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Positive Holes and their Role during the Build-up of Stress prior to the Chi-Chi Earthquake

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ABSTRACT

Before the 1999 Chi-Chi earthquake strong, pulsed magnetic field anomalies were recorded at the Liyutan and Tsengwen stations of the Taiwan magnetometer network, reaching peak intensities of 200 nT. To produce such large local magnetic field variations ground currents in the order of 10^6 Amp are required. We report on uniaxial rock deformation experiments on (quartz-bearing) granite and (quartz-free) anorthosite to study stress-induced changes in electrical conductivity. Already before loading the rocks exhibit a weak electronic conductivity, which is p-type due to the presence of positive hole charge carriers (p-holes). Upon application of stress the conductivity increases, due to the activation of more p-holes. However, the conductivity increases not only in the stressed rock volume but also in the surrounding rock. This suggests that p-holes flow out from stressed rocks, the "source volume", into the surrounding unstressed rocks. We show that, when rocks are subjected to stress, they release p-hole charge carriers like a battery. If we scale up the small rock volume subjected to stress during our "battery" experiment to the much larger rock volume assumed to be subjected to high levels of stress before the Chi-Chi event, 100 x 50 x 10 km^3, p-holes activated in that volume would produce 10^8 Amp. A conceptual model describes the p-hole outflow from the "source volume" coupled to an influx of H^+ from H_2O assumed to be available along the Chelungpu fault.

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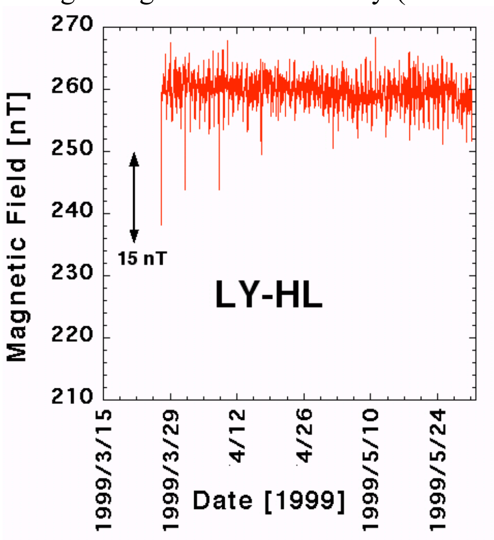
INTRODUCTION

Various non-seismic signals before major earthquakes have been reported for centuries, even millennia (Tributsch 1983). Others were added after modern technology made their detection possible such as bursts of electromagnetic (EM) emission from the ground and local magnetic field anomalies (Fujinawa and Takahashi 1990; Molchanov and Hayakawa 1998; Hayakawa et al. 2001). Though the causes of these signals are still poorly understood, we can say with a high degree of confidence that local magnetic field pulses as measured before the Chi-Chi earthquake (Yen et al. 2004) require transient electric currents in the ground. The magnitude of the currents can be inferred from intensity of the magnetic anomalies. In the case of the Chi-Chi event the currents must have been in the range of 10^6 Amp. This raises the question what mechanism may exist in Earth's highly resistive crust that could produce such large electrical currents.

In this report we shall not review the mechanisms proposed in the past how to produce ground currents and then argue point by point why these mechanisms fail to account for currents of such large magnitudes as inferred from some of the Chi-Chi observations. Instead we use the available space to present (i) the magnetic anomalies fortuitously recorded before the Chi-Chi event due to the confluence of favorable circumstances, (ii) laboratory experiments with igneous rocks to study the stress-induced activation of electronic charge carriers, and (iii) a conceptual ground current model to explain some of the salient features of the Chi-Chi magnetic field anomalies.

MAGNETIC FIELD ANOMALIES PRIOR TO THE CHI-CHI EARTHQUAKE

In 1987 Horng-Yuan Yen and his group set up an 8-station magnetometer network in Taiwan. The master station is collocated with the National Central University at Chung-Li in the north. Five stations are aligned along the Pacific coast, including HL and TT, while the two stations at Liyutan (LY) and Tsengwen (TW) are inland. Serendipitously the LY station is located close to the northern termination of the Chelungpu fault that broke 12 years later during the September 21, 1999 M=7.6 Chi-Chi earthquake. The TW station is located about 50 km south of the southern termination of the ruptured Chelungpu fault and close to the epicenter of the large aftershock at Chai-Yi. The total magnetic field intensity data collected by the network stations at a rate of one per 10 min were primarily intended for a study of the long-term drift in the regional geomagnetic field intensity (Yen et al. 2004).



In Figure 1 we plot the signals received at LY from March 27 to May 31, 1999, corrected for magnetic storm activity by subtracting the signals received at HL along the Pacific coast. During this particular time the LY-HL signals exhibit only a daily residual of less than ±5 nT reflecting the slight differences expected for two stations at slightly different latitudes.

Figure 1: LY-HL signal during a quiet time in early 1999 when there was no detectable anomalous magnetic activity from the ground.

The LY station was off-line from June 1, 1999 until the end of July 1999. When LY was put back into operation on August 1, 1999, it recorded strong magnetic field anomalies as shown in Figure 2a/b. The anomalies, which were already in full swing, reached 200 nT. They arrived in pulses that lasted several hours and were grouped in bunches that lasted several days.

(a) (b)

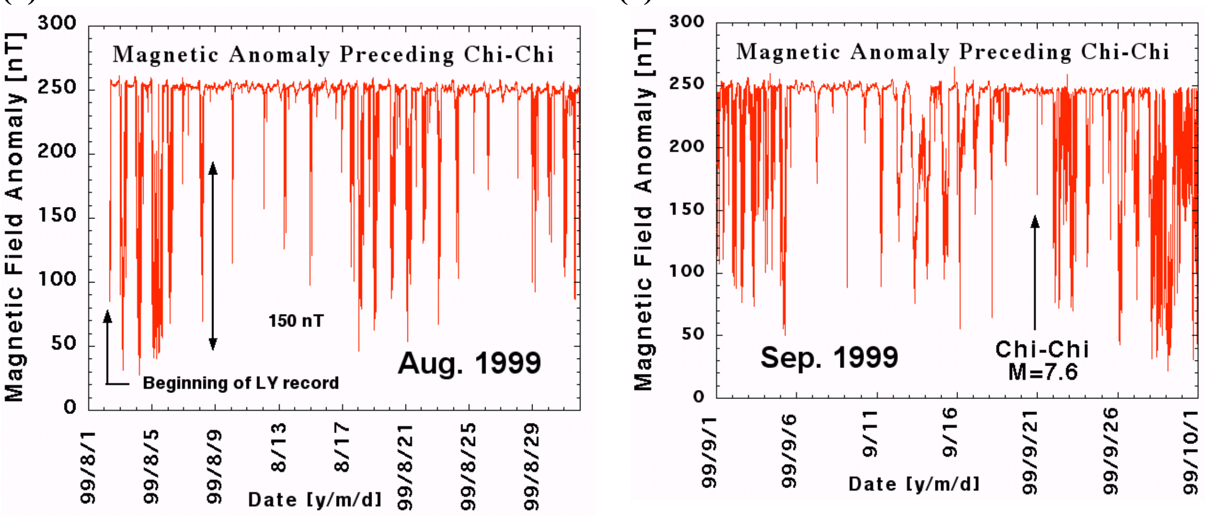


Figure 2: Anomalous LY-HL signals (a) during August 1999 and (b) during September 1999

(a) (b)

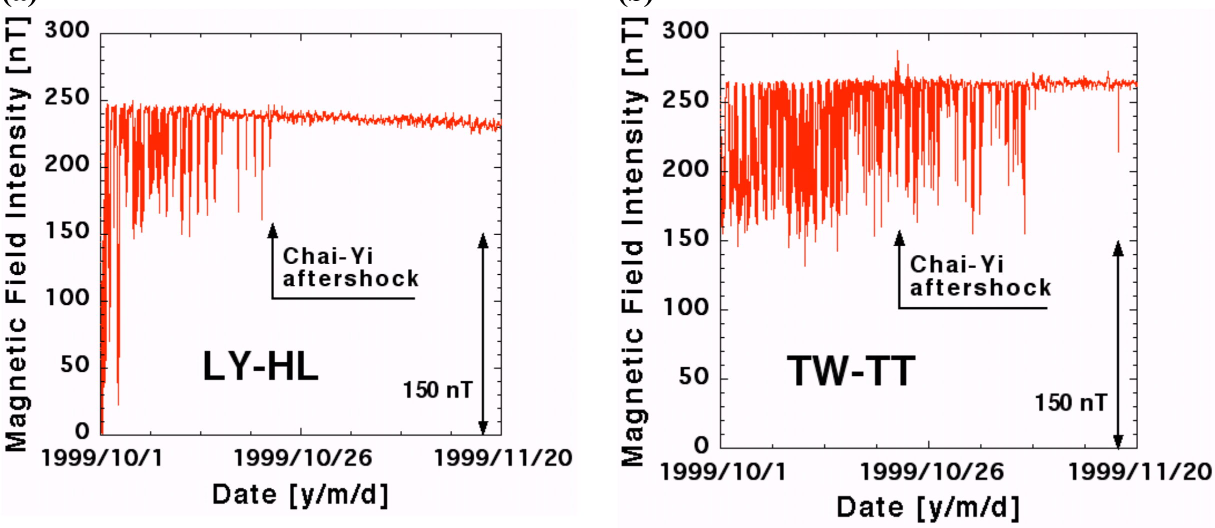


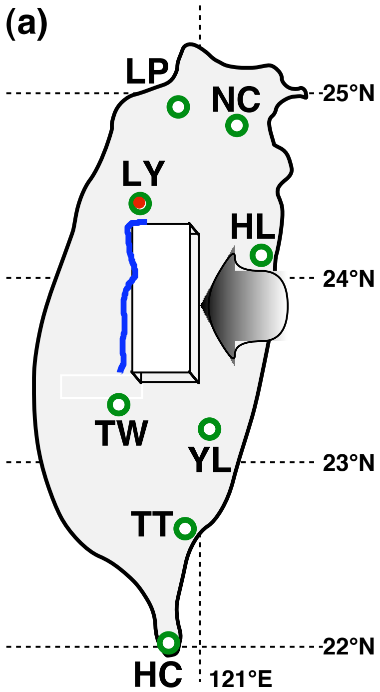
Figure 3: LY-HL signal (a) and TW-TT signals (b) between October 1 and November 20, 1999.

The TW station, which had also been off-line, was switched on within hours after the Chi-Chi earthquake. It recorded similar sequences of anomalous magnetic pulses as LY. Figure 3a shows the TW-TT signal from October 1, 1999 to November 20, 1999, corrected for magnetic storms with the data from TT along the Pacific coast. Figure 3b shows the LY-HL signal for the same period. During the four weeks of most intense aftershocks, which culminated in the major event near Chai-Yi on October 22, 1999, the magnetic activity migrated from the northern end of the Chelungpu fault toward the south. This is documented by the sustained high signal intensity at TW, while the LY intensity already tapers off to background levels. The LY and TW signals exhibit different intensity patterns indicating that the reported anomalies are not artifacts due the magnetometers fortuitously malfunctioning at both stations. We therefore support the conclusion reached by Yen et al. (Yen et al. 2004) that the magnetic anomalies are real.

MAGNITUDE OF THE INFERRED GROUND CURRENTS

The Chi-Chi epicenter was located at ~10 km depth along the S-N trending Chelungpu fault, which first dips steeply to the East and gradually becomes shallower at depth (Ma and Chiao 2003). Most aftershock activity occurred at 10 to 25 km depth (Hsu and Lo 2004), indicating that this is the depth range of maximum stress. If the magnetic anomalies were caused by stress-induced ground currents, these currents must have formed in the 10-25 km depth range. We also note that the local magnetic field had its dominant component opposite to the direction of the Earth's main field, implying a positive current flowing predominantly E-W.

To model this ground current we assume that the stressed rock volume extended 110 km in N-S and 50 km in the E-W direction, and was 10 km thick as shown in Figure 4a. We postulate that a p-hole current was established in this rectangular ground conductor. We placed 11 "wires" in this box, running E-W, each with a radius r = 5 km and buried 5 km below the surface as shown in Figure 4b. Assuming a homogeneous current through the wires we calculate the current needed to produce a magnetic field of 200 nT at the LY station 10 km N of the northern end of the ground conductor. With these admittedly crude assumptions we find 500,000 Amp. Horng-Yuan Yen's group has independently modeled the current and finds values in the order of 1,000,000 Amp (private comm). Taking into account the large cross section of the ground conductor, >1000 km^2, equal to >10^9 m^2, the current density would only need to be in the order of 1 mAmp/m^2.



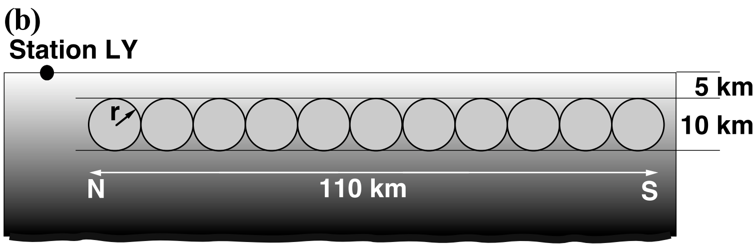


Figure 4a: Taiwan magnetometer network with rectangular "source volume" used for modeling the ground current. Solid line: approximate location of the Chelungpu fault. b: Cross section through the assumed ground conductor.

Next we ask what process, or processes, may exist in rocks in the upper portion of Earth's crust that can be activated by stress to produce electric currents with current densities of ≈1 mAmp/m^2.

EXPERIMENTAL

We report on experiments aimed at studying changes in electrical conductivity of rocks induced by stress. We used two igneous rocks: (i) a quartz-bearing, grayish-white medium-grained granite from Raymond, CA, available under the trade name Sierra White, with a bulk density 2.67 g/cm^3, a compressive strength 170 MPa, a tensile strength 13 MPa, and an average porosity 0.31 %; (ii) a quartz-free lower crustal anorthosite from Larvik, Norway, available under the trade name Blue Pearl, consisting almost entirely of Ca-rich feldspar (labradorite), with crystals 10-25 mm in size, a bulk density 2.68-2.72 g/cm^3, a compressive strength 180-190 MPa, a tensile strength 13 MPa, and a porosity 0.12-0.16 %. The granite was available in the form of slabs of different thickness with saw-cut surfaces. The anorthosite was available as 30 x 30 cm^2 tiles, 9.5 mm thick.

Contrary to the procedures used in most rock deformation studies (Lockner and Byerlee 1985; Lockner 1995; Yoshida et al. 1998; Takeuchi and Nagahama 2001) we did not load our rock samples across their entire cross section but only over a small subvolume, leaving the surrounding rock largely stress-free. All samples were air-dry. The rocks were loaded uniaxially between steel pistons, using a SATEC 500 QC hydraulic press at load rate from 1-5 MPa/min, using cylinders, 7.3 cm diameter or rectangular bars, 4 x 22 cm^2, electrically isolated from ground by 0.8 mm thick sheets of dense polyethylene with a resistance of >10^{14} Ω. We applied conductive Cu tape to the rock surface and used the pistons as electrodes. We measured the dc currents through the stressed and unstressed rocks or the dc current from the pistons, both biased at +100V, to the grounded metal frame. We used Keithley 486 and 487 picoampmeters for current and a Keithley 617 electrometer for surface potential measurements. (Freund et al. 2004).

GRANITE

We first describe an experiment with an 8 mm thick slab of Sierra White granite, larger than the piston diameter as shown in the insert in Figure 5a. The rock was loaded at 5.6 MPa/min. Before and during loading we applied dc voltages from 0 V to +1000 V in +100 V increments for 30 sec at each step. The response was ohmic, suggesting that the current through the rock is not controlled by charge carrier injection at the electrodes. Figure 5b shows the conductivity as a function of time. At zero load, the value is 10^{-6} S/m. Upon loading the conductivity increases rapidly by a factor of 4 and continues to increase slightly at higher loads. These results provide evidence that there is a stress-induced increase in the electrical conductivity of dry granite.

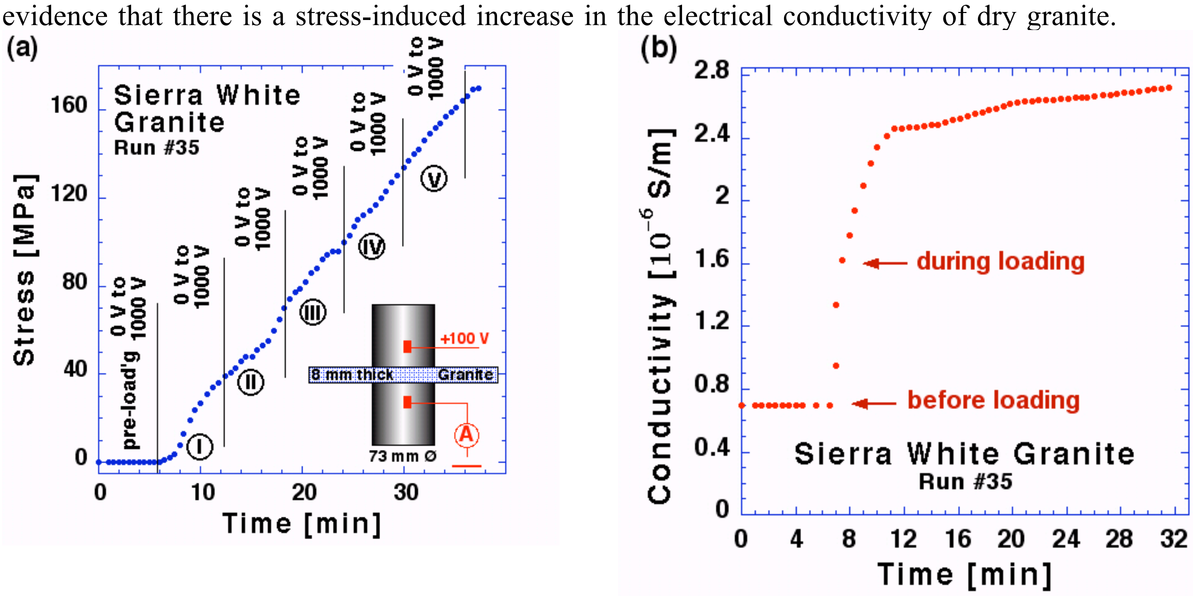
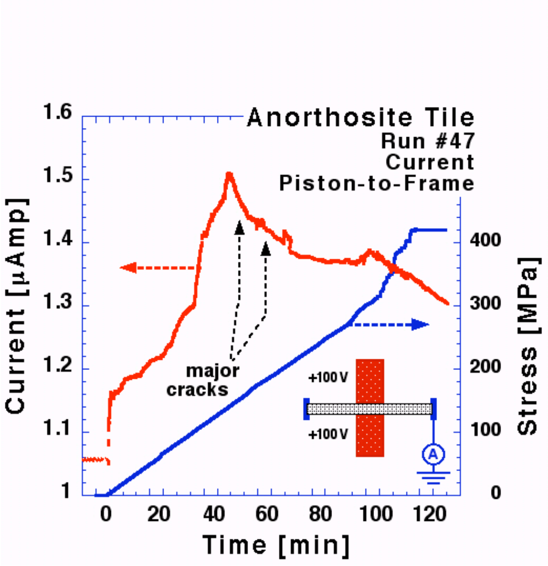


Figure 5a: Loading curve and b: stress-induced changes in conductivity of an air-dry granite slab.

We did additional experiments to address the question whether the conductivity increase is noted only in the rock that is being stressed between the pistons or also outside the pistons, in the nominally unstressed rock. The results showed that, indeed, the conductivity in the rock around the pistons was affected. This leads us to consider the possibility that charge carriers, which are activated in the stressed volume, the "source volume", flow outward, causing the conductivity in the surrounding rock to also increase.

ANORTHOSITE

Next we used a 30 x 30 x 0.95 cm^3 anorthosite tile confined in a metal frame. We biased both pistons at +100 V with the periphery of the tile to ground as depicted the insert in Figure 6. Under these conditions what is being measured is the current from the pistons to the periphery of the tile, i.e. the current flowing out of the source volume through essentially unstressed rock to the frame. Upon loading the current increased near-instantly from 1.06 to 1.16 μAmp as shown in Figure 6 and then continued to increase to ≈1.5 μAmp, before major cracks reduced it.

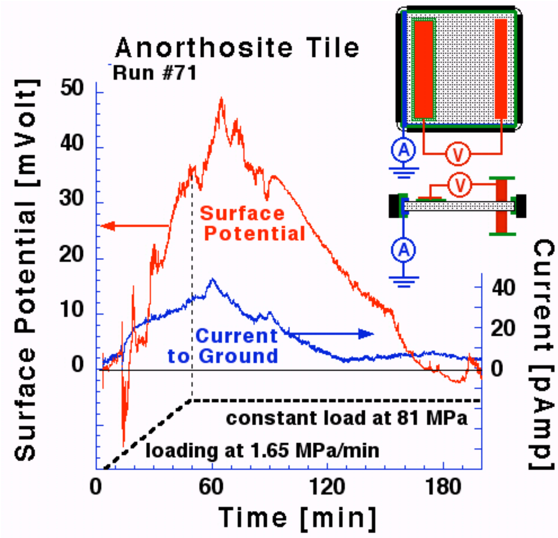


This experiment still left us with some uncertainty as to how much current was surface current, flowing along the surface of the rock. We therefore added guard electrodes on both sides of the tile halfway between the pistons and the frame made of 6.3 mm wide Cu stripes. The results indicate that the guard electrodes captured ≤30% of the current flowing from the pistons to the periphery, while ≥70% of the current passed through the interior (Freund et al. 2004).

Figure 6: Increase in the conductivity in air-dry (quartz-free) anorthosite stressed in the center of a 30x30 cm^2 tile, indicating outflow of p-hole charge carriers from the "source volume".

The experiments presented so far suggest that, upon application of stress, an electric current flows out from the stressed rock volume into the surrounding rocks. If this is true, the rock can be said to behave like a battery. To further test this idea, we set up an experiment, which we call the "battery experiment", where we did not apply any external voltage but simply loaded a partial rock volume and measured the outflowing electric current. We placed rectangular pistons with a 22 x 4 cm^2 footprint close to one edge of an anorthosite tile and a 12 mm wide collector electrode along a 22 cm long section of the opposite edge as depicted in the insert in Figure 7. Both pistons were in electrical contact with the rock but insulated from the press. In addition we placed a capacitive sensor made of Al sheet, 77 x 280 mm^2, 0.8 mm above the rock surface, measuring the potential difference to the pistons with the electrometer. We applied the load at a constant rate for 50 min and then kept the load constant at 81 MPa for the next 2 hrs, while continuously measuring the surface potential and the outflowing current to ground.

As shown in Figure 7 a potential difference developed between the pistons and the capacitive sensor as soon as we began loading, indicating that the rock surface about 20 cm away from the pistons acquired a positive charge. For this we infer that the "source volume" between the pistons



became negatively charged. When we switched to constant load the surface potential continued to rise for a few minutes, reached ≈50 mV, and then slowly decayed. The positive sign confirms the presence of positive charge carriers. Accordingly we record a positive current that flows out of the "source volume" to ground. The current reaches nearly 40 pAmp.

Figure 7: "Battery" experiment showing that, upon application of stress, charges flow out of the "source volume" between the pistons (right) through unstressed rock to the electrode (left). Current, surface potential and load versus time.

DISCUSSION

NATURE OF THE CHARGE CARRIERS

The experiments described here are diagnostic of changes in the electrical conductivity when air-dry granite and anorthosite are subjected to stress. Though we have not yet varied important parameters and did not yet include water-saturated rocks, we see evidence of charge carriers that pre-exist in these igneous rocks in an electrically inactive, dormant state and are being activated by the application of stress. The charge carriers are electronic in nature and positive. Hence, they are defect electrons. From earlier studies (Freund et al. 1993; Freund 2003) we know that these defect electrons reside in the O^{2-} sublattice. Hence, they are positive holes or p-holes for short.

A p-hole is best described as the electronic state that is associated with an O^- in a matrix of O^{2-}. The O^- tend to pair up to form O^-–O^- bonds. From a chemist's perspective an O^-–O^- bond is a peroxy bond or peroxy link, $O_3X/^{OO}\backslash XO_3$, with X = Si^{4+}, Al^{3+}, etc. From a physicist's perspective an O^-–O^- bond is a positive hole pair, PHP, localized and, hence, electrically inactive.

PHPs can be activated by breaking the O^-–O^- bond apart. Increasing levels of stress, for instance, generate dislocations, which are line defects, or shear planes, which are planar defects. During deformation dislocations appear in huge numbers (Rowell et al. 1981; Hanson and Spetzler 1994), in the order of 10^{10}–10^{12} cm^{-2} (linear cm per cm^3). They sweep through the crystal structures displacing rows of atoms in a zipper-like fashion. In the process they rip apart PHPs that lie in their path, thus activating p-holes and causing the electrical conductivity to increase.

SELF-GENERATED CURRENTS IN THE GROUND

Our "battery experiment" depicted in Figure 7 illustrates that p-holes spread out of the source volume into the surrounding unstressed rock. Such a p-hole outflow constitutes a current. The question is whether we can use this outflow current measured to estimate the currents that must have passed through the ground prior to the Chi-Chi earthquake generating a magnetic anomaly.

In the “battery experiment” the volume of rock between the pistons was 100 cm^3. The current flowing to the collector electrode peaked at 40 x 10^{-12} Amp. With 1 Amp defined as 1 Coulomb (6 x 10^{18} charge carriers) per sec, every cm^3 of rock released 2 x 10^6 p-holes per sec. To estimate the magnitude of a p-hole current prior to the Chi-Chi event we take the volume of rock under stress prior to the Chi-Chi earthquake. We assumed that this block is defined by the S-N extent of the Chelungpu fault, 110 km, multiplied with the thickness, 10 km^2, and multiplied in the E-W direction by, say, 50 km. The “source volume” thus defined is ≈50,000 km^3 or 5 x 10^{19} cm^3. Assuming that we can linearly extrapolate the data from our “battery experiment” we multiply 5 x 10^{19} cm^3 with the number of p-holes released per cm^3 per sec. We obtain ≈10^{26} p-holes sec^{-1} or ≈10^8 Amp, 10^2 times more than needed to generate a magnetic field of 200 nT at the LY station.

Since the magnetic field anomalies recorded at LY and TW were similar, we have to assume that the ground current formed a continuous sheet of a pulsating E-W flowing current sheet extending over the distance between the two stations, ≈150 km. For such a continuous current sheet to develop the “source volume” must have behaved as a single block. This means that the block was electrically continuous, i.e. it could not have been dissected by crisscrossing fissures and faults filled with brine-soaked gouges. Brine-soaked gouges have an electrolytical conductivity that is higher than the p-hole conductivity of rock by a factor of 10^3–10^4 (Revil and Glover 1998). In other words, a 1 km deep, 10 cm wide fault will carry as much current as a 1 km deep block of rock 0.1-1 km wide. If the “source volume” had been dissected by numerous crisscrossing brine-soaked fissures, they would have short-circuited the p-hole current, preventing the current sheet.

The idea of a rigid block capable of developing a current sheet is supported by the report that the section of the Chelungpu fault, which broke during the Chi-Chi event, had been relatively quiescent for some time (Wang and Chin 1998) and can therefore be assumed to have been rigid.

TWO-PRONGED CURRENT LOOP

So far we have considered only one leg of the postulated current, the current sheet formed by the stress-activated p-hole charge carriers. However, for any sustained current to flow, the circuit has to be closed. In our “battery experiment” circuit closure was provided through the electric ground as indicated by the dashed looped arrow in Figure 8a. In a geological situation such as before the Chi-Chi earthquake we may consider circuit closure through a different current path.

(a)

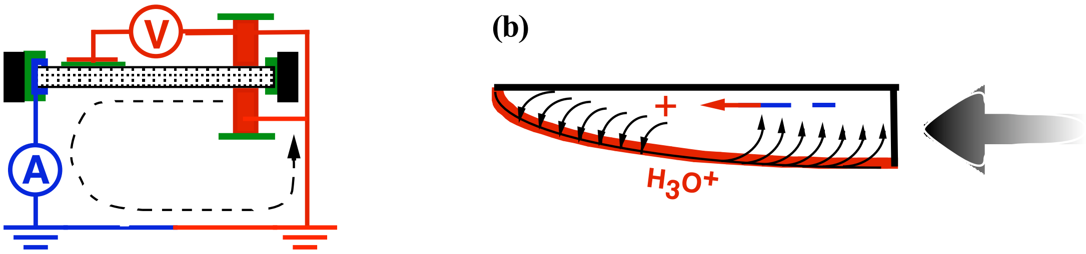


Figure 8a: Closed current circuit for p-hole current flowing through the rock and electrons flowing through ground. b: Proposed model for a ground current flowing E-W in the block east of the Chelungpu fault, connecting to the high electrolytic conductivity along the brine-soaked fault plane and closing the circuit by protons H^+ from H_3O^+ streaming into the “source volume”.

A possible scenario is depicted in Figure 8b, where we sketch an E-W cross section through a wedge-shaped block ~50 km wide and 10-25 km deep, assumed to extend 110 km in the S-N direction. The block rides on the curved Chelungpu fault to which we assign a high conductivity due to brine-saturated gouge. The block is being pushed from the east by the subduction zone off the Pacific coast of Taiwan. The build-up of stress causes a p-hole current, which will flow out of the "source volume" in all directions. The p-hole outflow sets up a polarization field, which counteracts the charge carrier outflow. However, along the western edge where the highly conductive Chelungpu fault intersects the Earth's surface, the p-hole current connects to an electrolytic current flowing downward and eastward along the fault plane. The fault plane thereby acts in two functions: (i) it focuses the p-hole currents in the predominant E-W direction and (ii) it provides closure of the circuit, possibly by way of protons H^+ streaming into the "source volume" to compensate for its negative charge as shown the upward curved arrows in Figure 8b.

REGIONAL GROUND POTENTIAL

Though such a scenario is not unique, it provides the opportunity to discuss qualitative features that may be testable in the field. One predictable consequence of p-holes being activated in the "source volume" and spreading out into the surrounding rocks would be changes in the ground potential at the Earth's surface. The area into which p-holes are spreading can be expected to acquire a positive ground potential relative to the surrounding areas and to the area above the "source volume". The surface above the "source volume" may acquire a negative charge. Such changes in ground potential have been considered as a cause for ionospheric perturbations above the epicentral regions of impeding large earthquakes (Pulinets et al. 2003; Liu et al. 2004).

CHANGES IN WELL WATER

In Figure 8b we hypothesize that the negative charge in the "source volume", caused by the outflow of p-holes, would attract an influx of protons from the fault plane below. A similar influx of protons could come from above the "source volume", i.e. from the water-saturated uppermost portion of the crust. In this case we may consider the possibility that the pH values of water in deep wells in this region above the "source volume" would tend to become more basic.

CURRENT PULSES

The model depicted in Figure 8b also allows us to address the question: Why did the pre-Chi-Chi magnetic anomalies occur in pulses?

A definite answer is not yet at hand but we note that, according to the model, the electric circuit is made of two at least partial currents, a p-hole current flowing out of the "source volume" and an electrolytic current along the Chelungpu fault plane closing the loop. In order for a net current to flow the circuit must be closed. The two partial currents will be coupled via their respective electric fields. Such coupled systems exhibit a wide variety of types of dynamical behavior including periodicity, quasi-periodicity and chaos (Kiss et al. 2000). Electric fields are particularly efficient in providing strong long-range coupling.

When p-holes are activated in ever increasing number by an ever increasing tectonic stress, they stream out of the "source volume". The "source volume" becomes negatively charged relative to its surrounding. Positive charge carriers available in the surrounding, for instance protons, H^+, will then experience a force pulling them into the "source volume". Depending on the geometry of the system, the diffusivity of the outflowing p-holes, and the diffusivity of the inflowing compensating charges conditions will exist (Hudson 1999) under which the two partial currents start to interact in such a way as to produce oscillations.

CONCLUSIONS

Igneous rocks such as (quartz-bearing) granite and (quartz-free) anorthosite, when placed under stress, activates dormant electronic charge carriers, i.e. defect electrons in the O^{2-} sublattice, also known as positive holes or p-holes for short. The p-holes spread out of the stressed rock volume into the surrounding nominally unstressed rock. The p-hole outflow represents an electric current. Scaling up the number of p-holes activated per cm^3 in laboratory experiments allows us to appraise the number of charge carriers activated prior to the Chi-Chi earthquake and compare this number with the estimated magnitude of the calculated ground currents.

Strong and persistent pre-earthquake magnetic anomalies such as seen before the Chi-Chi event have never been recorded. One reason may be that dense magnetometer networks, which register local magnetic fields at relatively high data acquisition rates, are rare. The fact that the stations LY and TW were fortuitously close to the Chelungpu fault allowed these anomalies to be recorded with almost unattenuated intensity. In addition, the Chi-Chi earthquake was unusual in other respects (Ma and Chiao 2003). It not only stands out as the largest earthquake of the 20th century in Taiwan, but it also occurred in along a section of the fault, which had not seen major seismic activity during the past 100 years (Wang and Chin 1998). From this we can infer that the block to the east of the Chelungpu fault was relatively free of crisscrossing gouge-filled fissures. We conjecture that the rigidity of the block allowed the stress-activated p-hole current to develop as a continuous E-W flowing current sheet. We further conjecture that the p-hole current coupled to an as yet unspecified countercurrent, leading to the observed oscillations. Using cross-correlation analysis [unpubl. results] the HL station along the Pacific coast can be shown to have registered the same magnetic field pulses as the LY station 150 km to the west but at a much reduced intensity level, <1%. Without the knowledge of the signals recorded at LY and their distinct time sequence, the signals at HL would have remained unrecognized, buried in the noise.

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