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Theoretical Investigation of Seismic Electric Field Associated with Faulting

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We present an electromagnetic model of a fault using the piezoelectric effect and the elastic dislocation theory to investigate theoretically the spatial distribution of the stress-induced charges associated with faulting. The relevant seismic electric field associated with these induced charges can be estimated quantitatively. Therefore, this simple model would provide a solid framework for additional theoretical developments on the explanations of the anomalous seismoelectric signals. The spatial distribution of the stress-induced charges around a vertical rectangular fault showed complicated characteristics. The estimation of the electric field associated with the stress-induced charges during the 1995 Kobe earthquake was consistent with the previous investigation from some reported anomalous seismic phenomena.

Key words: Charges, Earthquake, Fault, Piezoelectric effect, Seismoelectric signals.

I. INTRODUCTION

Numerous statements of precursory phenomena associated with the Kobe earthquake (January 17, 1995; $M = 7.2$) have been reported and collected in a popular scientific book (Wadatsumi, 1995). Similar reports on anomalous phenomena associated with earthquakes have also been presented in scientific papers (Finkelstein and Powell 1970; Derr, 1973; Tributsch, 1978; Buskirk et al., 1981; Tate and Daily, 1989).

Experiments of the electric field effect on animals indicated that anomalous animal behavior would be a kind of electrophysiological response to the stimuli of the seismoelectric signals (Ikeya et al. 1996, 1998; Huang et al. 1997). Earthquake lightning might be explained as the appearance of transient seismic charges (Ikeya and Takaki 1996). Earthquake clouds might be due to the ionization in the super-cooled atmosphere, and the experiment of the formation of clouds was performed using Van de Graaff electrostatic generator (Ikeya et al. 1997a). Anomalous EM signals could be induced

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by transient free charges and some simulation experiments considering a waveguide model were undertaken to explain the characteristics of the observations (Ikeya et al. 1997b; Huang and Ikeya 1997). These studies are attempts to establish an interdisciplinary field between physics and seismology, i.e., "electromagnetic seismology." Therefore, the reported precursory phenomena would be ascribed to the same physical stimuli as claimed recently (Ikeya et al. 1998).

Enlightened by research on the anomalous magnetic signals associated with earthquakes using the piezomagnetic effect (Johnston 1978; Sasai 1980, 1991; Banks et al. 1991), we present a piezoelectric model of a vertical strike-slip fault based on the classic elastic dislocation theory. This approach is valid as long as the elastic dislocation theory is applicable. We investigated the spatial distribution of the stress-induced charges around a vertical rectangular fault in an elastic half-space. The relevant electric field induced by these charges associated with the 1995 Kobe earthquake was estimated quantitatively. This study provides a theoretical framework for the quantitative interpretation of the characteristics of seismoelectric signals associated with faulting.

II. STRESS CHANGES ON A VERTICAL FAULT

We derived the expressions for stress changes from a uniform slip u of a rectangular fault. A vertical strike-slip fault model was described in Fig. 1. The detailed analyses of elastic dislocation theory and the stress changes on a vertical fault are given elsewhere (Steketee 1958; Chinnery 1963). Some brief mathematical formulas are summarized as follows.

The displacement field u_k in a semi-infinite elastic medium for a uniform slip u over the fault plane Σ can be expressed as follows.

$$u_k = \frac{u}{8\pi\mu} \int_d^D \int_{-L}^{+L} \omega_{12} Hx dx_1 dx_2, \tag{1}$$

where μ is the shear modulus, $\omega_{12}{}^k$ is Green's functions (Steketee 1958), and the fault parameters are described in Fig. 1.

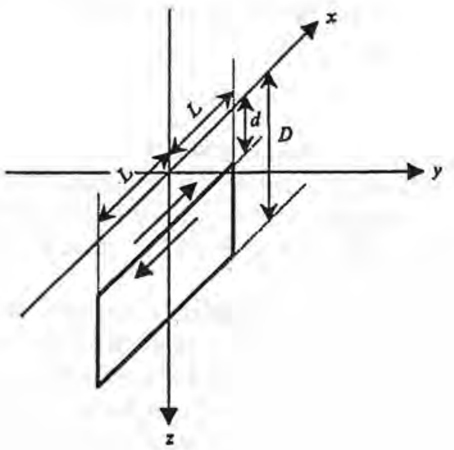


Fig. 1
A simple model of a vertical rectangular fault.
The pair of arrows indicates strike-slip along the x-axis.

Detailed expressions of the displacement field can be found elsewhere (Chinnery 1961; 1963). The stress field associated with the above displacement field will be derived using Hooke's Law and the boundary condition on the surface

$$\sigma_{ij} = \lambda\delta_{ij}u_{k,k} + \mu(u_{i,j} + u_{j,i}), \tag{2}$$

and

$$\sigma_{xz} = \sigma_{yz} = \sigma_{zz} = 0, \tag{3}$$

where λ is Lame's constant and δ_{ij} is a function satisfying

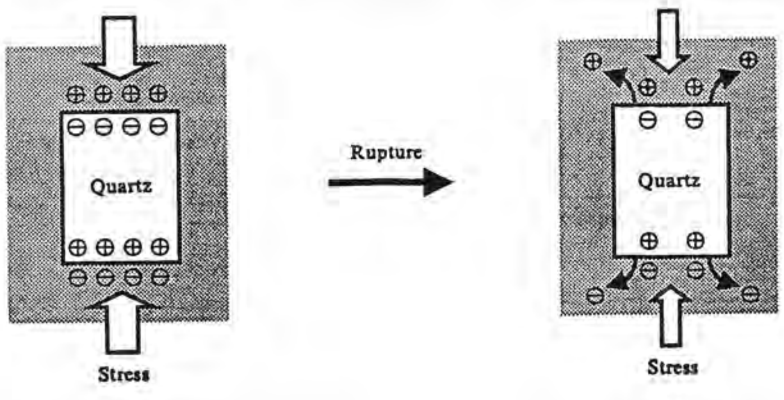
$$\sigma_{ij} = \begin{cases} 1, & i = j \\ 0, & i \neq j. \end{cases} \tag{4}$$

A positive value of the stress indicates an increase of either shear or compressive stress, or a relief of tensile stress, where a negative value represents a relief of either shear stress or compressive stress, or an increase in tensile stress. Detailed expressions for the stress components are too long to be given here.

III. AN ELECTROMAGNETIC MODEL OF A FAULT USING PIEZOELECTRIC EFFECT

When a stress is applied to a noncentrosymmetric crystal, a pair of polarization charges will appear on both edges of the crystal. The above phenomenon is called the piezoelectric effect. This physical property is also called piezoelectricity.

Piezoelectricity was introduced to explain earthquake lightning (Finkelstein and Powell, 1970). However, the conductive earth would cancel the polarization charges so that the above hypothesis was abandoned later. An electromagnetic model of a fault was presented to explain the earthquake lightning recently (Ikeya and Takaki 1996). It is not the piezoelectric polarization itself but the resident free charge in the earth which elicits some seismic precursory phenomena such as earthquake lightning, earthquake cloud, anomalous animal behavior, anomalous seismoelectric signals and so on. A schematic model is described in Fig. 2.



(a)
Bound charge q_b cancels the piezoelectric charge q_b in the conductive earth.

(b)
Release of bound charge due to rupture leads to the appearance of free charge, $q = q_b - q_p$.

Fig. 2
A schematic diagram of an electromagnetic (EM) model.

The resident free charge would be simply equivalent to the release of the piezoelectric charge due to the release of stress associated with faulting. The stress-induced polarization of a piezoelectric single crystal, e.g., quartz, would be expressed as a function of the stress vector

$$P_i = \sum d_{ij} \Delta S_j, \quad i = 1, 2, 3 \text{ and } j = 1, 2, \ldots 6, \tag{5}$$

where P_i are the components of the polarization vector, P, d_{ij} are the piezoelectric moduli, and ΔS_j are the stress changes. The transformation of ΔS_j and the symmetric stress σ_{ij} ($i = x', y', z'$ and $j = x', y', z'$) is $1 \Leftrightarrow x'x'$, $2 \Leftrightarrow y'y'$, $3 \Leftrightarrow z'z'$, $4 \Leftrightarrow y'z'$, $5 \Leftrightarrow z'x'$, $6 \Leftrightarrow x'y'$.

The piezoelectric moduli of quartz are described by the matrix

$$\mathrm{d} = \begin{bmatrix} d_{11} & -d_{11} & 0 & d_{14} & 0 & 0 \\ 0 & 0 & 0 & 0 & -d_{14} & -2d_{11} \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}. \tag{6}$$

Therefore, the included charges due to the release of stress associated with faulting can be quantified by the change density, ρ, which is described as follows:

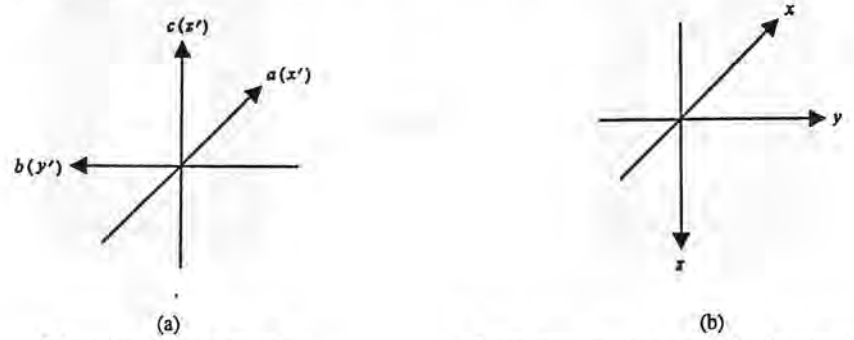
$$\rho = -\mathrm{div} P. \tag{7}$$

Equation (5) indicates that the stress-induced charges are related to both the stress change and the crystal orientation. For the homogeneous distribution of quartz crystals, we can obtain relationships between ΔS_j in Eq.(5) and the stress changes, σ_{ij} ($i = x', y', z'$, and $j = x', y', z'$), in the coordinate system as shown in Fig. 1 due to a uniform faulting.

If the orientation of quartz crystals is assumed as shown in Fig. 3, the transformation of the quartz orientation and stress field coordinate systems would be $x' \Leftrightarrow x$, $y' \Leftrightarrow -y$, and $z' \Leftrightarrow -z$. Therefore,

$$\begin{aligned} &\Delta S_1 = \sigma_{x'x'} = \sigma_{xx}, \Delta S_2 = \sigma_{y'y'} = -\sigma_{yy}, \Delta S_3 = \sigma_{z'z'} = -\sigma_{zz}, \\ &\Delta S_4 = \sigma_{y'z'} = \sigma_{yz}, \Delta S_5 = \sigma_{x'z'} = -\sigma_{xz}, \Delta S_6 = \sigma_{x'y'} = -\sigma_{xy} \end{aligned}. \tag{8}$$

The analytical expressions of the stress-induced charges around a fault would be derived from Eqs.(5), (7), and (8); the expressions of the stress changes due to a uniform faulting, and the piezoelectric moduli of quartz-bearing rocks. However, the explicit expressions of ρ for a rectangular fault are too long to be given here.



(a) Orientation of quartz crystals.

(b) Stress components expressed by the coordinate system of the fault model as shown in Fig. 1.

Fig. 3
Transformation of the coordinate systems of the quartz orientation and the stress field.

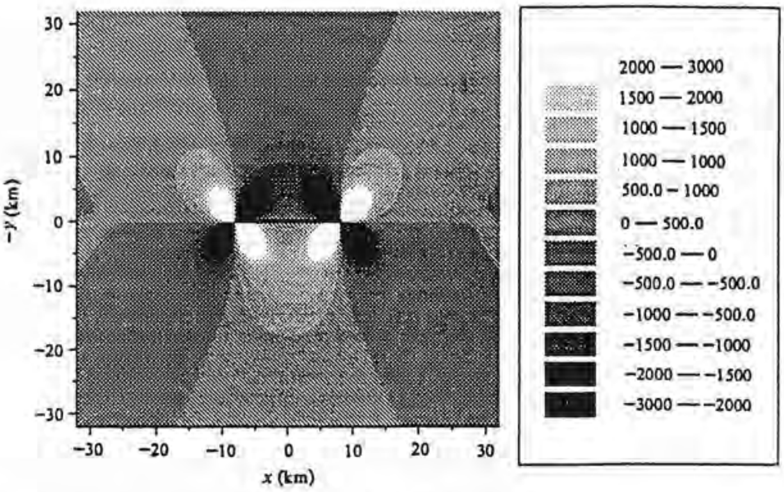


Fig. 4
The spatial distribution of stress-induced charges around the ground surface (a thin layer) associated with faulting. The black line in the center represents the Nojima fault. The charge density is in unit of 10^{-12} C/m^3.

IV. MODELING RESULTS AND DISCUSSIONS

Applying the model described in the above section to the Kobe earthquake, we can investigate the spatial distribution of induced charges associated with the main rupture. The earthquake fault (Nojima fault) can be treated approximately as a vertical rectangular strike-slip fault. Some fault parameters used here are: fault length $2L = 16$ km, depth of the upper edge $d = 0$, depth of the lower edge $D = 16$ km, and average slip $u = 0.8$ m. Lame's constants are assumed as $\lambda = \mu = 3.3 \times 10^{10}$ Pa.

Figure 4 shows the distribution of charge density around the ground surface (a thin layer with a thickness far smaller than fault depth). There are several alternating positive and negative lobes. An irradiation distribution of both positive and negative charges is found at each end of the fault. Note that a complicated character of the above spatial distribution of stress-induced charges was obtained even for the uniform medium as assumed in our model.

A rough estimation of the electric field associated with the stress-induced charges by faulting was made from our modeling result. For simplicity, we assumed the electric field to be uniform between two electric electrodes. The field intensity F can be estimated using $F = q/\epsilon$, where q is the surface density of charges and ϵ is the dielectric constant of the earth, e.g., for granite $\epsilon = 8\epsilon_0$, where the dielectric constant in vacuum $\epsilon_0 = 8.85 \times 10^{-12}$ F/m. The surface charge density q would be equivalent to the calibrated density around the ground (a very thin layer). Hence, an electric field with the intensity of 1–10 V/m would be obtained considering that the density of stress-induced charges in the local fault zone was about 10^{-10--9} C/m^3.

Although the predicted field intensity from our model is of the order of 10^{-3--2} V/m for granite considering that the effective piezoelectric coefficient of granite is experimentally about 0.1% of that of quartz (Sasaoka et al. 1998), this field is still about 2–3 orders of magnitude larger than the recorded seismic electric signals, which are usually of the order of 10^{-5} V/m. The comparison of our modeling results and the observations of electric potential during the Kobe earthquake by two observatories in western Japan is discussed elsewhere.

Seismic electric field can be estimated semi-empirically from the reported seismic anomalous animal behaviors and the experimental threshold values of electric field to animals' sensitivity. A previous investigation of the seismic electric field associated with the Kobe earthquake indicated that there would be an intense seismic electric field with the intensity of 1-100 V/m in the local focal zone considering the reported seismic phenomena (Ikeya et al. 1997c). Our present modeling calculation indicated that such an intense electric field would be formed in the local focal zone due to either the dominant orientation or piezoelectric fabrics of quartz-bearing rocks (Nikitin and Parkhomenko 1982) or due to the amplification effect of the local geological factors (Ikeya et al. 1996).

An electromagnetic model of a fault using the piezoelectric effect was developed to simulate the stress-induced charges associated with faulting. This would be the first theoretical discussion on the seismoelectric signals in the local focal zone. This simple model would provide a framework for further theoretical developments on the explanation of the seismoelectric signals. The numerical calculations based on this model may also provide some physical insights into the anomalous electric field associated with faulting.

We have not discussed the time effect of the induced charges in this paper because we intend to investigate the characteristics of the spatial distribution of the electric field associated with faulting. However, the stress around a natural fault should not change simultaneously. Hence, the electric field should be time-dependent, e.g., a pulsed decay field as discussed previously (Ikeya et al. 1997d). The real-time observation system of the pulsed electromagnetic signals has been developed and is working. The comparison of the modeling results and our real-time observations would give positive evidences for our present model if there are some moderate earthquakes in a certain region around our observatories.

V. SUMMARY

We presented an electromagnetic model of a fault to investigate the characteristics of the spatial distribution of stress-induced charges associated with faulting using the elastic dislocation theory and the piezoelectric effect. We obtained a complicated character of the spatial distribution of charges around a fault. We made a quantitative estimation of the electric field associated with the stress-induced charges during the 1995 Kobe earthquake.

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