeya, M.: Electromagnetic phenomena and anomalous animal behaviors accompanying earthquake , Kagaku **66** (1996) 408-418, (in Japanese).

M. Ikeya, S. Takaki and D. Takashimizu, "Electric shocks resulting in seismic animal anomalous behaviors (SAABs)", *J. Phys. Soc. Jpn*. **56** (1996) 710-712.Varatos, P. and Alexopoulos, K.

Ikeya, M., Takaki, S., Matsumoto, H., Tani, A. and Komatsu, T. : Pulsed charge model of a fault behavior producing seismic signals. *J. Circuit, Systems and Computers* **7**, (1997) 153-164.

Ikeya, M., Kinoshita, Y., Matsumoto, H., Takaki, S. and Yamanaka, C.: A model experiment of electromagnetic wave propagation over long distances using waveguide terminology. *Jpn J. Appl. Phys*. **37**, (1997) L1558-L1561 .

Ikeya, M. and Matsumoto, H.: Reproduced earthquake precursor legends using a Van de Graaff electrostatic generator: Candle flame and dropped nails. *Naturwissenschaften* **84** No.12(1997).

Ikeya, M. and Huang Q. : Earthquake frequency and moment mragnitude relations for mainshock, aftershocks and foreshocks: Theoretical *b*-values. *Episodes* **20**, (1997) 181-184.

Ikeya, M., Komatsu, T., Kinoshita, Y. , Takaki, S. , Teramoto, K., Inoue, K., Gondou M. and Yamamoto T.: Seismically-induced anomalous animal behavior (SAAB): Electric field before earthquakes at Kobe-Oji Zoo and Izu-Atagawa Tropical Banana-Alligator Garden. *Episodes* **20**, (1997) in press.

M. Ikeya: Why Do Animals Behave Anomalously Before Earthquakes - Birth of Electromagnetic Seismology - (NHK Publisher, Tokyo, 1998) in Japanese. 池谷元伺： 地震の前に動物はなぜ騒ぐのか？−電磁気地震学の誕生−、ＮＨＫブックス（1998）（印刷中）

Kumazawa, K. : Disturbances in electromagnetic field in rocks due to piezoelectric effects in connection with seismic waves , *J. Sci. Nagoya Univ.* **9** (1961) 54-79.

Sasaoka, H., Yamanaka, C. and Ikeya, M.: Measurements of electric potential variation by piezoelectricity of granite. *Geophys. Res. Letters* (1998) in press.

Terada, T.: On earthquake light. Bull. Earthquake Res. Inst., Tokyo Univ. 9 (1931) 225.

Varatos, P. and Alexopoulos, K. : Physical properties of the variations of the electric field of the Earth preceding earthquakes, *Tectonophysics* **110** (1984) 73-98.

Volarovich M. P. and Sobolev, G. A. : Use of piezoelectric effects of rocks for subsurface exploration of piezoelectric media , *Dokl. Akad. Nauk. SSSR* **162** (1965) 11-13.

Wadatsumi, K.: *1591 Witnesses Phenomena Prior to Earthquake*, Tokyo Pub, 1995 (in Japanese).