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Stick Slip, Charge Separation and Decay

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Abstract—Measurements of charge separation in rock during stable and unstable deformation give unexpectedly large decay times of 50 sec. Time-domain induced polarization experiments on wet and dry rocks give similar decay times and suggest that the same decay mechanisms operate in the induced polarization response as in the relaxation of charge generated by mechanical deformation. These large decay times are attributed to electrochemical processes in the rocks, and they require low-frequency relative permittivity to be very large, in excess of 10^5. One consequence of large permittivity, and therefore long decay times, is that a significant portion of any electrical charge generated during an earthquake can persist for tens or hundreds of seconds. As a result, electrical disturbances associated with earthquakes should be observable for these lengths of time rather than for the milliseconds previously suggested.

Key words: Induced polarization, earthquake.

Introduction

Induced polarization (IP) was first described by SCHLUMBERGER (1920). Since then it has proven valuable as a prospecting tool for discovering ore bodies, although its success has been limited by a lack of understanding of the complicated physical processes that produce polarization in rock. One fact that is generally agreed upon, however, is that in the range of 0.1 to 1000 Hz the polarization process in rock cannot be viewed as a simple resistor-capacitor circuit; that is, potential decays do not fit a simple exponential form (LOCKNER and BYERLEE, 1985a; SUMI, 1961; WAIT, 1958; VACQUIER et al., 1957). This has led to attempts to model rock impedance by more complicated circuit elements, such as Warburg impedance (MADDEN and CANTWELL, 1967), in which grain-electrolyte interactions are taken into account (WONG, 1979). A consequence of this approach is that in these models conductivity and permittivity are frequency-dependent (LOCKNER and BYERLEE, 1985b). In this paper we will examine some of the implications of this frequency dependence when applied to electrical phenomena associated with earthquakes.

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MADDEN and WILLIAMS (1976) have shown that for electrostatic charges the electric field created by a charge accumulation will in general cause that charge to disperse at a rate of

$$q = q_0 \exp\{ -(\sigma/\varepsilon_0\varepsilon)t\}$$

where σ is conductivity, ε_0 is permittivity of free space, and ε is relative permittivity. Using typical numbers for wet rocks of $\sigma = 10^{-2}$ S/m and $\varepsilon = 10$, measured at high frequency (OLHOEFT, 1979), Madden and Williams concluded that the relaxation time ($t_r = \varepsilon_0\varepsilon/\sigma$) should be on the order of microseconds. Although rock such as ultra-dry quartzite or granite can yield $t_r > 100$ sec, the addition of only trace amounts of water to the rock will greatly increase the conductivity. Then, if the permittivity remains low, the relaxation time will shorten. Madden and Williams concluded that, in general, electrostatic charges in rocks near the Earth's surface should dissipate very quickly. However, IP measurements and also measurements of stress-induced polarization (KUKSENKO et al., 1981; SOBOLEV et al., 1982) indicate that, for a large class of rocks and geological materials, electrical charges, once generated, can persist for many tens of seconds. If, as IP measurements indicate, frequency-dependent σ and ε are used in Madden and Williams's analysis, this apparent discrepancy is resolved.

Experimental method

We have conducted three different types of experiment in which electric potential and charge were measured. The measuring instrument in all cases was a Keithley model 624 electrometer (having an input impedance in excess of 10^{16} ohms) connected to the sample with low-noise coaxial cable. The electrometer, as used in these experiments, had a time constant of less than 0.2 sec. Samples of Westerly granite and quartzite were studied. Wet samples were saturated with distilled, deionized water. Dry samples were room-dry (i.e., exposed to air). All experiments were conducted at room temperature and a relative humidity between 30 and 40 percent.

In the first set of experiments samples of granite and quartzite were deformed in a 'sandwich' type direct-shear apparatus (DIETERICH, 1972); see Figure 1. The sample area of contact was 5.08 × 5.08 cm. Surfaces were prepared with 240-mesh SiC abrasive. Dry samples were deformed with clean, mated surfaces at a constant normal stress of 8.4 and 1.5 MPa. Granite samples with 0.11 cm layers of clay-rich fault gouge between the surfaces were also deformed at a normal stress of 8.4 MPa. All of these experiments were performed at a constant displacement rate of the piston applying the shear load. A 4.5 × 0.635 cm brass probe, separated from the sample by an air gap of nominal width 0.14 cm, was placed over one of the saw cuts in the sample assembly (Figure 1) for measuring charge. The probe was connected to the electrometer, which was set to measure voltage. The capacitance to ground of the input circuit (excluding the electrometer) was 80 ± 10 pF. This capacitance, as shown in Figure 2, results in 1 mV input offset being equal to 0.8×10^{-13} coul.

A second set of experiments was performed with samples measuring $5.18 \times 5.18 \times 2.54$ cm. In these experiments an Ag/AgCl electrode was attached as shown in Figure 3. The samples were then loaded uniaxially to approximately half

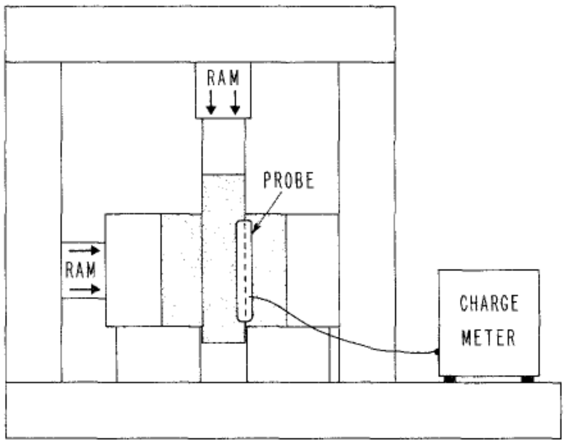

Figure 1
Biaxial press test geometry for measuring charge generated during deformation of simulated faults.

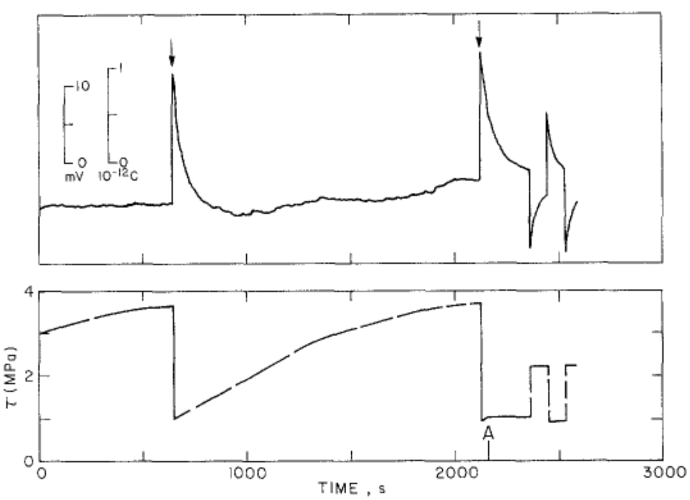

Figure 2
Shear stress (lower curve) and induced charge (upper curve) for stick-slip events during deformation of granite samples at 8.4 MPa of normal stress in biaxial press. Displacement rate at load point was 0.1 μm/sec (before time *A*). Response to stress changes without slip (after time *A*) indicate that charge generation is primarily stress-related. Arrows indicate stick-slip episodes.

of their failure strength and then abruptly unloaded, after which the potential to ground of the electrode was measured. In a variation of this experiment a copper probe (1.5 × 0.5 cm) was mounted 0.13 cm from the sample. The charge induced on the probe in response to uniaxial loading of the sample was then measured.

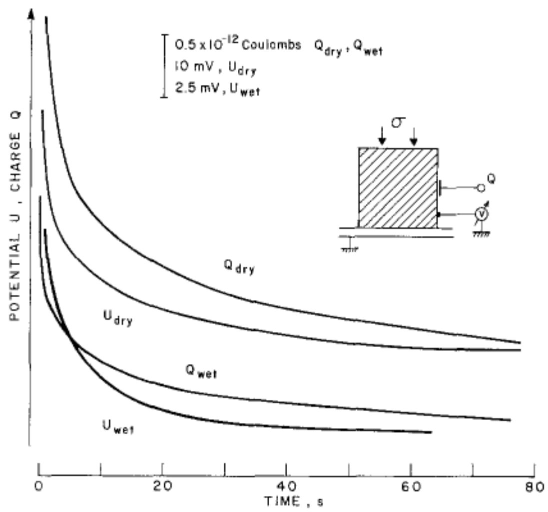

Figure 3

Induced charge (Q) and potential (U) response for saturated and unsaturated granite samples loaded uniaxially to approximately 100 MPa and released after 50 sec. Capacitance to ground of charge measuring circuit is approximately 100 pF. Ag/AgCl electrode (see diagram) was used for measuring potential.

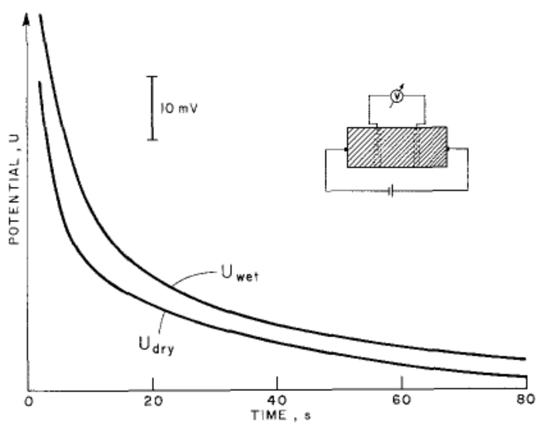

Figure 4

IP response to 50 sec, 6 v polarizing current for both saturated and unsaturated samples. Polarizing current was applied to ends of sample with Ag/AgCl electrodes and potential response was measured across central (Pt-black) electrodes (see diagram). Charging potentials measured just before $t = 0$ were $U^0_{\text{wet}} = 1.63$ V, $U^0_{\text{dry}} = 1.44$ V.

A third set of IP experiments was carried out, in which cylindrical samples of granite, 6.35 cm long by 2.54 cm in diameter, were used. In a four-electrode scheme Ag/AgCl current electrodes were attached to the ends of the sample (Figure 4) and Pt-black potential electrodes were inserted in holes 0.65 cm in diameter and 2.54 cm apart in the center of the sample. The holes were filled with a 0.1 M_{aq} KCl solution. Samples were polarized for 50 sec by a 6 V battery connected across the current electrodes. Then, when the battery voltage was switched off, the current electrodes were removed from the sample and the electric potential was measured across the central Pt electrodes.

Results

In the first set of experiments, with a biaxial press, samples of granite and quartzite were deformed at 8.4 and 1.5 MPa of normal stress at displacement rates of 0.1, 1, and 10 μm/sec, resulting in a series of sudden 'stick slip' motions of the sample. Two such episodes, at 8.4 MPa normal stress, are indicated by the arrows in Figure 2, where shear stress and probe voltage are plotted as a function of time. A second scale, converting voltage to charge, is also shown. The piston was advanced at 0.1 μm/sec until time A, at which point displacement was held constant. Coincident with the stick-slip events approximately 20 mV developed on the probe, corresponding to a charge of about 10^{-12} coul. After time A (Figure 2) the sample was subjected to a series of stepped stress changes without sliding, to show whether the observed voltage offsets were due to slip or to stress change. As may be seen, voltage offsets were primarily related to stress changes. Thus, piezoelectric effects (TUCK et al., 1977) may be the source of charge in these experiments, although other phenomena may also be operating. When the sample was deformed at a 1.5 MPa normal stress, smaller stick-slip events and correspondingly smaller voltage offsets occurred, indicating that the charge generated was proportional to the stress drop. Similar experiments with a quartzite sample gave nearly identical results.

In the second set of experiments the charge induced on a probe was compared with the electric potential of both wet and dry rock in response to sudden stress change. Samples measuring 5.18 × 5.18 × 2.54 cm were loaded uniaxially to approximately 100 MPa, allowed to sit for 50 sec, and then abruptly unloaded. The response to this sudden unloading is plotted in Figure 3. The two potential curves plot the voltage difference between the electrode attached to the sample and the loading frame. The two remaining curves, taken from separate experiments, represent the charge induced on a probe adjacent to, but not touching, the center of the sample. In all cases the decays are much longer than the instrument constant (0.2 sec) of the electrometer.

It seemed possible that the slow-decay curves plotted in Figure 3 were the result of discharging of the probe through the high-impedance input circuit of the electrometer. To test this theory, we placed a sample, as shown in Figure 3, in a vacuum chamber and applied a 6 V potential to the upper surface for 100 sec. When the voltage was abruptly removed, the decay of charge induced on the probe was then measured. Decay curves similar to those plotted in Figure 3 were observed in experiments before evacuation. However, after a 700 mm Hg vacuum had been applied to the sample for 10 min, almost no charge remained on the probe after 1 sec. Thus, we are confident that the charge measured by the electrometer was induced by charge concentrations in the rock samples and that the long decay times shown in Figure 2 and 3 reflect the slow dissipation of that charge.

In the final set of IP-style experiments, decay curves for potential response of wet and air-dry Westerly granite were measured. The results of two experiments are plotted in Figure 4. In both cases an excitation voltage of 6 V was applied for 50 sec. On the basis of the similarity of the curves in Figure 3 and 4 we assert that whether a space charge is generated in these samples by stress changes or by an external electric field, the same mechanism controls the charge decay.

Discussion

Decay curves for time-domain IP measurements are typically nonexponential, requiring conductivity and/or permittivity to be frequency-dependent. This has been verified by numerous researchers using laboratory and field measurements (WAIT, 1959; BERTIN and LOEB, 1976; WONG, 1979; NELSON et al. 1982; NELSON and VAN VOORHIS, 1983; LOCKNER and BYERLEE, 1985a, 1985b). Furthermore, the long decay times commonly observed in IP measurements suggest that the low-frequency permittivity is very great. In fact, WAIT (1958) has shown that over the frequency range of 0.1 to 100 Hz ε can exceed 10^6. Other researchers have measured large permittivities at low frequencies in rocks (HOWELL and LICASTRO, 1961; SCOTT et al. 1967; SAINT-AMANT and STRANGWAY, 1970; SHAHIDI et al. 1975; LOCKNER and BYERLEE, 1985b) and in clays (ARULANANDAN and MITCHELL, 1968; LOCKHART, 1980a, 1980b; LOCKNER and BYERLEE, 1985a). The mechanisms normally associated with charge separation are related to distortion of electron orbitals and molecular bonds, redistribution of ions within a material, and rotation of polar molecules, all of which have short relaxation times. At frequencies below about 10^3 Hz in rocks these mechanisms will often be dominated by such electrochemical phenomena as ion-exchange reactions at, and polarization of, grain-electrolyte interfaces and membrane polarization (cation exchange) in clays. These low-frequency polarization mechanisms are in general responsible for long-period IP response, and they may be expected to occur in a large variety of rock types.

Other means of polarizing rocks exist, besides the application of an external electric field. Changes in stress can result in charge separation through piezoelectric effects, streaming potentials (FITTERMAN, 1979), interaction of grain double layers

(KUKSENKO et al. 1981), and possibly other effects. As shown in Figures 2 and 3, these can result in long decay times. Besides stress changes, shearing can generate charge in rocks. For example, in other biaxial experiments we deformed samples containing natural fault gouge at constant shear and normal stress and produced charge separation of the same order as that shown in Figure 2.

Since clay minerals are often found in naturally occurring faults, we may expect natural faults to have large low-frequency permittivities. IP measurements indicate that this will be true for saturated as well as unsaturated rocks. Then, charge generated during sudden deformation at the time of an earthquake should persist for many tens of seconds. In a related paper LOCKNER et al. (1983) proposed a mechanism by which earthquakes could generate earthquake lights and other electromagnetic phenomena. In this scheme the fault zone was required to be heated by frictional sliding until pore water was vaporized. In this way the conductivity of the fault was reduced, to allow for long relaxation times. Our present results do not conflict with this mechanism but, rather, indicate that the constraints posed in this model may be less restrictive. While the vaporization of pore water is still a likely source for generating charge in the fault zone (POUNDER, 1984), once the charge is produced, it may not dissipate immediately, even when the ground is saturated: a significant percentage of it may remain and allow the persistance of related electromagnetic phenomena.

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