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# Measurements of electric potential variation by piezoelectricity of granite

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**Abstract.** From laboratory experiments, we observed that unloading stress on a piece of granite induced a pulsed electric potential variation, which decays exponentially with a time constant ranging from 1.5 to 4.0 s. The electric potential variation depends on the magnitude and the sustaining time of applied stress, indicating that the variation is due to piezoelectricity and migration of bound charges that compensate the piezoelectric polarization. An apparent piezoelectric coefficient of granite was obtained to be about $1.4\times10^{-15}$ C/N, three orders of the magnitude smaller than that of a single crystal of quartz.

## 1. Introduction

Since the Russian study in which a detonation induced a piezoelectric field in a quartz vein [*Volarovich et al.*, 1959], piezoelectric polarization in rocks has been attributed to seismoelectric phenomena. For example, Finkelstein and Powell [1970] explained earthquake lightning as piezo-induced electromagnetic phenomena. However, they later withdrew the proposal because charge carriers bound the piezoelectric polarization in the conductive earth.

Piezoelectricity in quartz-bearing rocks has also been measured in laboratory experiments. The main goal of some of these experiments was to clarify the presence of piezoelectric fabrics caused by preferred orientation of a quartz grains [*Tuck et al.*, 1977; *Nikitin and Parkhomenko*, 1982:*Ghomshei and Templeton* 1989]. In general, the results supported the presence of piezoelectric fabrics, though the piezoelectric effects for granite obtained by Tuck et al. [1977] were smaller than the background fluctuations. They concluded quartz grains in their samples were paired or twinned.

Here we can suggest that the low piezoelectric fields observed by Tuck et al. [1977] resulted from of cancellation of piezoelectric polarization by charge carriers.

To our knowledge, there are no published results on the behavior of bound charges in rocks. In our model, electric field variation appear at stress change; in case of unloading, piezoelectric polarization in granite reduce promptly, then the charge carriers that compensated the piezo-polarization diffuse with a certain relaxation time, considering the mobility of charge carriers.

To quantify this role, we measured the electric fields that were induced by bound charges in granite after unloading stress, from which we obtained the apparent piezoelectric constant of an unheated granite sample and the relaxation time of bound charges. Our results indicate that bound charges are an important part of observed seismo-electric signals.

## 2. Experimental

### 2.1. Samples

We prepared cubic samples ($10\times10\times10$ cm$^3$) of granite (province of Fujian, China), olivine trachybasalt (Genbu cave, Hyougo, Japan), and pure aluminum. The grain-size of minerals in granite ranges from 0.5 to 3 mm (average 1.5 mm) and the quartz content is about 30 volume percent judging from the surface textures. The DC resistivity was measured to be $3.7\ \times10^{6}\Omega\cdot$m for the granite sample using an universal electrometer and accessory electrodes (P617 electrodes with a guard ring in the shield box from Yokokawa Inc. MMAII-17A).

### 2.2. Apparatus

**2.2.1. Electric potential measurements.** Figure 1 demonstrates the measurement system of electric potential variation near a specimen surface using an electrometer (Advantest R8240). The input impedance and response time of the electrometer are more than $10^{13}\Omega$ ($R_i$) and less than 2 ms, respectively. The copper electrodes were placed at a distance of about 5 mm from the sample surface and insulated by teflon pillars to avoid triboelectricity and contact electrification at their interface. The electric potential measurements were separately carried out from stress measurements to reduce noise.

The variation of the voltage measured by the electrometer ($V_m$) is lower than that of real electric potential appearing at the surface of rock ($V_r$). The relationship is

$$V_r = \frac{C_s}{C_i}V_m \tag{1}$$

where $C_i$ is total input capacitance of this system as much as 50 pF. $C_s$ is capacitance between each electrode (E1 to E5) and the granite sample ranging from 7.1 pF to 7.5 pF, respectively. Considering the leakage of charge at electrodes, the time constant of this system was confirmed to be more than 13 s by analyzing the stability of the offset voltage after supplying charges to the electrodes. Outputs of the electrometer through a low pass filter (less than 100 Hz) were recorded using a digital storage oscilloscope software package installed on a personal computer at the sampling frequency of 200 Hz.

**2.2.2. Compression and release.** A specimen was loaded vertically with a hydraulic compression ma-

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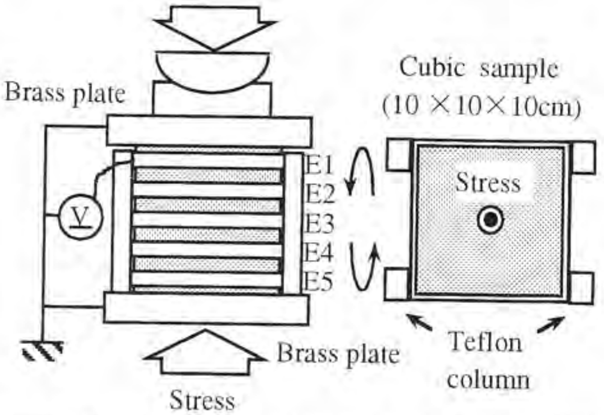

**Figure 1.** Schematic diagram of the experimental apparatus. The electric potential measurement is made near a specimen surface with an electrometer having an input impedance more than $10^{13}\Omega$. The hydraulic compression machine is electrically grounded and the system is in an electrostatic shielding box. Copper electrodes (E1 ~ E5) are insulated by teflon columns.

chine. A spherical sheet consisting of a half sphere and a dish of stainless steel were inserted between a sample and the jack to correct distortion of angles between the both surfaces as demonstrated in Figure 1. The hydraulic compression machine was electrically grounded to reduce electrical noises due to triboelectricity between the metal cylinder and oil.

The variation of the stress was evaluated by using piezoelectricity of synthetic X-cut quartz crystal. The X-cut quartz and insulated electrodes were placed between the sample and the compression machine. The electrodes were connected to a pico-ammeter (Advantest R8240). When the stress is unloaded, charges bound by the piezoelectric field of the X-cut quartz are released at the electrode and flow through the pico-ammeter. The current is proportional to the stress rate. A example of abrupt stress reduction from 4.9 MPa is shown in Figure 2(b) by integrating the current data stored with a digital oscilloscope.

## 3. Results and Discussion

Figure 2 (a) demonstrates an electric potential variation at the central electrode E3 for a granite, a basalt and an aluminum samples after abrupt release of stress from $\sigma$=4.9 MPa. The basalt and aluminum samples showed no potential variation with stress release except for a very small step. This step is likely caused by capacitance changes of $C_s$ or $C_i$ which result from a movement of the compression machine. The electric potential is stable after movements of the jack within the time constant of the measurement system.

In contrast, the electric potential of the granite sample displayed an abrupt increase when the stress was released (Figure 2 (a)). This was followed by an exponentially decay in the potential with a time constant, $\tau$, of 3.7 s. Closer examination of the abrupt increase in electric potential for a granite sample is shown in Figure 2 (b), where it can be seen that the potential rise corresponds to the fall in stress. The electric potential variation will be correlated to piezoelectricity of quartz in granite because the basalt sample without quartz grains did not show such the variation.

Figure 3 shows the dependence of the peak voltage value at stress reduction from 2.0 MPa on the stress-sustaining time. The peak value became smaller as the stress-sustaining time was shorten. This fact strongly suggests that the electric field is caused by bound charges after the disappearance of piezoelectricity. When the stress-sustaining time is less than 5 s, the quantity of bound charges to compensate the piezoelectric field was not enough. This electric field decays

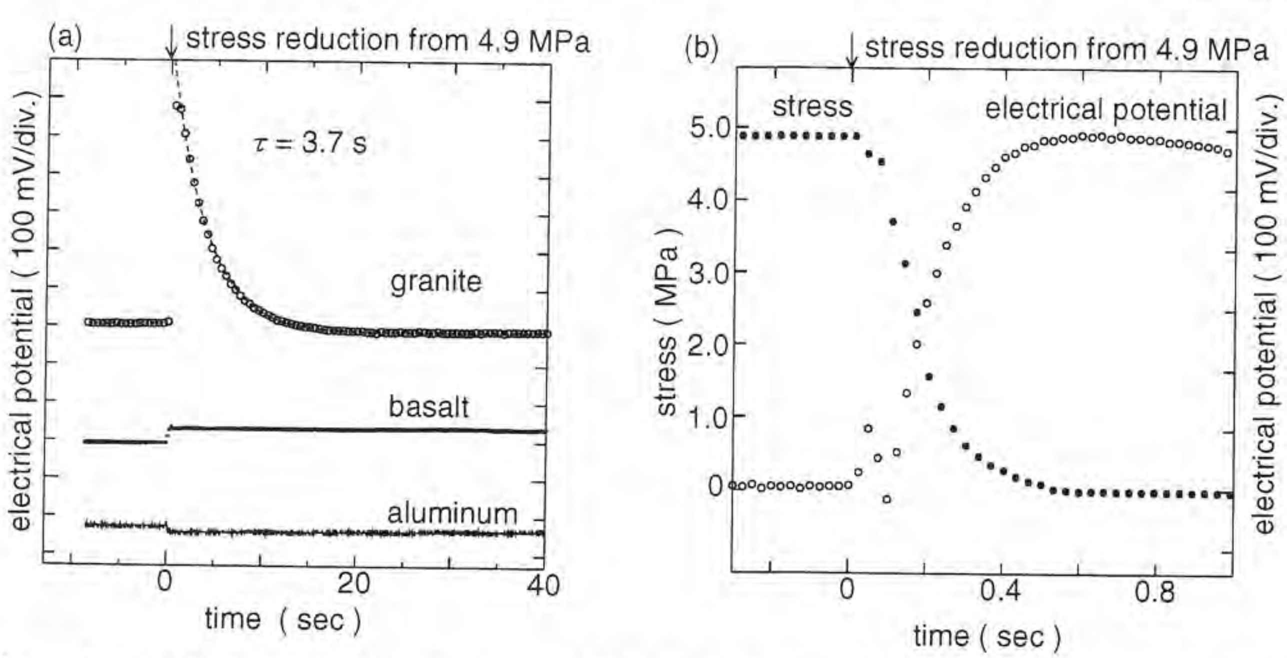

**Figure 2.** (a) Electric potential variation at an E3 electrode for granite by releasing the stress from $\sigma$=4.9 MPa. An exponential curve was fit to the data by the least-square method. (b) Comparison of stress reduction and electric potential rise.

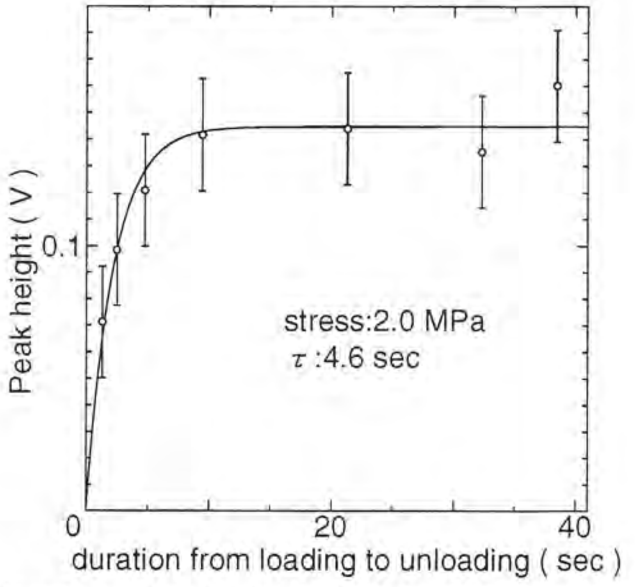

**Figure 3.** Peak heights in electric potential variation of the granite sample as a function of the sustaining time of applied stress of the constant stress of 2.0 MPa. The curve fitted to the data by least-square method assuming the exponential saturation.

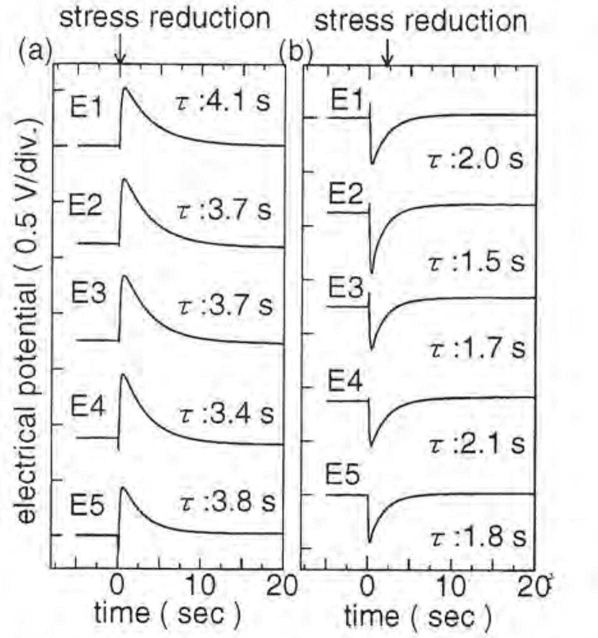

**Figure 5.** Electric potential variation at several electrodes in Figure 1 when the same sample was compressed along different directions.

exponentially with the relaxation time of bound charges in granite.

According to an electromagnetic model of a fault [*Ikeya and Takaki*,1996], the relaxation time for bound charges in granite is described by the product $\epsilon\rho$, where $\epsilon$ and $\rho$ are an averaged dielectric constant and electric resistivity. The relative dielectric constant, $\epsilon^*$ is estimated to be $1.1\times10^5$, using $\epsilon^* = \tau/\rho\epsilon_0$, where $\rho$ is the measured value of $3.7\times10^6 \Omega{\cdot}\mathrm{m}$ and $\tau$ is the average relaxation time of 4.6 s and $\epsilon_0$ is the dielectric constant in vacuum. The estimated $\epsilon^*$ is much larger than those frequently used in literatures in high frequency range ($\epsilon^* = 5$ to 10), even after considering that our electric resistivity data may have an error of several factors due to polarization at the electrodes. The dielectric properties of granite rocks containing water was reported to have anomalous low-frequency dispersion [*Lockner*, 1981]. The granite, which was presaturated with 0.01 $M$ KCl solution and confined in 200 MPa, had a resistivity of about $10^5 \Omega{\cdot}\mathrm{m}$ and a relative dielectric constant of about $10^5$ at $10^{-1}$ Hz [*Lockner*, 1981]. The $\epsilon^*$ we estimated is thus in good agreement with Lockner's work. The anomalous low-frequency dispersion was observed in various materials whose conductivities are largely influenced by the water content. Such frequency dependence of dielectric constants of rocks should be taken into consideration in the estimation of transmission of electromagnetic waves.

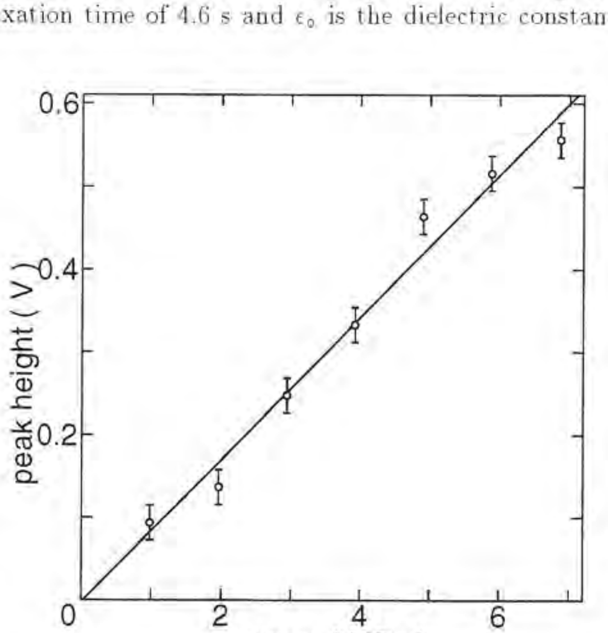

**Figure 4.** Plot of the peak height in the electric potential obtained by releasing stress on the granite sample. The line fit by least-square gives an apparent piezoelectric coefficient.

The stress-dependence of the peak heights of the potential variation for granite indicates a good linearity as shown in Figure 4. The apparent piezoelectric constant $\alpha_{eff}$ can be estimated to be $1.4\times10^{-15}$ C/N from the variation of the electric potential (about $7\times10^{-4}$ times of that of a single crystalline quartz) assuming that the electrostatic field was due to charges related with piezoelectricity. The value is in good agreement with previous data [*Kondrashev*, 1980].

Figure 5 (a) and (b) shows the electric potential at the different electrodes when the same sample was compressed along different directions. The polarity and intensity of the peak height at all electrodes are almost homogeneous when the the direction of compression is same. It is difficult to explain the homogeneity of electric potential variations by the fabric of piezoelectric polarization. Such homogeneity was observed in other granite samples and also reported by other investigators of rock piezoelectricity [*Nikitin and Parkhomenko*, 1982]. The structures of the measurements system seem to determine the polarity, which will be discussed elsewhere.

An apparent piezoelectric moduli of granite consisting of $N$ grains of quartz can be expressed as

$$\Delta_{ikl} = \sum_{n=1}^{N} \frac{V_n}{V} \delta(g_n) \tag{2}$$

where $V_n/V$ and $\delta(g_n)$ are the volume fraction and the piezoelectric moduli of the $n$th quartz with orientation $g_n$ [*Bunge*, 1985]. Assuming the volume ratio of quartz grain, 0.3 and the grains size of $1.5^3$ mm, the longitudinal piezoelectric constant is given by

$$\Delta_{iii} = 0.3 \sum_{n=1}^{N} \frac{\delta_{iii}(g_n)}{N} \tag{3}$$

The variance of a longitudinal piezoelectric constant of randomly oriented quartz grains ($\alpha_{eff}$) is equal to that of a quartz grain, stressed along randomly oriented direction, $(\theta, \phi)$. Therefore the variance are simply expressed as

$$\sigma^2 = \frac{1}{4\pi} \int_0^{\pi} \int_{-\pi}^{\pi} [d_{11} \sin\theta (|\cos\phi| - |\sin\phi|) \cos\phi \cos(\frac{\pi}{2} - \theta)]^2 \sin\theta d\theta d\phi \tag{4}$$

where $d_{11}$ is longitudinal piezoelectric constant of quartz, $2 \times 10^{-12}$ C/N. The deviation of the mean value of N quartz grains is $\sigma/\sqrt{N}$ according to central limit theorem.

The piezoelectric effect due to statistical deviation is estimated to be $10^{-3}$ $d_{11}$, which is comparable to our experimental result for the granite sample, $\alpha_{eff}$.

## 4. Summary

An electric potential changes after sudden stress drop can be explained by bound charges compensating the piezoelectric polarization. The relative dielectric constant of the granite sample was estimated to be $1.1 \times 10^5$ from the electric resistivity and the relaxation time of the bound charges. This anomalously large value is in good agreement with of Lockner's. results[*Lockner*,1981]. The apparent piezoelectric coefficient of granite estimated from the charge carriers was about $1.4 \times 10^{-15}$ C/N, three orders of the magnitude smaller than that of quartz.

The time constant of the exponential decay for granite ranged from 1.5 to 4.5 s, which may correspond to the anomalous electric field at ULF before earthquakes [*Fujinawa et al.*, 1992] and to the seismic electric signal (SES) observed in the VAN method [*Varotsos and Alexopoulos*, 1984a, b].

In VAN method, SES is distinguished from noises empirically by linear dependence of signal magnitude on the distance between electrodes. However, the variation of the electric potential measured by VAN method would be caused not by the electric current but by the local electrostatic field at measuring sites. To make that clear, the input impedance and capacitance of the measurements system should be described in the papers of VAN method because those parameters determine the measurable electric fields in the measurements system.

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